MINISTRY OF EDUCATION
National University of Science and Technology
POLITEHNICA Bucharest
Doctoral School of
Industrial Engineering and Robotics

# PHD THESIS

# Research with regard to structural optimization of industrial products manufactured using additive technologies

*PhD student,*
**Alexandru – Mihai C. Cișmilianu**

*Scientific Coordinator*,
**Prof. Univ. Dr. Ing. Ec. Cristian – Vasile Doicin**

**- Bucharest -**

**- 2023 -**

**MINISTRY OF EDUCATION**
**National University of Science and Technology**
**POLITEHNICA Bucharest**
**Doctoral School of**
**Industrial Engineering and Robotics**

# PHD THESIS

## Research with regard to structural optimization of industrial products manufactured using additive technologies

## SUMMARY

***PhD student,***
**Alexandru – Mihai C. Cișmilianu**

***Scientific Coordinator*,**
**Prof. Univ. Dr. Ing. Ec. Cristian – Vasile Doicin**

**- Bucharest -**

**- 2023 -**

**MINISTRY OF EDUCATION**
**National University of Science and Technology**
**POLITEHNICA Bucharest**
**Doctoral School of**
**Industrial Engineering and Robotics**

**CSUD decision UPB no. 976 from 08.12.2022**

# PHD THESIS

## Cercetări privind optimizarea structurală a produselor industriale fabricate prin tehnologii aditive / Research on structural optimization of industrial products manufactured through additive manufacturing

***PhD student,***
**Alexandru – Mihai C. Cișmilianu**

## DOCTORAL COMMITTEE

| | | |
|---|---|---|
| President | Prof. univ. dr. ing. IONESCU Nicolae | National University of Science and Technology POLITEHNICA Bucharest |
| Scientific Coordinator | Prof. univ. dr. ing. DOICIN Cristian - Vasile | National University of Science and Technology POLITEHNICA Bucharest |
| Member | Conf. univ. dr. ing. ULMEANU Mihaela | National University of Science and Technology POLITEHNICA Bucharest |
| Member | Prof. univ. dr. ing. BÂLC Nicolae | Technical University of Cluj-Napoca |
| Member | Prof. univ. dr. ing. OANCEA Gheorghe | Transilvania University of Brasov |

**- 2023 -**

**CONTENTS**

# INTRODUCTION

Additive manufacturing technologies are used and improved for over 30 years, but while they dramatically broaden the horizon of parts that can be produced, there are still strict limitations and rules. The limitations differ depending on the additive manufacturing technology chosen for production and depending on the field for which the part is made, it is often necessary to introduce additional steps and additional checks for parts with complex cavities, both in design and manufacturing.

Structural optimization is a tool used for reduction part development time thus adding value to it, through improving experience and strengthening the designer's intuition by using an automated process. (Abaqus Docs, 2020).

Structural optimization has been used in the industry for decades, indicating, over time, the need for commercial software applications and their constant improvement in order to perform and differentiate themselves from their competitors.

By implementing structural optimization techniques, whether it is the realization of new parts or the optimization of an existing product, the number of iterations between the design team and the structural analysis team is reduced. This can lead to a much lower cost of time and personnel, from input data to a detailed concept and final result.

Structural optimization is becoming an increasingly used part of the product development process, especially in areas where mass minimization brings significant cost reductions, such as aeronautics and space.

Taking into account all the elements presented above, the **general objective of the doctoral thesis** is to develop a robust structural optimization methodology starting from the practical experience of optimizing complex products, to demonstrating the possibility of its customization for different technologies, including additive manufacturing technologies with metal powders, to defining the design rules required for cavities, powder evacuation methods, additional manufacturing steps required to manufacture a complex part with cavities.

# LIST OF NOTATIONS AND ABBREVIATIONS (extract)

| *Nr. Crt* | *Abrev.* | *Semnificație/ Significance* |
|---|---|---|
| 1. | AESO | Optimizare structurală evolutivă aditivă / Additive ESO |
| 2. | ALM | Fabricație aditivă prin adăugare de straturi / Additive Layer Manufacturing |
| 3. | AM | Fabricație aditivă / Additive Manufacturing |
| 4. | ASTM | Societatea Americană pentru testare și materiale / American Society for Testing and Materials |
| 5. | BESO | Optimizare structurală evolutivă bidirecțională / Bidirectional ESO |
| 6. | CAD | Proiectare asistată de calculator / Computer Aided Design |
| 7. | CAM | Fabricație asistată de calculator / Computer Aided Manufacturing |
| 8. | CNC | Control numeric computerizat / Computer Numerical Control |
| 9. | CT | Tomografie Computerizată / Computed tomography |
| 10. | DDP | Programare dual-discretă / Dual Discrete Programming |
| 11. | DED | Depunere directă de energie / Directed Energy Deposition |
| 12. | DLP | Procesarea digitala a luminii / Digital Light Processing |
| 13. | DMD | Depunere direcționată de metal / Direct Metal Deposition |
| 14. | DMLS | Sinterizare directă prin laser a pulberilor metalice / Direct Metal Laser Sintering |
| 15. | DOF | Degree Of Freedom / Grade de libertate |
| 16. | DSC | Optimizare structurală hibridă deformabilă / Deformable Simplicial Complex Structural Optimization |
| 17. | ESA | Agenția Spațială Europeană / European Space Agency |
| 18. | ESO | Optimizare structurală evolutivă / Evolutionary Structural Optimization |
| 19. | FDM | Depunere de material topit / Fused Deposition Modelling |
| 20. | FFF | Fabricație cu filament topit / Fused Filament Fabrication |
| 21. | HEX | Hexadecimal |
| 22. | HIP | Presare izostatică la cald / Hot Isostatic Pressing |
| 23. | HM | HyperMesh |
| 24. | MAM | Fabricație aditivă cu materiale metalice / Metal Additive Manufacturing |
| 25. | MEF | Modelare cu Element Finit / Finite element Modeling |
| 26. | MIG | Gaz inert metalic / Metal Inert Gas |
| 27. | MIT | Institutul de Tehnologie Massachusetts / Massachusetts Institute of Technology |
| 28. | MUCN | Mașină Unealtă cu Comandă Numerică / Numerically Controlled Machine |
| 29. | NASA | Administrația națională de aeronautică și spațiu / National Aeronautics and Space Administration |
| 30. | NC | Control numeric / Numerical Control |
| 31. | NOM | Microstructuri non-optimale / Non-Optimal Microstructures |
| 32. | NP ND | Spațiu de non-proiectare / Non-Design Space |
| 33. | OMP | Microstructură optimă cu penalizare / Optimal Microstructure with Penalization |
| 34. | OT | Optimizare Topologică / Topology optimization |
| 35. | P DS | Spațiu de proiectare / Design Space |
| 36. | PBF | Fuziune pe pat de pulbere / Powder Bed Fusion |
| 37. | RAMP | Aproximarea rațională a proprietaților de material / Rational Approximations of Material Properties |
| 38. | RP | Prototipare rapidă / Rapid Prototyping |
| 39. | SIMP | Microstructuri izotropice solide cu penalizare / Solid Isotropic Microstructure with Penalization |
| 40. | SLM | Topire selectivă cu laser / Selective Laser Melting |
| 41. | SLS | Sinterizare selectivă cu laser / Selective Laser Sintering |
| 42. | SPC | Single Point Constraint / Constrângerea gradelor de libertate a unui singur punct |
| 43. | xFEM | Modelare cu element finit extinsă / Extended Finite Element Method |

# LIST OF DEFINITIONS (extract)

The definitions presented in the table represent an extract of the general terminology used in structural optimization, as it is used in the thesis.

Tab. 1 Definitions

| *No.* | *Name* | *Definition* |
|---|---|---|
| *1.* | **Concept** | Term used in thesis as initial/preliminary 3D model. |
| *2.* | **Manufacturing constraint** | Phrase used in structural optimization software applications. It requires the generation of optimization results similar to manufacturing methods (casting, extrusion, etc.). |
| *3.* | **Safety factor** | Factor imposed by regulations or calculation procedures specific to each field or project. |
| *4.* | **Objective function** | a function of a design variable that must be minimized or maximized, which is the key function in any structural optimization calculation; (Abaqus, 2017). |
| *5.* | **Topological optimization** | It is a method of identifying the distribution of material in the defined design space, by respecting the imposed constraints. The distribution of material is made according to the imposed objective function. (Brackett D. A., 2011)<br><br>Theoretical contribution:<br>Topological optimization identifies the best distribution of material in a design space defined so that the objective function (stiffness, modal frequency), respecting a series of imposed constraints (boundary conditions, direction of displacements, symmetries), to tend to an extreme (maximum or minimum) by reducing volume or mass. |
| *6.* | **Structural optimization** | Structural optimization is a method of determining design variables, which controls the shape, material properties or dimensions of a structure so that it complies with certain restrictions and improves certain properties to obtain optimal structures in terms of better mechanical properties. (Vlădulescu, 2022) |
| *7.* | **Design constraints** | Conditions imposed on the structure to be optimized. (CRM, 2017). |
| *8.* | **Sensitivity** | The sensitivity analysis is a modern instrument used for deepening the knowledge of the behavior of a system of any nature: technical, economic, biological, social, and so on. In essence, if the course of a process (the behavior of a system) described by the trajectories of the state and output in time and/or spatial coordinates undergoes significant changes to relatively small deviations of a parameter, for example, from its nominal value, we will say that the process (system) is "sensitive" to that parameter (Ştefan Ungureanu, 2021). |
| *9.* | **Non-design space** | Theoretical contribution:<br>Non-design space is the geometrically defined space/multitude of spaces in which the optimizer cannot act. |
| *10.* | **Design space** | The design space is a solid or an assembly of solids or finite elements that imposes the outer geometric limits of the shape resulting from optimization. (Altair, 2021) |
| *11.* | **Design variables** | real numerical quantities characterizing the structure from a geometric and functional point of view (CRM, 2017). In the case of structural optimization, they represent the parameters that change during the optimization process (Abaqus, 2017). |

## STRUCTURE AND CONTENT OF THE DOCTORAL THESIS

The doctoral thesis consists of 13 chapters and 6 annexes, containing 238 figures and 111 tables, presented in 361 pages.

In the first chapter, the current state of the art on additive manufacturing technologies is presented, and in the second chapter, the current state of the art on structural optimization is presented. The information in these chapters represents the foundation for customizing the process of optimizing a concept for additive manufacturing technology. In the third chapter, the main objective of the research and development activity, the research and development directions and the methodology proposed to achieve the main objective are presented. In the fourth chapter, contributions on the development of an initial optimization methodology are presented, following that it will be validated in the case studies from the paper. In the fifth chapter, an example of applying and validating the developed methodology and at the same time customizing the structural optimization process for non-dismountable assemblies is presented. In the sixth chapter, the optimization methodology for the case study on structural optimization customization for manufacturing the redesigned result for milling on a CNC center is validated. In the seventh chapter, the optimization methodology is validated again, in this case, for customizing the structural optimization towards milling on a CNC center of an assembly of parts. In the eighth chapter, the customization of structural optimization for additive manufactured parts in the context of a project with ESA (European Space Agency) is presented, the optimization methodology being validated. In the ninth chapter, starting from chapters 5-8, a summarized comparative analysis is made on the application of the initial methodology and the general methodology for structural optimization is generated. In the tenth chapter, contributions with regard to the design rules for powder evacuation from complex structures with cavities manufactured through additive manufacturing with metallic powders are presented. Chapter eleventh presents contributions on the production and verification steps required for a part with cavities produced through additive manufacturing with metallic powders within projects with ESA. In the twelfth chapter, the successful use of the optimization methodology is highlighted by applying it in two new study cases and three distinct software applications, applications for which a comparative study is carried out between them. In the last chapter, the general conclusions of the thesis are presented, the author's own contributions are highlighted and future research directions are exposed. It is observed that the general objective and the specific objectives stated by the author in this thesis are achieved.

## TOPIC CHOICE JUSTIFICATION

Within the doctoral thesis, *Research with regard to structural optimization of industrial products manufactured using additive technologies*, research and contributions are presented, all with the focus on the principal objective, that of developing a robust structural optimization methodology starting from the practical experience of optimizing complex products, to demonstrating the possibility of its customization for different technologies, including additive manufacturing technologies with metal powders, to defining the design rules required for cavities, powder evacuation methods, additional manufacturing steps required to manufacture a complex part with cavities.

In the thesis an in-depth and undocumented subject is addressed, that of a robust structural optimization methodology and variations thereof in which structural optimization can be customized for pre-selected manufacturing technology. This methodology has been applied in real cases, either from scratch or from existing models.

# PART I

# STATE OF THE ART OF ADDITIVE MANUFACTURING AND STRUCTURAL OPTIMIZATION OF INDUSTRIAL PRODUCTS

## Chapter 1. State of the art on additive manufacturing

### General notions

The current chapter contains information on the state of the art on additive manufacturing technology starting with general notions, followed by a comparison between additive manufacturing technology and conventional milling manufacturing, classification of additive manufacturing technologies, production steps in additive manufacturing and conclusions.

### Additive manufacturing vs. conventional manufacturing

Since it has appeared, the technology initially described as Rapid Prototyping (RP) revolutionized the industry because prototypes could be obtained at low cost, even if the lead times for a single prototype were significant. But technologies have evolved, the time to make a single part has decreased, as well as costs, the volume of documentation required and the number of steps required. The evolution of this technology has led to the elimination of problems and, at the same time, of many common manufacturing constraints. As the technology has evolved, the name of Rapid Prototyping, was used also as Additive Layer Manufacturing (ALM), Additive Manufacturing (AM), 3D Printing and so on. (Walmart, 2017), (H. Paris, 2016)

The main difference between additive manufacturing and conventional manufacturing is represented by the difference in the manufacturing process structure. In conventional manufacturing (e.g. milling on a CNC machine) the technological process involves removal of material, and in additive manufacturing, the technological process involves the addition of material. (Walmart, 2017), (H. Paris, 2016), (S.T. Newman, 2015)

### Classification of additive manufacturing technologies

To date, a multitude of additive manufacturing technologies have emerged, many of which go beyond just obtaining a prototype or demonstration model. In the development of the technology, it was aimed at developing new methods to be able to use more and more materials, regardless of their state of aggregation.

According to Wohlers, in 2011, approximately 300, millions of dollars were spent on the raw material needed for additive manufacturing (Wohlers, 2021). Although there is a wide variety of materials types, the Wohlers group divided, similar with the ASTM F2792 standard, all available materials for the additive manufacturing process in the following categories:

Tab. 2 Material compatibility – additive manufacturing process (Wohlers T. , 2012)

| | Binder Jetting | Direct Energy Deposition | Material Extrusion | Material Jetting | Bed Fusion | Sheet Lamination | Vat Photopolymerization |
|---|---|---|---|---|---|---|---|
| Polymers and variations | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Composites | ✓ | | | ✓ | ✓ | | ✓ |
| Metal | | ✓ | | ✓ | ✓ | ✓ | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Metallic hybrid** | | ✓ | | | | ✓ | |
| **Ceramics** | ✓ | | | | ✓ | | ✓ |
| **Paper** | | | | | | ✓ | |

Additive manufacturing technologies used for metallic materials are presented below.

Metal-Additive Manufacturing (MAM) has huge potential to offer unprecedented conceptual freedom, this is only possible if the concept is properly designed for the chosen manufacturing technology (Huang S. H., 2013), (Ulu, 2018). This type of manufacturing brings added value because it makes it possible to produce lighter parts with similar performance by taking advantage of the increased freedom in the concept of parts, producing environmental and economic advantages in industries where these elements are critical, such as aerospace, space, medical and power generation (Huang S. H., 2013), (Huang R. R., 2016), (Khajavi, 2014), (Ulu, 2018). Relatively high (apparent or real) production costs for MAM slow down the adoption of the technology in most cases (Huang S. H., 2013), (Thomas, 2014), (Ulu, 2018). Studies show that structural optimization applied to parts that are intended to be manufactured MAM can reduce material consumption, in this case, the consumption of metal powders, thus reducing the cost of material while maintaining the same performance for which the part was calculated (Tomlin, 2011), (Cheng, 2017), (Wang X. X., 2016), (Ulu, 2018). Classical topological optimization minimizes structural load up to the constraint imposed by varying the volume fraction of the total working volume made available (Bendsoe M. P., 2013), (Eschenauer H. A., 2001), (Rozvany, 2001), (Suzuki, 1991), (Ulu, 2018), the result of this analysis directly influencing the cost in terms of material consumption (Rosen, 2014), (Doubrovski, 2011), (Zegard, 2016), (Gaynor, 2014), (Dede, 2015), (Ulu, 2018). The cost associated with material consumption is only one of the factors driving the total cost of the part, depending on the design of the part, associated costs can be added, such as energy costs, technical waste, including the positioning of the part in the working volume of the machine represents an important factor in increasing the total manufacturing price. (Thomas, 2014), (Ulu, 2018)

**The steps of the technological manufacturing process**

The additive manufacturing process of a part, usually, contains several steps (see (Ulmeanu & Doicin, 2018)):

1) Designing the 3D CAD model;
2) Saving it as a .STL file;
3) Processing the .STL file in the additive manufacturing machine software application;
4) Machine preparation and start of manufacturing;
5) Post-processing of the final part.

Although the steps are relatively similar for the rest of the technologies, the steps described below will relate to the additive manufacturing process with metal powders. The first step is to design the 3D CAD model taking into account a minimum set of rules, the part being "Designed for AM". In step two, the designed 3D CAD model generated in the previous step is saved as a .STL file. The designer of the part generates a 2D technical drawing which is then exported as a .PDF file. The third step is to process the STL. File. After receiving the model, depending on customer requirements and specifications in the 2D drawing, an additive manufacturing consultant checks the model and gives feedback with the necessary changes to obtain a higher quality part. The fourth step in the manufacturing process is the preparation of the additive manufacturing machine, which involves checking the powder level, completing the level with additional powder, if needed, and so on. In the same step, the manufacturing itself is being done. The last stage in the manufacturing process is represented by the post-processing of the part obtained through additive manufacturing, here including all the steps necessary to bring a part from the intermediate state and geometry, from the bed of the additive manufacturing machine, to the final state and geometry. (M.K. Thompson, 2016), (H. Paris, 2016), (S.T. Newman, 2015) In the sequence of classic post-processing phases presented in the paper, there may also be various options available (see Fig. 1 marked with **green**).

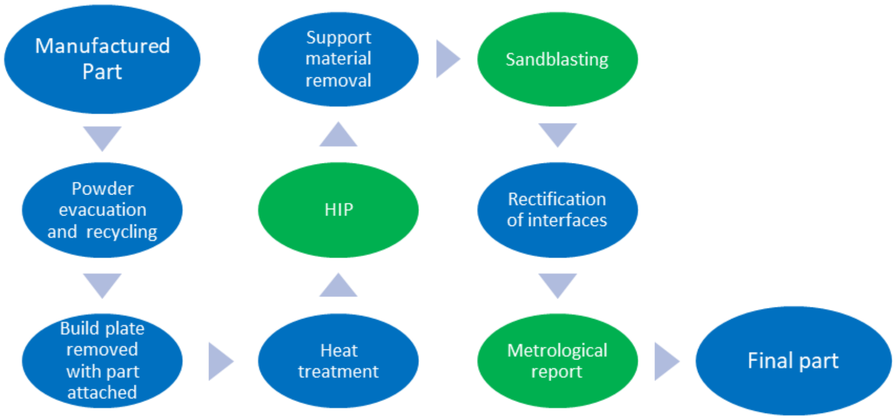



Fig. 1 Alternative to classic post-processing steps

**Conclusions**

From the analysis of the state of the art of additive manufacturing the following conclusions resulted:

- Additive manufacturing (at least for technologies working with metallic materials) can replace in particular cases conventional manufacturing that involves milling on CNC machines, especially in the case of complex parts. The resulting parts cannot be used directly because they often have to be finished at the interface areas of the assemblies in which they will be integrated. Hybrid additive manufacturing processes can produce finished parts from a single production step.
- From the point of view of the semi-finished product, additive manufacturing technologies have an advantage over milling technologies because it does not need semi-finished products, but only the raw material.
- In the pre-processing step, in the case of additive manufacturing, the process is much more direct and is not majorly impacted by the level of complexity of the piece.

1. From a production chain point of view, the additive manufacturing technology presents a much lower risk of possible delays due to third parties.

## Chapter 2. State of the art on structural optimization

**Introduction**

The state of the art on structural optimization is presented in the thesis starting with a classification of the structural optimization types, followed by the algorithms used in structural optimizations and continued with applying the structural optimization types in examples used in the aerospace industry.

Structural optimization is a method of determining design variables, which control the shape, material properties or dimensions of a structure, so that it respects certain restrictions and improves certain properties to obtain optimal structures from the point of view of mechanical properties. (Vlădulescu, 2022)

In the thesis, the study of structural optimization will focus especially the field of structural parts with space applications. In the space industry, a major impact on cost is given by the mass of the payload. By applying structural optimization methodologies and manufacturing components through additive manufacturing, space mission costs can be minimized. The costs for a payload to be sent into orbit are very high (**Error! Reference source not found.**), especially until the year 2010.

Tab. 3 Launch price in LEO (Low Earth Orbit)-extract (Jones H. W., 2018)

| Vehicle/Launcher | First launch date | $k/kg | Reference |
|---|---|---|---|
| **Ariane 44** | **1988** | **17.9** | (Wertz, 1996) |
| **Ariane 5G** | **1996** | **13.1** | (Futron, 2002) |
| Atlas IIA | 1991 | 19.8 | (Wertz, 1996) |
| Delta 3910 | 1975 | 28.0 | (Koelle, 1996) |
| Delta II | 1989 | 15.3 | (Futron, 2002) |
| Delta III | 1998 | 11.7 | (Koelle, 1996) |
| Falcon 9 | 2010 | 2.7 | (Spacex.com, 2020) |
| Falcon Heavy | 2018 | 1.4 | (Spacex.com, 2020) |
| H-2 | 1994 | 26.4 | (Wertz, 1996) |
| Rockot | 1994 | 10.4 | (Futron, 2002) |
| Saturn V | 1968 | 5.2 | Williams, 2016 |
| Space shuttle | 1981 | 61.7 | (Pielke, 2011) |
| Soyuz | 1966 | 7.6 | (Futron, 2002) |
| **Vega** | **2012** | **10.0** | **Wikipedia, Comparison, 2018** |

According to (Konstantinos, Evangelos, Alikem, Jack, & Lukas, 2019), structural optimization problems are presented mathematically under the expression:

$$Structural\ optimization \left\{ \begin{matrix} minimizes/maximizes\ f(x,y) \\ subject\ to \left\{ \begin{matrix} behavioural\ constraints\ on\ y \\ design\ constraints\ on\ x \\ equilibrium\ constraints \end{matrix} \right\} \end{matrix} \right\}$$

(Konstantinos, Evangelos, Alikem, Jack, & Lukas, 2019)

where, **f(x,y)** – **Objective function** – In a structural optimization problem, it aims to maximize or minimize the selected value (weight, volume, stress, etc.), **x** – **Design constraints** – vectors or functions describing the geometric or material properties of the concept, **y** – Function or vector describing the structure's response to the value x. (Vanderplaats, 1983)

**Classification of structural optimization variants**

Structural optimization can be divided into two broad categories, depending on the area to be optimized: local optimization, targeting specific areas of interest in a model, and global optimization, targeting the entire model or volume. Local optimization can be carried out directly using detailed optimization methods (see Fig. 2). Global optimization can be achieved with optimization methods to obtain a concept (see Fig. 2). In some specific cases, concept optimization methods, with additional steps introduced in the pre-optimization process, can be used in local optimization.

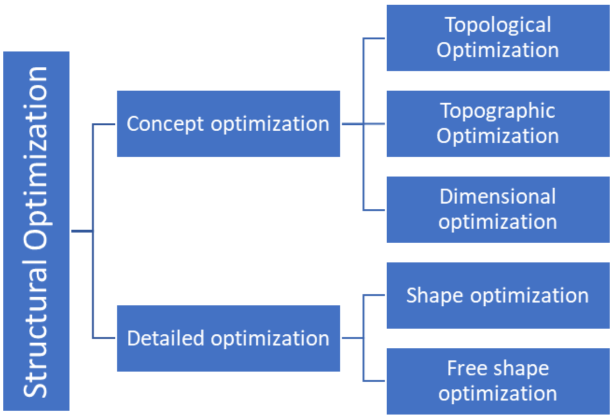



Fig. 2 Structural optimization classification

In this abstract only topological optimization is presented, the rest of the optimization types being detailed in the extenso version of the thesis.

Structural optimization, which is performed in order to obtain a concept, contains the most used types of structural optimization, including: topological optimization, topographic optimization and free size optimization.

Topological optimization (for definition see Tab. 1) is the first option in the case of structural optimization, which is carried out in order to obtain a concept of a part.

By using topological optimization, the optimal construction geometry can be established in a predetermined work envelope, based on principal stress-induced directions in the material, while taking into account constraints (interfaces, symmetry, production, etc.) and predefined objective function. Topological optimization is not limited to a specific type of elements. Topological optimization is used in a wide range of industries, from aeronautics, space, mechanics to civil engineering. Most manufacturing technologies require adaptation of the model for the chosen method. Post-processing is done even in the case of additive manufacturing with the Design for AM concept in mind.

Some examples of optimization are presented in the thesis, below is presented an example of topological optimization:

**Example 1. Topological optimization for a payload adapter**

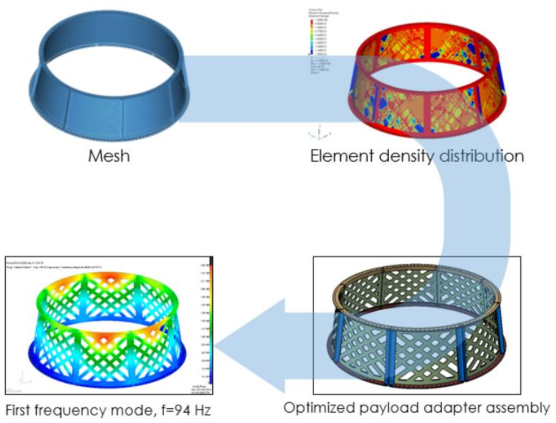



Fig. 3 Topological optimization for a payload adapter (Cismilianu, Petre, Liliceanu, & Bibire, 2017)

The example highlights the applicability of topological optimization to a part of an assembly in order to obtain a concept with minimum mass that distributes the stresses in the structure and achieves positive safety margins.

**The algorithms in structural optimization**

The current section presents the common algorithms used in structural optimization and the method of their operation. Among the optimization algorithms that can be at the basis of these commercial optimization software applications we find: SIMP (Solid Isotropic Microstructure with Penalization), RAMP (Rational Approximations of Material Properties), OMP (Optimal Microstructure with Penalization), NOM (Non-Optimal Microstructures), DDP (Dual Discrete Programming), "The Bubble-method" (Topological derivatives), Level set, Phase field, ESO (Evolutionary Structural Optimization), AESO (Additive ESO), BESO (Bidirectional ESO), xFEM (Extended Finite Element Method), DSC (Deformable Simplicial Complex).

Most optimization algorithms in commercial topological optimization software applications are similar in that they "juggle" with the density value to calculate and represent the resulting shape as optimal. According to (Johnsen, 2013), in order for them to be usable, they need a domain of geometrically fixed size ($\Omega^{mat}$) which is sometimes part of a larger domain (Ω) included in $R^2$ or $R^3$. The larger domain (Ω) is known generically as "design space" or design space, the domain in which the optimizer can act. The most widely used topological optimization algorithms are based on identifying compliance minimization, such as:

$$Stifness = \frac{1}{Compliance}$$

Hence resulting that minimizing compliance [dimensionless] induces maximization of structure stiffness [dimensionless].

**SIMP Algorithm** (Solid Isotropic Microstructure with Penalization)

The first most important algorithm in structural optimization is SIMP. It or versions of it is one of the main algorithms in topological optimization, being used at all levels, from handwritten programs for simple problems to commercial software applications in certain situations. (Johnsen, 2013)

SIMP is one of the optimization algorithms that is based on changing the density value to represent the resulting shape as optimal.

$$E_{ijkl}(x) = \rho(x)^p E^0_{ijkl}, \qquad p > 1$$
$$\int_\Omega \rho(x) d\Omega \le V; 0 \le \rho(x) \le 1, x \in \Omega \qquad (5)$$

(Johnsen, 2013)

where, $\rho$ – interpolated element density between 0 and 1 [dimensionless], $E_{ijkl}$ – element density at numerical value 1 [N/m], $E^0_{ijkl}$,– interpolated element density between 0 and 1 [N/m], $V$ – material limit imposed in % [dimensionless]], $\Omega$ – design space, the domain in which the optimizer can act [dimensionless], $p$ – penalization [dimensionless]

SIMP interpolates between the extreme values according to equations (5) where the choice of the penalization factor [dimensionless] ”$p$” less than 1 imposes a low probability that densities in the "grey" area will be considered, thus decreasing the stiffness/volume ratio. According to Hans (Eschenauer H. A., 2001), the numerical value which is to be imposed to the penalization factor in order for the optimization to provide correct results for „grey” area is minimum 3.

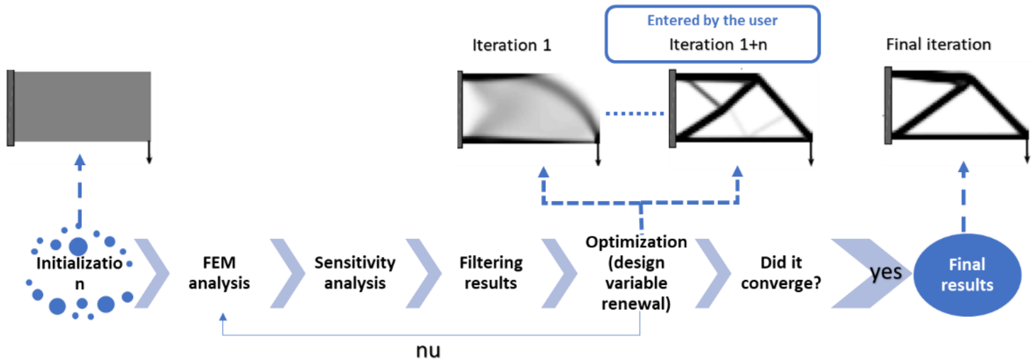



Fig. 4 SIMP algorithm workflow (Krylov, 2007)

**RAMP Algorithm** (Rational Approximations of Material Properties)

RAMP, as presented in (Johnsen, 2013) and in (Gersborg-Hansen A, 2005), is an algorithm that can also work with inputs in form of pressures, such as those from nature, taken from wind, water, snow, etc.

Although both SIMP and RAMP are density-based algorithms, RAMP shows clearer results when solutions are needed in compute cases with low required volume fraction (Johnsen, 2013).

**ESO Algorithm** (Evolutionary Structural Optimization)

ESO, as presented in (Querin, Steven, & Xie, 2000), is a "hard-kill" algorithm that only allows the removal of material with the ideology that an efficient structural component has stresses as evenly distributed as possible. (Johnsen, 2013)

**AESO/BESO** - ESO algorithm variants (Additive ESO Respectively Bidirectional ESO)

Based on the ESO algorithm, its variations, BESO and AESO, appeared in structural optimization. While ESO removes elements based on their stresses, AESO adds elements to obtain an optimal structure as shown in the schematic below. (Johnsen, 2013)

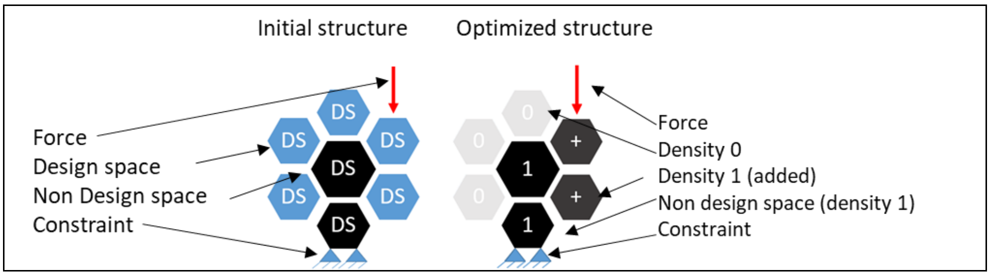



Fig. 5 Schematic example of AESO algorithm action – Input and result data (pictographic representation is own contribution)

BESO, on the other hand, is a topological optimization algorithm, first presented also by (OM Querin, 1998), which works by removing (or adding) a finite amount of material (or elements) from the working domain (design space) according to the schematics below.

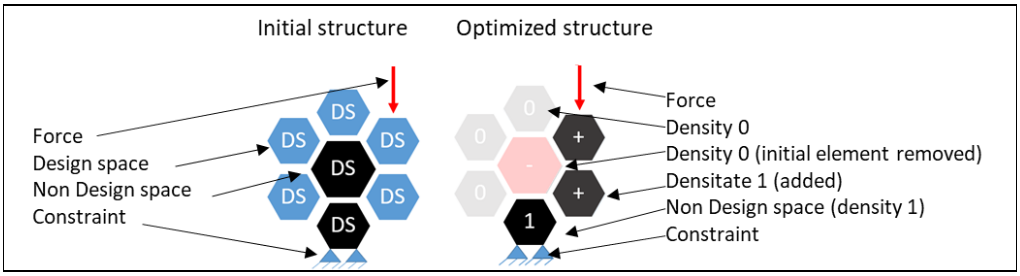


Fig. 6 Schematic example of BESO algorithm action – Input and result data (pictographic representation is own contribution)

In ANNEX 5 of the full version of the thesis, an exhaustive table comparing the topological optimization algorithms was extracted and translated.

**Comparison of basic algorithms compiled in Matlab with those existing in commercial applications**

An example of topological optimization is presented where a basic algorithm written in Matlab is compared with the commercial equivalent in the commercial MSC Nastran solver. From (B. Barroqueiro, 2019), the results of a classical cantilever beam problem are extracted. This comparison between a commercial software application and code written in Matlab (Andreassen, Clausen, Schevenels, Lazarov, & Sigmund, 2011), (Sigmund, 2001) is performed between Matlab and MSC Nastran, but also between two structural optimization algorithms. The optimization results are presented in all situations at the same increments of iterations 20, 90, 150, 300 in order to observe similarity between the results.

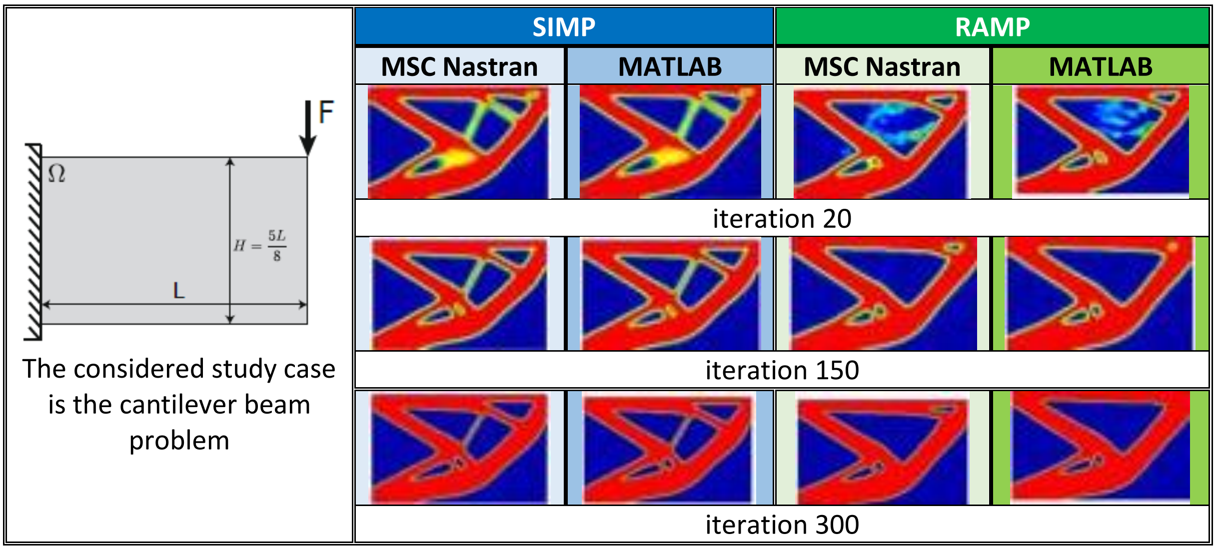


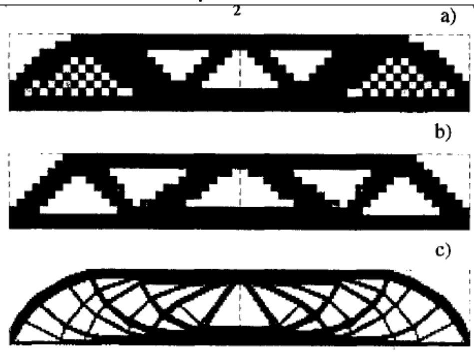

Fig. 7 Topological optimization of a cantilevered beam using MSC Nastran for comparison and code written in Matlab (B. Barroqueiro, 2019)

The complete results and their explanation are presented in extenso version of the thesis.

**Specific errors in structural optimization**

Regardless of the software application in which structural optimization is done, there are some specific errors that can occur in certain cases.

Tab. 4 Visual exemplification of errors in topological optimization (Petersson & Sigmund, 1998)

| | |
|---|---|
|   | (a) Exemplifying the checker board error |
| | (b) Exemplifying the error of meshing dependency - The solution in case of a 600 elements mesh. |
| | (c) Exemplifying the error of meshing dependency - The solution in case of a 5400 elements mesh. |

## Conclusions

From the start of the art on structural optimization the following conclusions resulted:

- The main structural optimization methods were identified and their classification was carried out.
- The introduction of topological optimization on the path between design and structural analysis drastically reduces the number of iterations between these steps, but does not completely eliminate them, because the optimization itself can represent an iterative process of optimizing and redesigning the results in CAD, also optimizing the remodeled result until the constraints are met and the desired objective functions.
- According to (B. Barroqueiro, 2019), where comparison was made between SIMP and RAMP algorithms from a literature MATLAB code and a commercial MSC Nastran solver, simplistic 2D computational cases give similar results. In complex cases with multitude of constraints, different materials, 3D, etc. it becomes irrational to use personal software applications in terms of time consumption in pre- and post-processing computational cases.
- Common algorithms used in topological optimization were identified, presented and compared. In topological optimization, these algorithms present a set of specific calculation errors, in this chapter these errors were identified and presented, but also possible solutions to remedy or prevent their occurrence.

# PART A II-A

# CONTRIBUTIONS REGARDING THE DEVELOPMENT OF A STRUCTURAL OPTIMIZATION METHODOLOGY

## Chapter 3. Directions, main objective and methodology of research and development

**The main objective of the doctoral thesis** is to develop a robust structural optimization methodology starting from the practical experience of optimizing complex products, to demonstrating the possibility of its customization for different technologies, including additive manufacturing technologies with metal powders, to defining the design rules required for cavities, powder evacuation methods, additional manufacturing steps required to manufacture a complex part with cavities.

The analysis of the current state regarding the use of additive manufacturing technologies at an industrial level and the structural optimization of additively manufactured products highlighted that the development of a robust optimization methodology, the finding of practical solutions for the use of customized structural optimization variants for a specific additively manufactured product and the documentation of some key elements in projects with space application are, at the moment, topics of interest. Starting from these observations, the following directions of research and development were generated:

*Developing a robust, customizable methodology and detailing each step of it with developing rules for achieving structural optimization and interpreting its results, starting from the practical experience of optimizing complex products.*

*Demonstration of the possibility of customizing the structural optimization methodology for different technologies, including additive manufacturing technologies with metal powders.*

*Definition of the design rules necessary for the introduction of cavities, methods of powder discharge, additional production steps necessary for the manufacture of a complex cavity part.*

*Elaboration of a methodology to evacuate the powder from the resulting components, where appropriate.*

### Research and development methodology

Additive manufacturing and structural optimization technologies are often not used to their full potential. For each optimization process, there may be inflections that can maximize the effect of optimization in the space industry, but also in other industrial fields.

In order to fulfill the main objective, as well as the specific ones, the research will be carried out in four main stages:

A. Development and validation of an original topological optimization methodology;
B. Development of methods for customizing structural optimization;
C. Development of processes necessary for the design, adaptation and validation of a part with cavities fabricated through additive manufacturing with metal powders for the aerospace industry, requested in projects with the European Space Agency;
D. Analysis of the behavior of parts made through customizing the optimization for selected manufacturing technologies through respecting the structural optimization methodology.

# Chapter 4. Development and validation of a topological optimization methodology

The introduction of a topological optimization step between design and structural analysis drastically reduces the number of iterations between these processes, but does not eliminate them entirely, since optimization itself is a process that involves iterations, optimizing also the remodeled result until the constraints and desired objective function are met.

A structurally optimized product can be subsequently manufactured by a multitude of technologies. The optimization approach can be customized to produce products that can be made by one technology or another. Thus, a certain product can be structurally optimized considering that it will be manufactured by any of the following technologies: Semi-fabrication technologies (Casting, Extrusion); Manufacturing technologies (machining on CNC, assembly, etc.); Additive manufacturing technologies.

The structural optimization methodology represents, in this form, the author's personal contribution, in Fig. 8 the initial form of the methodology is being presented, it follows that after validations carried out by applying it to the case studies in the thesis, it will be checked if it is robust and customizable.

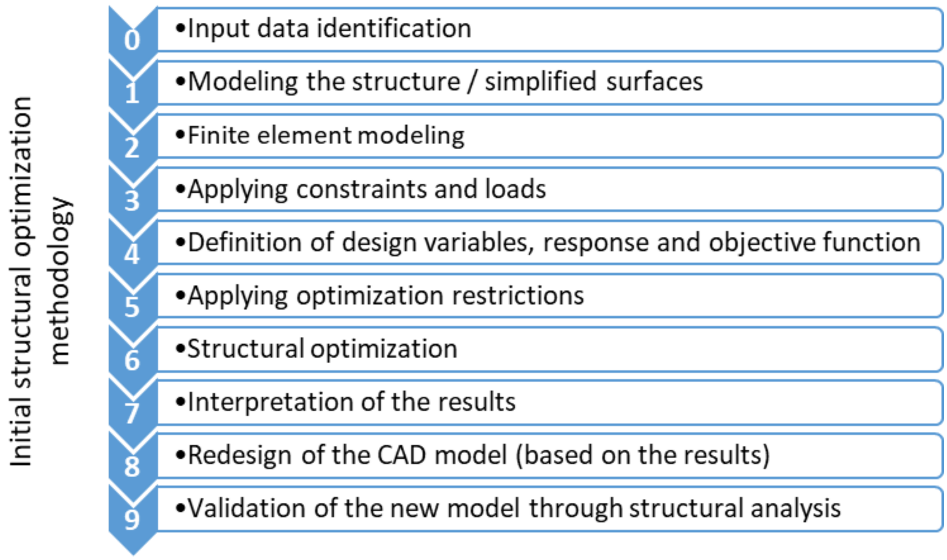



Fig. 8 Initial structural optimization methodology

In the thesis it will be studied the applicability of the structural optimization methodology and the rational definition of the methods to customize the result obtained for three distinct manufacturing technologies. Four study cases are defined and gone through aimed at obtaining four products that can be manufactured by distinct manufacturing technologies. The results obtained for the manufacturing technology defined as a process constraint will be redesigned.

# Chapter 5. Application of the methodology for non-dismountable assemblies

## Context

In recent years, there has been an avalanche of complex space missions (Dart, Web, Parker, Euclid, etc.) that involve the creation of reusable launchers and re-entry vehicles, with the aim of reducing operating costs to a minimum. The cost of refurbishing them and reusing them is tiny compared to the cost of creating a single object for one use. One of the critical design objectives to reduce costs is to minimize mass and streamline the material distribution of parts.

**Description of the study case**

For the current case, it was necessary to conceptualize a metal structure joining milled interface elements of auxiliary interface equipment, used in connection with the helicopter, using structural optimization. The resulting structure is intended to be manufactured from standard rectangular profiles and assembled through welding, thus taking over their advantage given by a large moment of inertia with a minimum area, resulting in a minimum mass. The welded structure will be sandwich type to greatly improve the behavior of the resulting structure when buckling.

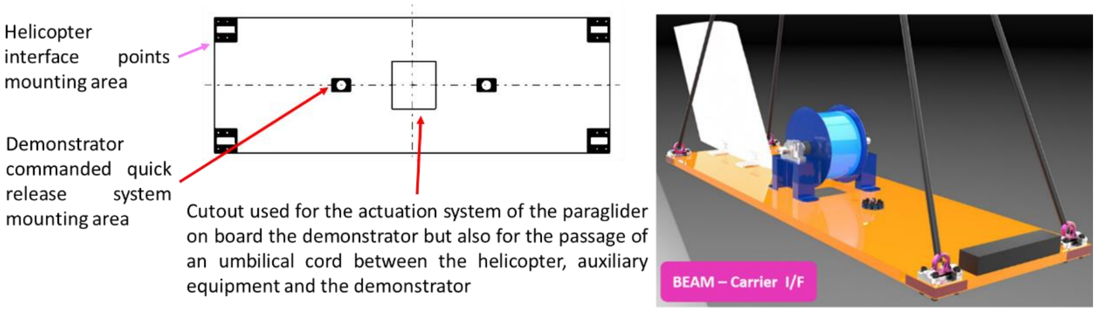



Fig. 9 Auxiliary equipment interface between Space Rider Drop Test demonstrator and the helicopter (PERSONAL CONTRIBUTION Source: Space Rider Drop Test PROJECT – INCAS ANNEX 3.1)

Starting from geometric data, a CAD design software application was used to clearly delimit the space in which a result is allowed to be obtained (design space (D)) versus the space in which the geometric environment cannot be altered by optimization (non-design space (ND)).

A 2D model was generated for HM's specialized software, consisting of a flat surface and a set of lines that will be used to delimit work areas.

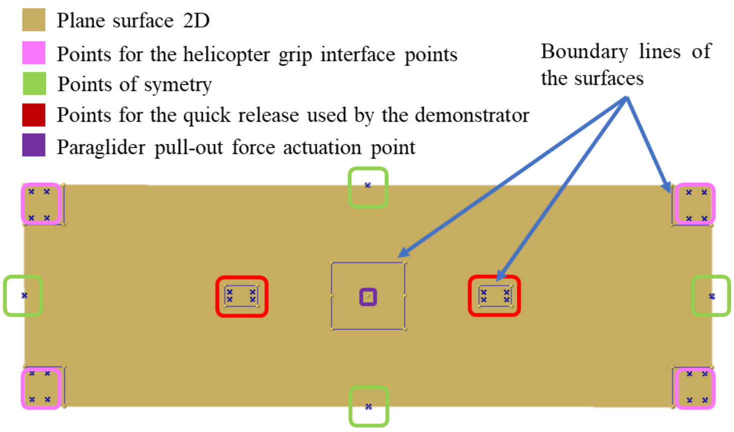



Fig. 10 Geometry and boundary lines in HM

The D and ND areas are discretized with 10 mm elements, also imposing the discretization nodes to be identical to the nodes used to add constraints or forces. The meshing was achieved by imposing continuous elements (from a dimensional point of view), and the elements used in FEM are mostly quads. The meshing is also divided into two areas, by D and ND, exactly like the initial surfaces, into two distinct groups, both of which are connected by common nodes.

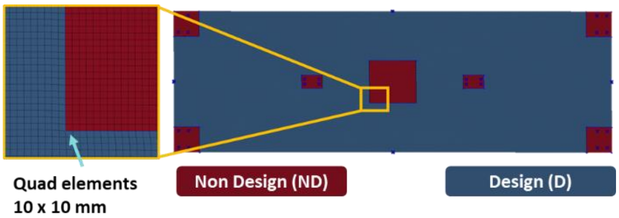



Fig. 11 Design spaces meshed in HM

For the generated mesh, generalized material properties for aluminum are introduced into the MAT1 material card along with the 40 mm thickness for the elements. In addition to geometric input data, numerical input data such as forces, constraints and so on are introduced. The application of constraints and forces was made using the points inserted in the geometry according to the schematic below.

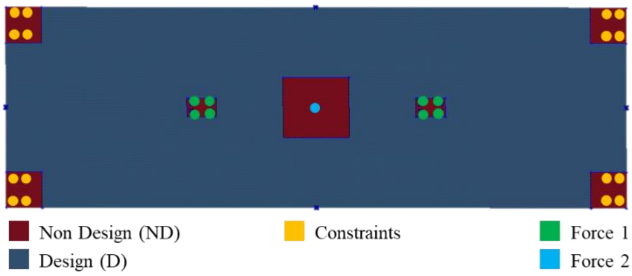



Fig. 12 Identification of application nodes for constraints and forces (PERSONAL CONTRUBUTION Source INCAS - PROJECT Space Rider Drop Test. More information in ANNEX 3.1)

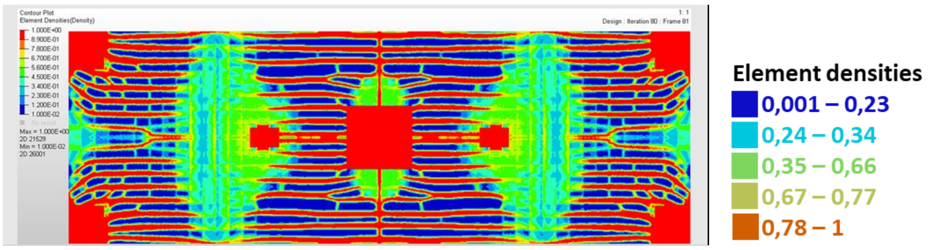
Following the application of forces and constraints, a static linear case was created in the specialized software application HM. The type of optimization used in the calculation process was defined, for the current study case topological optimization was chosen. The purpose of this optimization analysis is to define the geometry of the structure so that it can support the required loads and fit into the required design space. Achieving the goal is done by respecting the imposed constraints. The objective function of this analysis is to minimize the response, which in our case is mass. The definition of the study case for topological optimization begins by introducing calculation variables on the targeted elements. In our case, the targeted elements are the 2D ones in the Design space (P).

**Results and their processing**

The results obtained are visualized with the HyperView software application from the Altair suite (see ANNEX 6). They can be viewed iteration by iteration, to see the calculation path, or you can directly see the last iteration that represents the result of optimization, the moment it stops. The optimizer stops the calculation under one of two conditions: it has reached a successful result, or it has tried up to a number of iterations to reach the best result, but has failed to identify it.

The optimizer converts the initial mesh, element by element, depending on the direction of the main requests, into "1" and "0" value items. "1" being shown in red in Tab. 5 and highlighting the main directions of the loads, respectively "0" being colored blue highlighting unsolicited areas.

Tab. 5 Summary of parameters used to obtain the results of the optimization of the current case study and the result of the optimization (extract)




Using the results summarized above and taking into account the fact that it is desired to use a profile of 50x50 mm section, the optimal areas of placement of profiles are determined by adding the width of the components (strings of elements of density 1) to determine the number of profiles required in the structure by length and width. A complete 3D model is reconstructed by means of a CAD design software application. For the 3D model, taking into account the magnitude of loads, but also the area gathered in sections of the elements with density 1, aluminum profiles with the maximum thickness commercially available at that time at local suppliers for the 50x50 mm section are chosen, this is 5 mm. The redesigned result in CAD consists of aluminum profiles represented in Fig. 13 with orange.

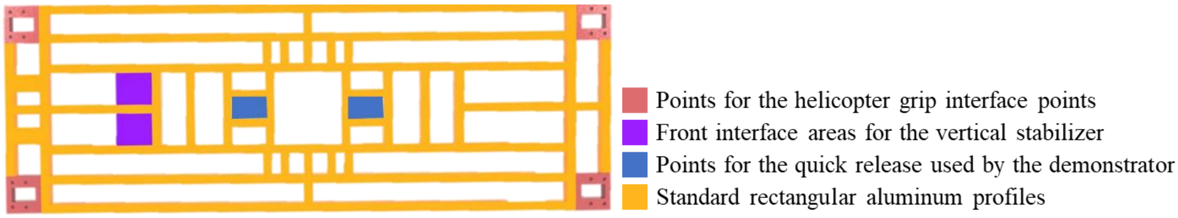



Fig. 13 CAD redesign of the result

The standard rectangular profiles are chosen of the maximum available identical thickness (5mm) and will be welded by the interface areas that will be machined by milling aluminum (EN AW 7075). Below and above the presented structure, a 3 mm EN AW 7075 aluminum sheet will be mounted, through fasteners, to give a higher stiffness. Once all other elements are integrated, the device is ready to perform its intended purpose.

The resulting structure presents, according to the imposed calculation variables, a symmetry in two planes (longitudinal and transversal) that ensures the uniform distribution of loads, but also simplifies the manufacturing process.

**Conclusions**

The result was verified by the INCAS structural analysis team [source INCAS – PROJECT Space Rider Drop Test ANNEX 3.1] in full configuration and was structurally validated.

The initial structural optimization methodology was used and validated in this case customized for welded assemblies, it is noticed that the developed methodology is robust being fully respected.

A set of rules is extracted from the case study presented for simplified optimization cases on surfaces respectively 2D elements, these are presented in the extenso version of the thesis.

# Chapter 6. Application of the methodology for machined parts

## Context

In recent years, there has been an increasing trend towards autonomous vertical take-off and landing demonstrators (VTVLs). The purpose of using such vehicles is to reduce operating costs to a minimum by refurbishing them, if necessary, and reusing them on a new mission, the cost being tiny compared to that required to create an object for a single use. Contributions are being made to the customization of structural optimization for CNC machining manufacturing of a vital structural component for a VTVL turbojet vehicle as part of the Demonstrator Technology Vehicle (DTV) project (see ANNEX 3.2) in a project with the European Space Agency (ESA) led by the National Institute for Aerospace Research and Development "Elie Carafoli". This project is part of ESA's Future Launchers Preparatory Programme.

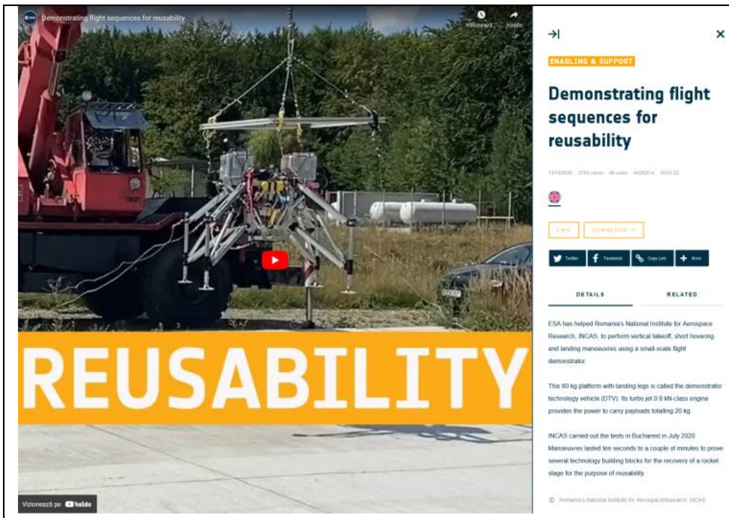


Fig. 14 DTV vehicle in captive flight (ESA, Demonstrating flight sequences for reusability, 2020)

The DTV vehicle is an autonomous, reusable vertical take-off and landing platform, which has damped landing gear and has a total mass of approximately 60Kg. The vehicle is powered by an EASA-approved turbojet engine and is currently in test campaigns performing autonomous takeoff, flyover and landing sequences. The navigation system behind these maneuvers is the basis for the recovery of a launcher stage by vertical landing.

The vehicle is the only one of its size in Europe and INCAS is the only entity to have developed in contract with the European Space Agency a prototype of this size.

Fig. 15 Highlighted landing gear structural element (ESA, Demonstration Technology Vehicle, 2020)

The vehicle is composed of 4 shock-absorbing landing gear, designed entirely by the author. Each of them has a total of 2 tracks used in the current study. In total, there are 8 identical parts on the vehicle as the one in the current case study.

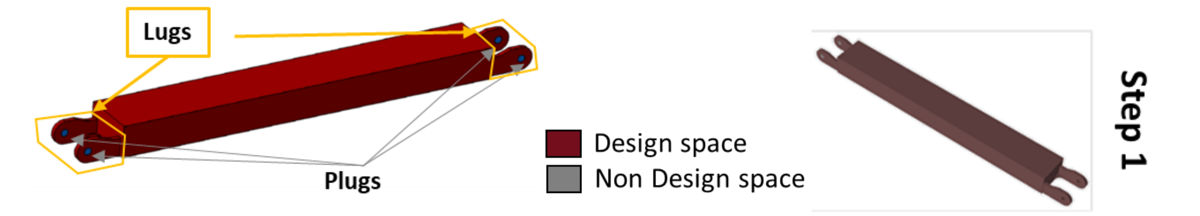
To be agile in handling, the mass of the vehicle must be as small as possible, therefore, a structural element was chosen that is identical in 8 instances per vehicle, 2 pieces each on the landing gear, thus amplifying the optimization result.

## Description of the study case

The study case aimed to demonstrate the use of structural optimization customization for parts to be machined on 3-axis CNC milling machines.

Study object for this optimization was a structural element in an assembly of a landing gear for a vertical take-off and landing vehicle (see Fig. 15).

There are several software applications specialized in structural optimization on the market, in the current case we wanted to obtain a quick result, with minimal pre- and post-processing effort. For this case, the INSPIRE software application is the most suitable for this type of calculation because the optimization is made with 3D elements. When it is desired to optimize an already existing geometry, having as objective function that of mass minimization, it is necessary to expand the workspace in CAD design applications or directly in the optimization application, in other words of the D area.




The optimization areas are divided into 2 groups, Design space (**burgundy**) and Non Design spaces (**gray**). ND spaces are imposed by the author considering the diameter of the screw used to mount the landing gear. A cylinder is created in each hole, and all cylinders created are grouped as ND spaces.

Fig. 16 CAD model delimited in D and ND spaces

The generated result was entered into INSPIRE, divided into distinct spaces for D and ND according to Fig. 16, the mesh is performed automatically by the optimization software program with an average mesh element size of 10 mm (numerical value imposed by the author), the material properties for aluminum EN AW 7075 are entered and the constraints respectively forces are applied using points inserted in the geometry according to Fig. 17.

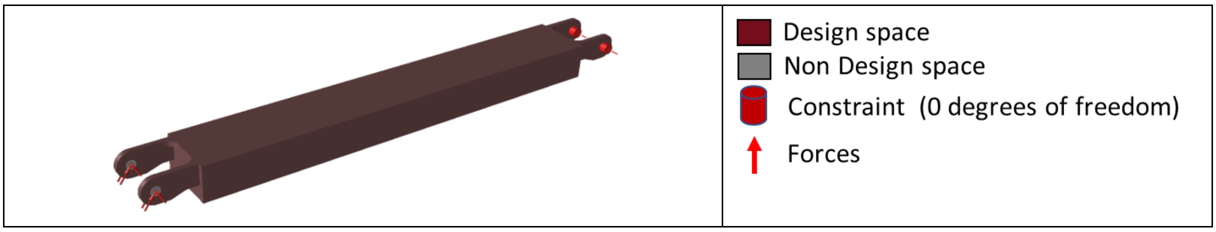



Fig. 17 Loads and constraints applied in INSPIRE

The type of optimization used in the calculation process was defined, for the current calculation case topological optimization was chosen. The purpose of this optimization analysis is to define the geometry of the structure so that it can support the imposed loads and fit into the required design space. Achieving the goal is done by respecting the imposed constraints. Once the study cases were defined, the steps of a set of optimization scenarios were established in which the parameters where varied, in steps, as presented below:

- Step 1 Design (Step 1 D.) – the extended model initially introduced in the optimization software application;
- Step 1 Optimization – the first set consisting of 8 phases of optimizations and obtained results;
- Step 2 Redesign (Step 2 Red.) – Identifying key or common structural elements between the results obtained from Step 1 and their 3D CAD redesign;
- Step 2 Optimization – the second set consisting of 4 phases of optimizations and results obtained;

- Detailed redesign – Identify key or common structural elements between Step 2 results and their 3D CAD redesign.

The steps of the optimization methodology begin with the design step of the model described in the previous subchapters and continue with the optimization step. For each phase of optimization steps, the study cases were varied depending on the sets of parameters presented in the extenso version of the thesis. In interpreting the results, the author generates and uses rules of interpretation and redesign of the results of structural optimization adapted for manufacturing by machining on CNC milling machines in 3 axes. Design-optimization steps are reiterated to reach a final result.

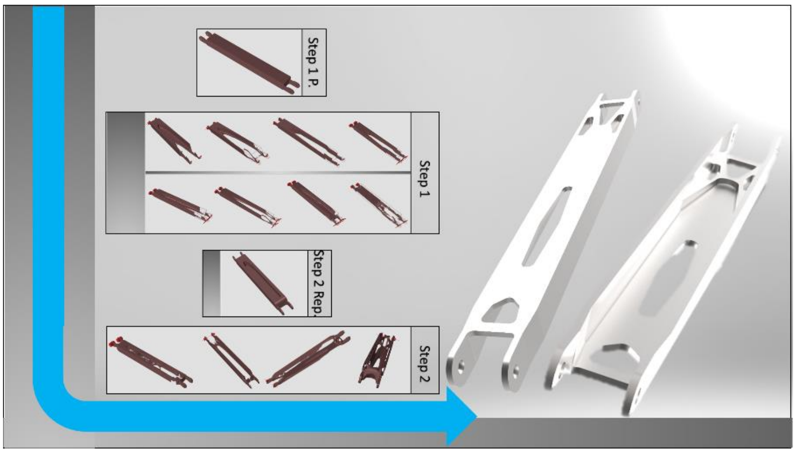



Fig. 18 Complete course of the study case (Own contribution. Source INCAS - DTV PROJECT. More information in APPENDIX 3.2)

The obtained part was manufactured without problems in multiple number of parts and is part of a much newer version of a landing gear than the one presented at the beginning of the study case.

**The influence of structural optimization parameters in INSPIRE, extracted from the calculations performed for the current case study**

Based on Step 1 and its calculation phases, necessary to obtain a result for redesign, a summary of parameter variation was made to highlight their impact on the optimization result. The same summary of parameter variation was made for Step 2 optimization and its calculation phases. The variation of tabular parameters together with the author's conclusions regarding the obtained results are presented in extenso version of the thesis.

**Conclusions**

The result was verified by INCAS structural analysis team [source INCAS – DTV PROJECT ANNEX 4.2] in full configuration and structurally validated.

The initial structural optimization methodology was used and validated in the study case in this chapter. By going through this study case, it is demonstrated that the mentioned methodology is robust and customizable, not requiring its steps to be modified, but only requiring the multiplication of specific steps, in iterative system, to obtain the desired results.

Structural optimization can be customized to achieve feasible results for a multitude of manufacturing technologies.

In this case, it was necessary to refine the results by running a new phase of structural optimization.

Geometric redesign in this case is done by identifying key areas common in all cases of calculation (areas with lack of material or areas with structural elements).

A set of rules is extracted from the case study presented to obtain a part by structural optimization with 3D elements adapted for manufacturing by machining on CNC milling machines in 3 axes.

Fig. 19 DTV Vehicle Test Campaign in captive flight – the studied component is part of the landing gear (Source: INCAS - DTV PROJECT. More information in ANNEX 3.2)

# Chapter 7. Case study 1 – Assembly of machined parts manufactured through milling on a CNC machine

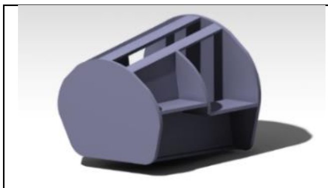
In recent years, there has been an increasing trend of new launchers and re-entry vehicles with the aim of minimizing operating costs. The cost of refurbishing and reusing them is tiny compared to that required to create a single object for one use.

One of the critical design objectives is to minimize mass and streamline material distribution of parts while also improving structural shape in terms of mechanical behavior.

The case study contributing to the structural optimization of assembly customized for milling on a CNC center was used as part of the Space Rider Drop Test project in a project with the European Space Agency (ESA), the Italian Aerospace Research Centre (CIRA), Thales Alenia Space Italia Turin branch (TAS-I), (see ANNEX 3.1).

**Description of the study case**

In the current study case, the aim was to demonstrate the customization of structural optimization of an assembly of parts designed to be manufactured by milling on a CNC center in 3 axes. The aim is to separate the result of the optimization into distinct parts that can be assembled together with a bolt-nut or screw-helical insert. Manufacturing by 3-axis CNC machining is specifically aimed at reducing production cost.



a.

The studied structure was optimized for the Space Rider Drop Test demonstrator. In order to provide the same space and interfaces for equipment to be mounted on the Space Rider Drop Test demonstrator, identical equipment and interfaces as on the Space Rider vehicle, the current structure and optimization workload is imposed by the customer for INCAS.

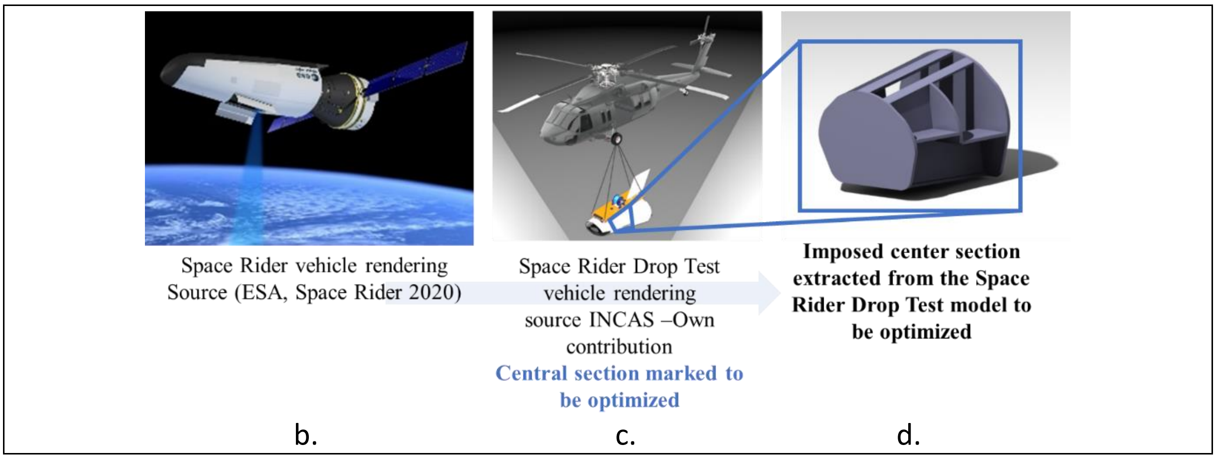



Fig. 20 a-d Initial structure (a (Cismilianu, et al., 2022))

The original structure has been reduced to surfaces in a CAD design software application. The set of surfaces were used as input into the specialized HM software and divided into two groups that will become design and non-design spaces. The spaces of D and ND are discretized with 10 mm elements, imposing the discretization nodes to be identical to the nodes used to add constraints or forces. The material properties are assigned to the finite elements properties through ”MAT1” together with the thickness (T) of the elements which was initially consider 40mm. Constraints and forces are then applied using the points inserted in the geometry as in Fig. 21. The applied loads shall be deemed to be similar to those induced by the landing of a re-entry vehicle and the imposed points shall be considered to be the interface points of the landing gear mounted with fasteners.

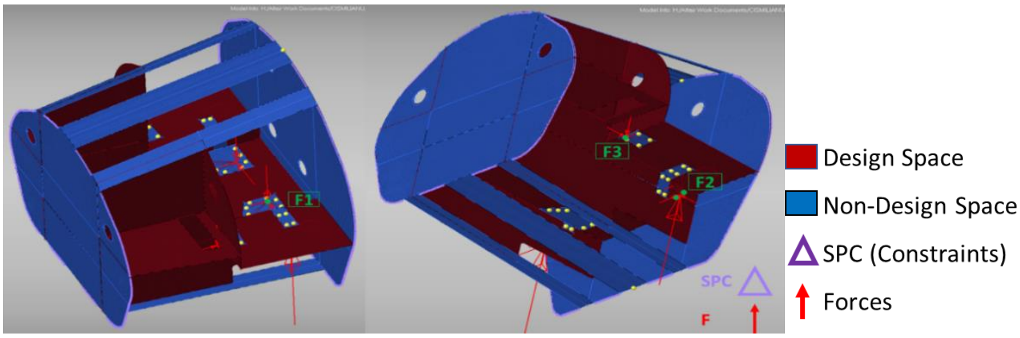



Fig. 21 Application constraints and loads (Cismilianu, et al., 2022)

Following the application of forces and constraints, a static linear case was created and the type of optimization was defined, for the current calculation case topological optimization was chosen. The purpose of this optimization analysis is to define the geometry of the structure so that it can support the imposed loads and fit into the required design space.

**The influence of parameters in structural optimization**

The influence of several parameters in the results of structural optimization is analyzed. Thus, the thickness (T) of the elements, the minimum size (mD) and the maximum size (MD) of the components generated by optimization were varied. At the same time, a symmetry was imposed in the XOZ plane. The minimum distance between components will be considered autogenerated by the optimizer based on the numerical input values for mD and MD, and the yield strength and applied forces will not be changed from the values in the input data.

The objective function is to minimize the response, which in this case is mass

Parameter variations and their influence on results were presented, starting with the initial case. Only relevant cases were presented and not all cases studied.

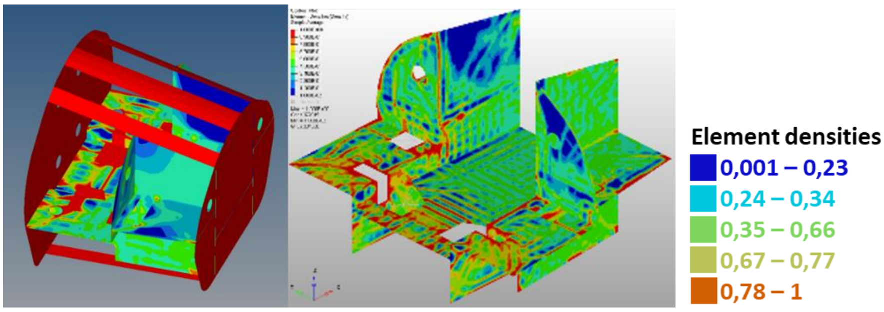



Fig. 22 Comparison of case optimization results 1 (a.) and 5 (b.) (Own contribution) (Cismilianu, et al., 2022)

As can be seen in Fig. 22, the correct variation of parameters T, mD and MD can transform a result that is difficult to interpret into something coherent.

**Conclusions**

The result has been redesigned and verified by INCAS design and structural analysis team (see ANNEX 3.1) in full configuration and has been structurally validated.

In the current study case, the initial structural optimization methodology is fully respected and validated, demonstrating that it is robust even if the optimization has been customized for an assembly of machined parts manufactured through milling on CNC centers.

The influence of parameters on optimization results is observed and a ratio between mD and MD parameters is determined to find faster conclusive results that can be used in CAD redesign. It is presented that, once this ratio is maintained, by changing the thickness from one case to another, the result can be refined.

A set of rules extracted from the presented case study is developed and presented for an assembly of parts simplified to surfaces or 2D elements manufactured through milling on a CNC machine.

The optimization of an assembly whose components were obtained by milling on a CNC center is feasible and represents a relatively fast process, where the results obtained led to a weight reduction of ~37% and an increase in the results of structural analyzes by ~26.5%.

## Chapter 8. Case Study 2 – Structural optimization customization variants applied to parts manufactured through additive manufacturing

**Context**

The structural optimization of a product/part to be manufactured by additive manufacturing technologies can be applied in a wide range of industries (aerospace, military, vehicle engine manufacturing, medical/dental), (Ciobota, Gheorghe, & Despa, 2019)). In the aerospace field, there are many types of parts/products with high weight reduction potential in the context in which they would be manufactured by additive technologies, (Uriondo, Esperon-Miguez, & Perinpanayagam, 2015), (Najmon, Raeisi, & Tovar, 2019). Structural optimization can be applied in the aerospace industry to current launchers, launchers in development, vertical take-off and landing vehicles, but also to large-scale satellite missions.

All major satellites have certain cold gas thrusters strategically positioned so that the attitude can be adjusted, keeping orientation or modifying it to accomplish the mission. These thrusters come in a wide range of sizes in terms of driving force, but also with different operating principles (Krejci & Lozano, 2018), (Wang & Xie, 2009).

The case study through which the author contributes on the structural optimization customization for additively manufactured parts was used as part of the EUCLID project, (see Fig. 23). The project was carried out with the European Space Agency (ESA), and ANNEX 3.3 involving 100 EU institutions, but also NASA in the USA. INCAS had a role in designing, analyzing, testing, assembling and integrating into the clean-room all structural flight elements that have the role of keeping EUCLID satellite thrusters in predetermined position.


Fig. 23 INCAS integration team near EUCLID satellite structure in clean-room TAS-I Torino. Team led by **Alexandru Cişmilianu** [The settlement suggestion and the main image represent personal contribution of the author from the source INCAS- EUCLID PROJECT. More information in ANNEX 3.3]

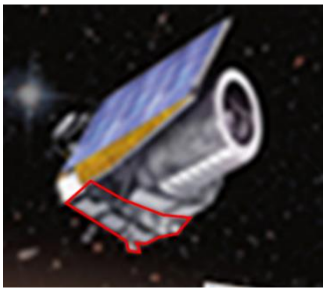


Fig. 24 Rendering of EUCLID satellite structure highlighted with red (ESA, ESA's fleet across the spectrum poster, 2017 edition, 2017)

Behind the integration team is the structure of the EUCLID satellite. As an order of magnitude, the structure behind us is the one marked in Fig. 24 with red.

The EUCLID spacecraft, although it was planned to be launched with Ariane 6 and later with Soyuz, it was launched on July 1, 2023 with the SpaceX Falcon 9 launcher (see Fig. 25) from Cape Canaveral Florida. EUCLID is a medium-sized satellite developed for astronomy and astrophysics, with the main role in investigating dark energy and dark matter. It will investigate the history of the expansion of the universe over the past 10 billion years by verifying the current expansion fueled by a momentarily mysterious component, dark energy.


Fig. 25 Euclid satellite launch with SpaceX Falcon 9 and a picture from the video of the Euclid satellite decoupling into space (SkyNews, 2023)

Two of these structural elements were originally chosen to be manufactured by additive manufacturing, and contributions on one of these are presented in the following subchapters.

### Identification of input data

Input data, interface points, workload and so on are imposed by OHB Sweden. The largest loads occur at launch. The requirements presented are the most important in the case of spacecrafts structures, the most important being the fulfillment of the minimum modal frequency. By meeting this harsh requirement, the others are generally fulfilled automatically or only small local changes are needed.

The design envelope, attachments and position of the thrusters are required by OHB Sweden and shown in Fig. 26.

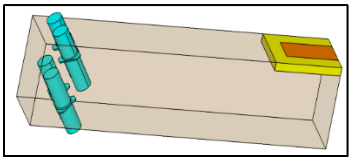


Fig. 26 Geometric input data (Cismilianu, et al., 2017)

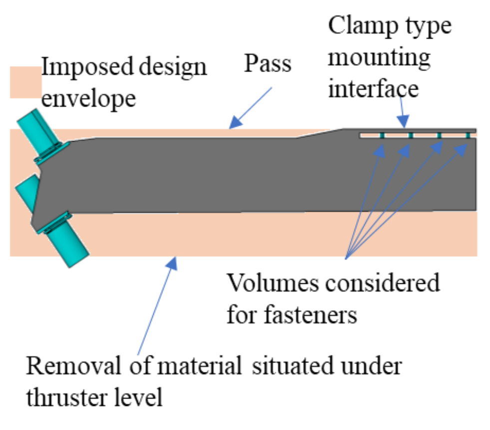
| |
|---|
| Thrusters’ positions |
| Design envelope |
| Fastening interface |

Tab. 6 Legend geometric input data required by OHB Sweden

### Preparing the geometry for optimization

In the case of optimization, the area where the optimal structure is to be obtained must be clearly defined in design and non-design space. In the current case, we consider the design space the gray area in Tab. 7and the non-design space, the turquoise area.

Tab. 7 Geometry modified for optimization

| | |
|---|---|
|  | Starting from the design envelope (see Fig. 26 and Tab. 6), in the mounting area we consider a clamp type interface (see Tab. 7). This is considered suitable because the stresses to which the resulting structure must withstand are very high, and the suggested grip radically improves the clamping area in terms of structural stiffness. In Tab. 7, in the lower part, material has been removed outside the direct attachment area of the thrusters. In Tab. 7 in the upper part a transition was implemented from the level of the attachment of the thrusters. |

In the case of calculations in which the maximization of the modal frequency is desired, experience proves that for long pieces the aim is to achieve a firmer grip, and as we move away from the grips, a smaller and smaller mass must be allocated. Basically, one wants a smooth transition from a firm grip to the end of the part where minimal mass is desired.

### Finite Element Modeling (FEM)

For the current optimization, a software application from the Altair Hypermesh suite called INSPIRE Solidthinking was used. Here a multitude of different optimizations and analyzes can be performed to verify the results. A discretization with 3D HEX elements with a general order of magnitude of 20 mm was considered. In INSPIRE, FEM modeling is done automatically, with the user having minimal impact on the modeling technique.

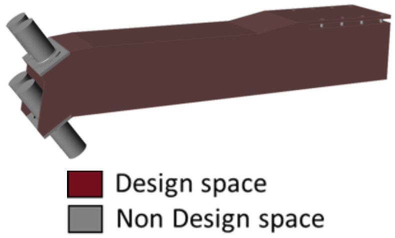



Fig. 27 Model separated in design spaces (**burgundy**) and non-design spaces (**gray**) modeled with finite element

The workspaces are divided into 2 groups, Design spaces (**burgundy**) and Non Design spaces (**gray**). ND spaces are dictated by thrusters with their attachment surfaces and bolt assembly area from the clamp grip. To obtain the correct results, forces and constraints will be applied only on ND spaces (see Fig. 27).

**Establishing loads and optimization parameters**

Given that optimization starts from a design envelope, practically from "0", one of the concept optimizations will be applied Since it is desired to achieve a conceptual optimization from a 3D volume, the only type of optimization that can be applied in this case is topological optimization. The purpose of this optimization analysis is to define the geometry of the thruster holding structure so that it can withstand the required loads and fit into the design space represented in Fig. 26. Achieving the goal is done by complying with the constraints. Thus, the value of the frequency of the first natural mode of the structure must be at least 90 Hz. Also, the resulting structure must withstand a combined load of 30g in each main direction. The objective function of this analysis is to maximize the response, which in this case is stiffness, while respecting the previously mentioned constraints and loads. By maximizing the stiffness, the value of the first modal frequency of the structure is increased.

In the current case, after finite elements modeling, the constraints are introduced in the removable attachment area of the part that is intended to be topologically optimized (see Fig. 28).

Fig. 28 Constraints definition

Design space
Non Design space
Constraint (0 degrees of freedom)

Constraints are applied on the Non Design space with 0 degrees of freedom in the imposed points on the left-side of the model (see Fig. 28).

Considering that the part will be manufactured through additive manufacturing technologies with metal powders, the materials used in the aerospace industry, as well as in the automotive industry, were identified, on which a part of this length can be manufactured.

Fig. 29 Additive manufacturing machine Concept Laser X-Line 1000R (LaserSystemsEurope, 2014)

The only compatibility between the dimensions of the manufacturing part, manufacturer and additive manufacturing machine was identified as an additive manufacturing machine from Concept Laser company, X line 1000R of an INCAS subcontractor (Fig. 29). The material specially developed for this machine is AlSi10Mg.

The objective function for the topological optimization is maximizing stiffness by reducing the mass. The objective function is to maximize stiffness with the goal of reaching 90 Hz frequency by minimizing the mass of the design volume (space) by 95%. Since the structure is perfectly symmetrical in a plane, a constraint was imposed in the model for the optimization result to be symmetrical.

**Customization of the study case and the obtained results**

Once the loads and constraints of the calculation case were defined, we set the steps to a set of optimizations, like this:

- Step 1 Design (Step 1D) – the extended model originally introduced in the optimization software application Fig. 28;
- Step 1 Optimization – the first set of optimizations and results obtained;
- Step 2 Redesign (Step 2 Red.) – Identifying key or common structural elements between the results obtained from Step 1 and their 3D CAD redesign;
- Step 2 Optimization – the second set of optimizations and results obtained;
- Detailed redesign – Identifying key or common structural elements between Step 2 results and their 3D CAD redesign.

**<u>Step 1 Design</u>**

Step 1 design was presented in previous subchapters.

**<u>Step 1 - Optimization</u>**

The parameters used in optimization are presented in the form of tables containing sets of parameters regarding geometric constraints and objective function.

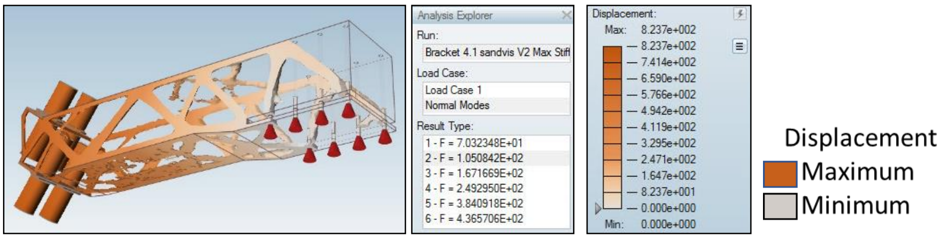



Fig. 30 Step 1 result

In the above result we notice that the first frequency obtained is below the initial requirements, namely 70.2 Hz compared to 90 Hz, as required from the input data considered initially. This shift in the result is attributed to considering mass minimization to within 5% of the original design space using a very large mesh size. Considering the resulted frequency of the first iteration is 13% below the target frequency, it is assessed that the obtained result has potential, thus, it was considered the redesign of the obtained result followed by a new run of the optimization algorithm.

**<u>Step 2 - Redesign</u>**

The results obtained in Step 1 Optimization have the potential to obtain a valid result, for these reasons it is chosen to continue the optimization process through Step 2 redesign. When redesigning, the minimum inclinations that can be achieved without requiring support material in the additive manufacturing process are taken into account. In areas where we have not obtained relevant structural elements or we have achieved what in optimization is known as the "checkerboard" effect error, a board with a considerably greater thickness is redesigned to leave room for the software application to optimize in the second stage of optimization and the clamping area is reshaped (see Fig. 31).

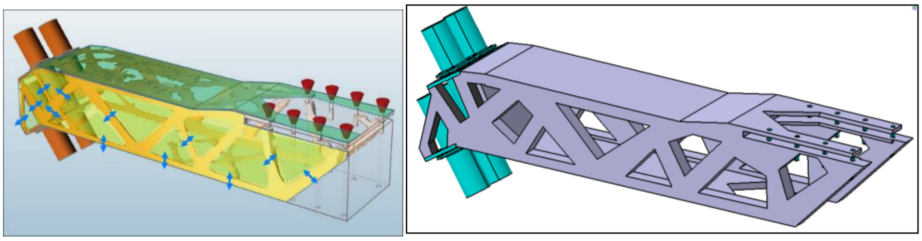


Fig. 31 Redesign of Step 1 optimization results (Cismilianu, et al., 2017)

**Step 2 - Optimization**

The topological optimization inputs in the second optimization step were considered the same, except for the discretization, which was reduced from 20 mm elements to 5 mm elements. After running the previously prepared model in the first stage of CAD redesign, the result is presented in Fig. 32.

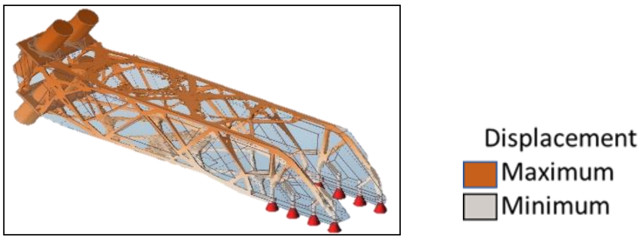



Fig. 32 Step 2 results

In Fig. 32 We have the result of optimization subjected to a modal analysis. The first modal frequency obtained from the first optimization stage is 90.07 Hz, and in the visualization, you can see a transition from white-orange to dark-orange. The white-orange area indicates minimum displacement and thus maximum stiffness, and the dark-orange area indicates high displacement and minimal stiffness. In the upper and lower areas, where initially we did not have connected elements and there were optimization errors, now there are structural elements defined as a result of the topological optimization process. The structural elements obtained initially were better defined at the second run.

**Detailed redesign**

As in the first CAD redesign, the results obtained from the second stage of optimization are transposed into a design program (Catia), and around the elements resulting from optimization, 3D reconstruction is performed. At this stage, the aim is to reconstruct the elements as close as possible to the result obtained, but also taking into account the constraints imposed by the additive manufacturing process.

Fig. 33 Translating CAD redesign (**turquoise**) over optimization results (**burgundy**)

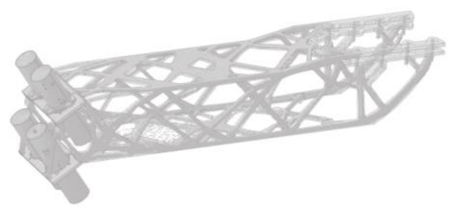


Fig. 34 Detailed redesign

**Conclusions**

The result was verified by the INCAS structural analysis team [source INCAS – EUCLID PROJECT ANNEX 3.3] in full configuration and structurally validated.

The initial structural optimization methodology is validated for the current study case. This methodology is robust and customizable for study cases where optimization and redesign are done iteratively, there is no need to modify steps from it, but only their multiplication.

In this case, it was necessary to refine the results by running a new structural optimization step.

A set of rules, additional to those defined at the end of the previous subchapters, is extracted from the case study presented to obtain a part by structural optimization with 3D elements adapted for additive manufacturing from metal powders.

# Chapter 9. Validation of the topological optimization methodology

Starting from the results and conclusions of chapters 5, 6, 7 and 8, the customized defining elements of the initial optimization methodology were synthesized, depending on the type of technological process used to manufacture the analyzed part.

**A. Non-dismountable assemblies**

The initial structural optimization methodology presented was introduced in a customized form in the description of each case. For non-dismountable assemblies, the developed methodology does not need to be altered, it can be fully respected.

**B. Parts manufactured through milling on a CNC center**

The initial structural optimization methodology presented was used for the study case in 0. The mentioned methodology is robust, it is not necessary to modify its steps for such study cases, but only to multiply specific steps, in iterative system, to obtain the desired results.

**C. Assembly of parts manufactured through milling on a CNC center**

The initial structural optimization methodology presented is fully respected also in the study case where the optimization has been customized for an assembly of parts manufactured through milling on a CNC center.

**D. Parts made through additive manufacturing**

The original structural optimization methodology can be used for the calculation case in Chapter 8 because the optimization-redesign was done in several steps. The customization is done identically to case study B. without altering the methodology, it being quite robust from the point of view of not needing to modify its steps for such study cases, so that it only requires the multiplication of steps 6 (Structural Optimization), 7 (Interpretation results) and 8 (CAD model redesign (based on obtained results)).

**Conclusions**

The methodology identified is robust from the point of view of the lack of need to modify its steps for such study cases and can be applied in cases of structural optimization to have an overview of progress and direction of work. Regardless of the type of analysis, 2D/3D or the direction towards which they are guided, the identified methodology can be used. In some situations, multiple phases / steps of optimization – redesign are needed.

The initial methodology of structural optimization becomes, following its validation through case studies in the thesis, a general methodology for structural optimization, robust and customizable.

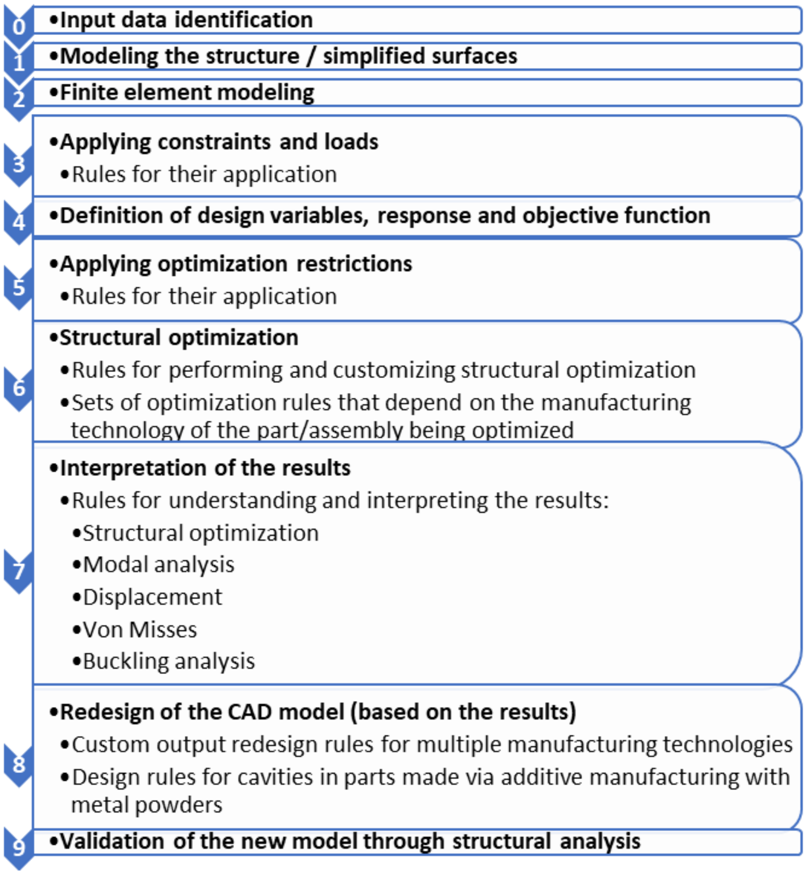



Fig. 35 General structural optimization methodology

### Rules for performing topological optimization

Correlating the results obtained in chapters 5-8, several sets of optimization rules have been defined, which depend on the manufacturing technology of the part / assembly subject to optimization. These are presented in the extenso version of the thesis.

### Quick method of interpretation and understanding of the results

Based on the topics addressed in the thesis, I developed a quick method of interpretation and understanding of the results obtained in various analyses, this being present in the extended version of the thesis.

### Design rules for cavities in additive manufacturing parts with metal powders

The design rules for cavities in the case of additive manufacturing with metal powders defined by the author were extracted from Chapter 10, and these are tabulated in the extended version of the thesis.

## Chapter 10. Design for manufacturing – rules for powder evacuation from complex additively manufactured metal structures

### Context

To be applicable in aerospace, all components must be designed to have minimum mass and maximum structural properties. It is precisely for this reason that topological optimization in this area can be ideal in achieving these two objectives in the case of structural components.

A less discussed topic in space is the creation structures with cavities through additive manufacturing, the main reasons being that this increases the complexity of the part and the number of checks required. There is a set of advantages and disadvantages regarding the introduction of cavities in parts used in the space industry.

| Advantages | Disadvantages |
|---|---|
| + High stiffness | - The appearance of powder evacuation holes and their structural evaluation |
| +++ Lower mass | - Implementation of a powder evacuation method |
| | - Increase in the number of checks |

**Approach**

In the case of additive manufacturing a part with cavities with a technology within the PBF (Powder Bed Fusion) process, the existence of cavities implies the introduction of additional steps, from the design stage, in creating the final version of the part.

Starting from the initial geometry, which takes into account the constraints of the clamping interfaces of the analyzed part, the geometry is adapted to add cavities in defining the part model. They must be subsequently adapted, depending on the orientation of the part on the additive manufacturing machine, in order to be self-supporting, thus eliminating the need for support structures to appear inside. Support geometry should be avoided because it brings non-structural mass and at the same time can block the flow of metal powder into its exhaust step, which cannot be eliminated later. A powder evacuation method is defined for each previously generated cavity, thinking of the best approach to achieve it (compressed air, optimization of airflow direction in the part, orientation).

**Design rules for cavities in case of additive manufacturing with metal powders**

**Study**

Design rules for cavities are divided into:

a) technological rules;
b) rules of form, in order to avoid the formation of the support structure;
c) rules for adapting the shapes of cavities to streamline powder removal.

Technological rules are imposed, first of all, by the minimum wall thickness of the part, respectively, the cavity, this thickness must be over 1 mm. This minimum thickness is not limited by the possibilities of the machine, which manages to create smaller thicknesses, but under this thickness the third-party manufacturer of the institute claims that there are not enough "layers" to ensure structural integrity and no deformations of the part in the case of manufacturing the part from metal powders.

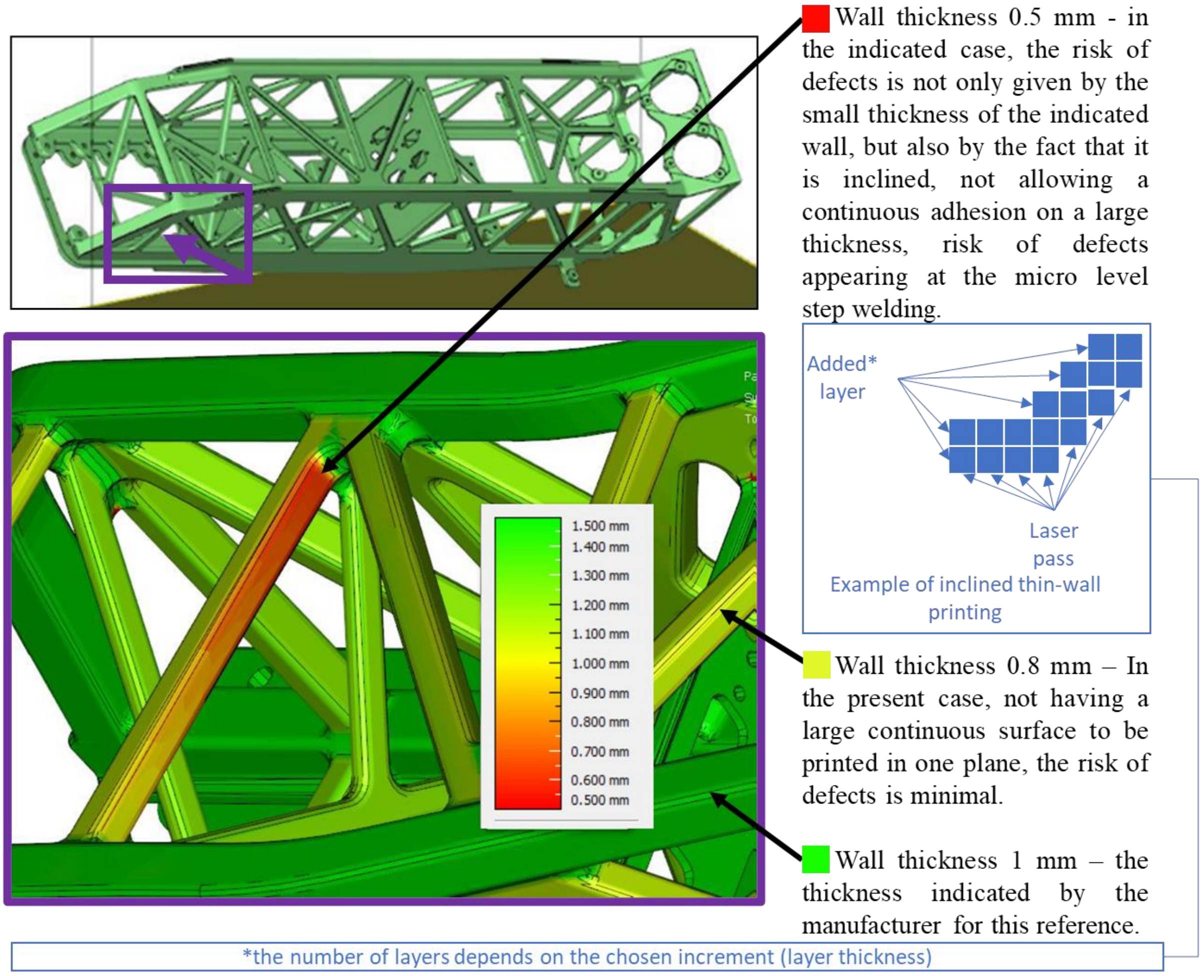



Fig. 36 Wall thickness for cavity parts manufactured additively with metal powders (The images on the left come from SOURCE INCAS - EUCLID PROJECT. More information in ANNEX 3.3)

Considering the classic rules of literature (recommended self-sustaining angles between 30 and 45 degrees, height ratio: maximum width: 20:1, 40:1, 8:1 etc. (Obeidi, 2022), (Bracken, et al., 2020), (Allison, Sharpe, & Seepersad, 2019), (Laser, 2022) and (Openadditive, 2019)) through which the support structure on the outside of the part can be minimized, these have been extrapolated into rules of shape and profile of the cavities that can be applied to the parts. This eliminates the need to insert support material inside cavities, support material that could not be removed. Ideal shapes/profiles that do not lead to the creation of support structures in cavities are presented in Fig. 37.

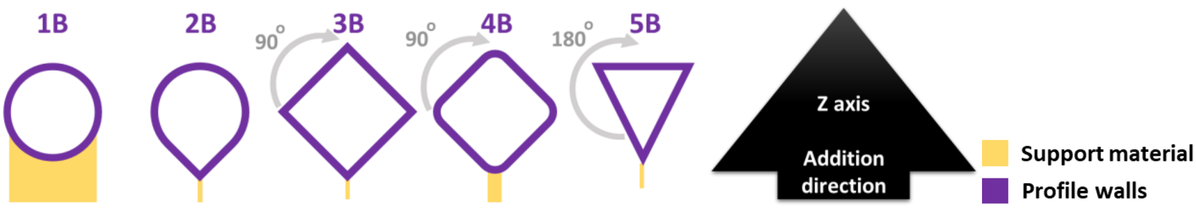



Fig. 37 Dependence of ideal forms for cavities according to the orientation of the part in the additive manufacturing machine platform (own contribution)

It is noted that some of the profile variants are suitable for avoiding supporting structures, but under strict conditions of orientation on the additive manufacturing machine build platform.

Moreover, these rules cannot be universally valid, therefore, in the case of particular areas, the solutions found will be presented and described. It is also necessary that the orientation of the part on which this design stage is made be defined based on the recommendations of the machine manufacturer.

The studied part is a truss beam like one, with shell elements, hollow inside, where the junctions are spherical to facilitate the joining of pipes, keeping cavities together. In certain spherical areas there was a need to assemble other components by screwing into the part. Thus, the identified spherical areas have been locally redesigned to have a flat surface, but also a bossage with a threaded hole. The purpose of the boss and threaded hole is to mount a helicoil-type metal insert to increase the thread's resistance to pull-trough (see Fig. 38).

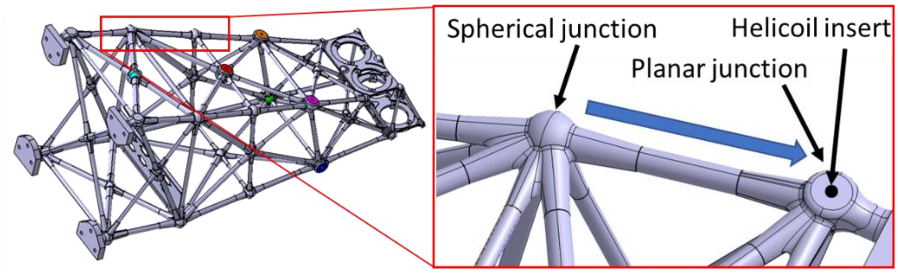
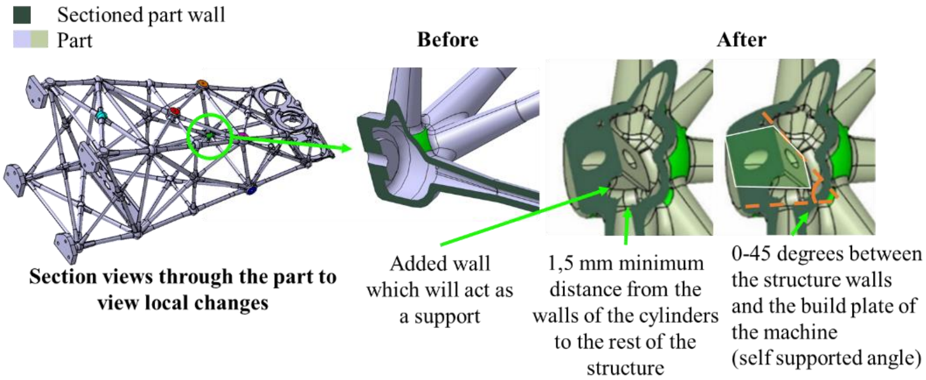



Fig. 38 Creation of assembly interfaces [3D model SOURCE INCAS - EUCLID PROJECT. More information in ANNEX 3.3]

While, from the point of view of additive manufacturing technology rules, a thin-walled spherical structure is self-supporting and does not require internal support material, modified spheres, which contain a flat surface, bumps and holes, locally require support material in cavities. This support material can cause problems in completely removing the powder from the cavities. The author identified local solutions for redesigning the structure, so as to eliminate the appearance of the support material, an example from the extract is presented below.

Tab. 8 Local concept rules to eliminate the need to use backing material and improve powder flow in the process of its evacuation

| No | Oriented sections according to placement position in the additive manufacturing machine (local methods of removing support material from cavities) |
|---|---|
| 1. |   [3D MODEL SOURCE INCAS - EUCLID PROJECT. More information in ANNEX 3.3. Part manufactured by third parties.] |
| In the identified area it is necessary to find a solution for removing the supporting material that will appear inside the cavity. After manufacturing, the hole in it will be threaded and a helicoil insert will be inserted to become an assembly surface. The hole has a double role, as it will also be used to remove internal dust after the manufacturing process is completed. | |

**Design rules for creating a method of metal powders evacuation from cavities**

In the space industry, as the examples in previous chapters show, there is a structural element to support cold gas thrusters strategically positioned to be able to adjust the attitude while maintaining orientation or modifying it to accomplish the mission.

The purpose of this structural element is to hold gas thrusters in position to provide propulsion at the required distance and angle to the satellite structure, so the pipes of these thrusters and wiring must be mounted along the length of the structural element.

The additive manufacturing process of parts with cavities requires ongoing dialogue between the designer or design team and an additive manufacturing specialist of the manufacturer entity. This close connection is necessary in order to be able to solve some specific aspects related to this type of parts. One of them would be the minimum required size of the channels (3-5mm diameter) and evacuation holes (3mm), and another important factor is their positioning. The more correct the position, (those holes can be positioned where needed without presenting a structural risk), the easier, faster and more correct the evacuation.

According to (Laser 2022), (Obeidi 2022), (Bracken, et al. 2020) and (Allison, Sharpe and Seepersad 2019) Choosing the optimal orientation of the part in the additive manufacturing volume of the machine has a big impact on the roughness of parts, surface defects and on the needed support material.

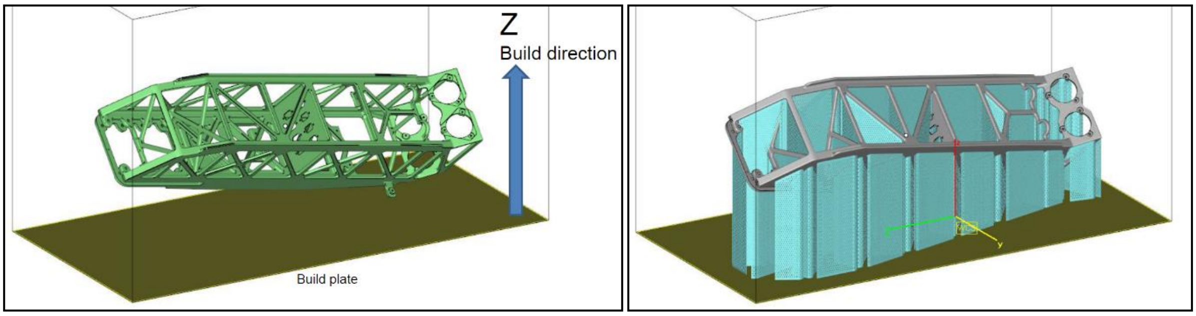
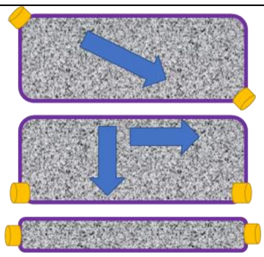



Fig. 39 Orientation of the part in the software application of an additive manufacturing machine without and with support material. Part manufactured by third parties. (Cismilianu, și alții, 2017)

Local changes are made if support material appears in the cavities following the simulation of the additive manufacturing process of the part, with the help of the dedicated software application of the chosen manufacturing machine. Considering the section of each pipe, in order to minimize the volume of the support material, a square section was used with rounded corners inside the pipes, which in the present case becomes rhombic, by changing the orientation of the piece as it was also presented in the previous chapter. This section is one of the most effective in terms of minimizing support material from hollow section parts.

In order to achieve an efficient air flow necessary for the evacuation of the powder, at least two holes (3mm min.) are designed for the evacuation of the powder, imposed in two fillet corners of the cavities, depending on the orientation of the cavity with respect to the build table of the additive manufacturing machine (see Tab. 9). Air flow is important when evacuating the powder in the post-processing steps of the additive manufacturing process to ensure complete removal of the powder and avoid the risk of equipment contamination.

Tab. 9 Rule for placement of powder evacuation holes

| | |
|---|---|
|   | Method of placing powder evacuation holes in the case of an inclined cavity relative to the build table of the machine. |
| | Method of placing powder evacuation holes in the event of a cavity parallel to or perpendicular to the build table of the machine. |
| | Method of placing powder evacuation holes in the case of a cavity of thickness close to the diameter of the implemented outlet. |

To improve the air flow required for powder evacuation and to minimize the number of needed evacuation holes, as many cavities as possible have to be joined, continuously or by methods similar to the rules for placing powder exhaust holes presented above by creating cylinders with an internal diameter of at least 3 mm.

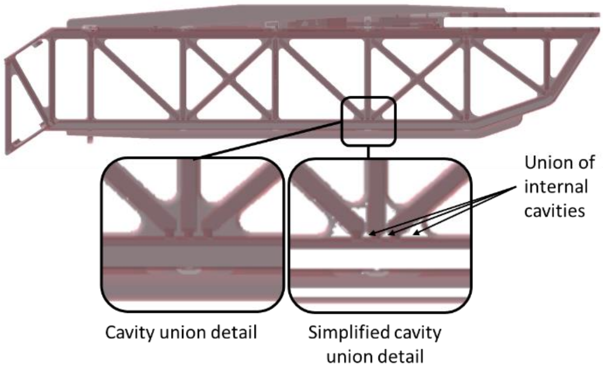



Fig. 40 Rule of joining cavities through cylinders of 3mm diameter [Model 3D SOURCE INCAS - EUCLID PROJECT. More information in ANNEX 3.3. Part manufactured by third parties.]

| | |
|---|---|
| Adhering to the methods presented in Tab. 9, all internal cavities are joined to each other. | In the simplified detail, the adjacent material has been deleted to make it easier to visualize the connections of internal cavities. |

After joining the cavities in Fig. 40, a powder evacuation procedure is followed by adding circular powder holes (minimum diameter 3 mm) to critical areas, taking into account the current orientation and the fact that the powder inside must be removed before removing the piece from the plate.

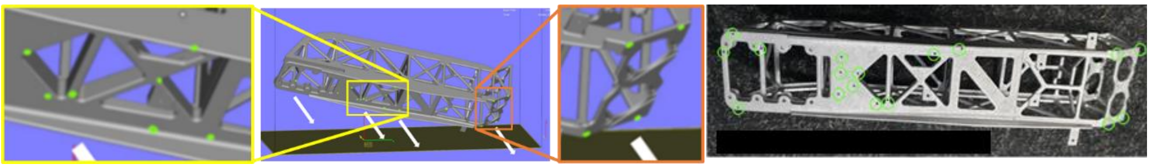


Fig. 41 Direction of positioning: powder evacuation holes (holes marked in green). Part manufactured by third parties. (Cismilianu, și alții, 2017)

It is important that the design is interconnected with manufacturing. In order for the part to be designed for additive manufacturing, by locally modifying the internal geometry, a cavity part can be made, which does not need a support structure. The appearance of the supporting structure in the cavities leads to jamming of the powder inside and makes the part ineffective.

**Conclusions**

- Right from the design stage, there must be a close connection between the designer and an additive manufacturing specialist. Thus, the part can be designed of for additive manufacturing from the design stage.
- According to (Laser 2022), (Obeidi 2022), (Bracken, et al. 2020) and (Allison, Sharpe and Seepersad 2019) choosing the optimal orientation of the part in the additive manufacturing volume of the machine has a big impact on the roughness of parts, surface defects and on the support material.
- Parts with cavities require a custom powder evacuation procedure.
- A set of design rules have been generated to create a method of powder evacuation from cavities of parts manufactured through additive manufacturing with metal powders.

# Chapter 11. Additive manufacturing of a part with cavities and qualification procedure for use in space

**The technological process of manufacturing a part with cavities used in space**

Post-processing steps for additive manufactured parts with metallic powders (PBFs) have been defined and described in Chapter 1, hereinafter will be considered necessary steps to be **added** within the **classic** post-processing steps to obtain a part with cavities.

In the case of parts with cavities, following the manufacturing process it is found that there are problems regarding the total removal of powder, areas not completely sintered, potential unwanted inclusions, the presence of porosities and cracks. To solve these problems, an additional step of non-destructive inspection of the resulting part through the additive manufacturing process was introduced, but some of the usual additive manufacturing steps were modified with dedicated elements for parts with cavities.

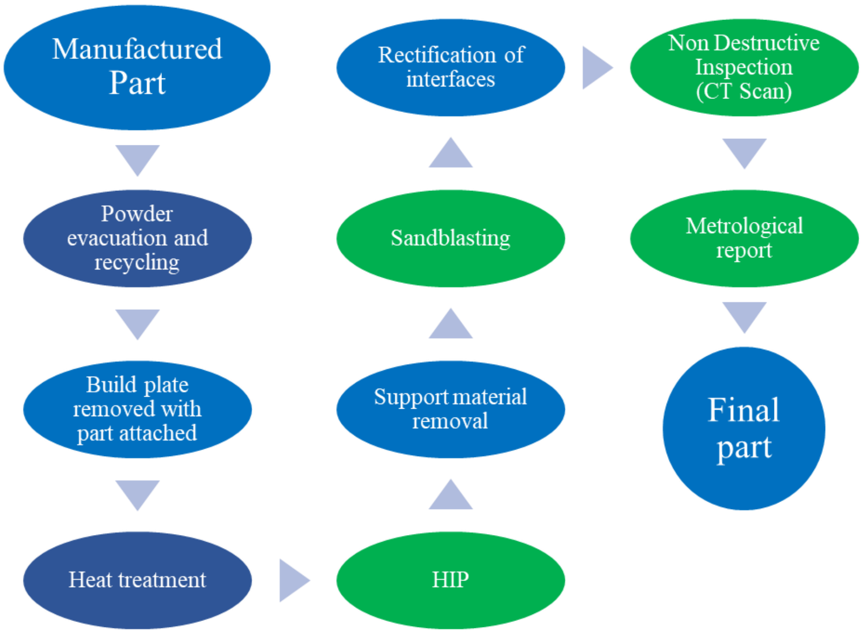
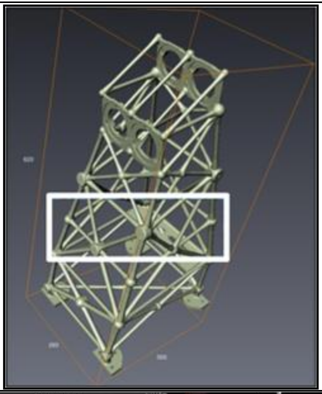



Fig. 42 Post-processing steps for parts with cavities and additional options

- **Computer Tomography Scan**

In some cases/industries, total powder evacuation is vital, which is why an additional step for verification can be carried out upon completion of the entire production process. The check is non-destructive and is done by scanning the part with a computer tomograph machine. The structural integrity of the part can also be checked. This verification shall be carried out, in particular, in the space industry in the case of parts with cavities. This is generally needed in the space industry where residual dust poses a risk of contamination.

Space Tech Expo Europe 2019 Bremen



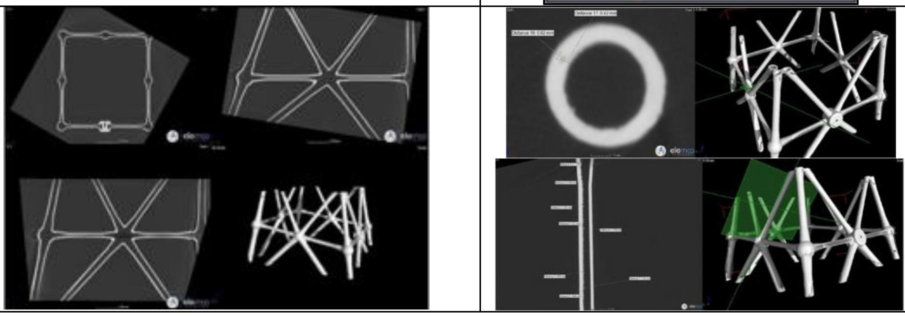


Fig. 43 CT scan. (Cismilianu, et al., 2017)

## Chapter 12. Topological optimization of a landing gear for a vertical take-off and landing vehicle (VTVL)

### 12.1. Optimization for a VTVL vehicle with turbojet engine

#### Introduction

In recent years there is an increasing trend regarding reusable vertical take-off and landing vehicles, which is why the general structural optimization methodology for a landing gear for a vertical take-off and vertical landing vehicle (VTVL) with a turbojet engine was applied.

For the quick identification of a concept, it was considered a vehicle with a generic shape consisting of 4 landing gear arranged axially equidistant. For this reason, Fig. 44 shows a generic shape, as a substitute for a vehicle (marked in turquoise) and 4 volumes in standard positions for a landing gear (marked in black).

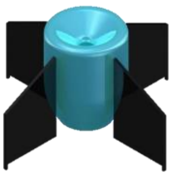


Fig. 44 Substitute for a vehicle with design volumes at landing gear positions (Munteanu & Cismilianu, 2016) [OWN CONTRIBUTION]

We started from the premise that the landing will be done by stopping the traction at 1 m from the ground, and the vehicle will have approximately 60Kg. The distance of 1 m from the ground and the mass of 60 Kg represents the estimated mass of the DTV vehicle (see ANNEX 3.2), this value is considered as a reference for this case study. We consider that, on average, the vehicle will first land on one of the trains and then on the others, so we impose a load/landing gear of 600 N. The optimization was performed in 3 different software applications, highlighting the particularities of each as follows:

- Inspire – Software from the Altair suite, the suite that uses the Optistruct solver, used in commercial software programs Inspire and Hypermesh, solver which been studied and improved in terms of structural optimization since 1994;
- Patran/Nastran – Solver and software dedicated to structural analysis that have a structural optimization module;
- Matlab – Programming environment.

**Optimization made with INSPIRE**

The dimensions in Fig. 45 are chosen identically to those in (Munteanu & Cismilianu, 2016) to compare the results of the study started in (Munteanu & Cismilianu, 2016) where the geometric dimensions of the design space allocated for optimization for the landing gear of a vertical take-off and vertical landing vehicle (VTVL) with turbojet engine are indicated.

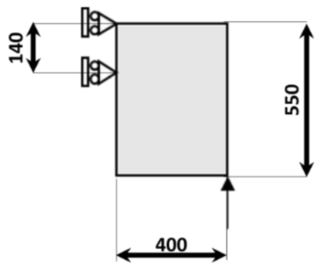



Fig. 45 Geometric dimensions of the considered design space

Constraint and force points were imposed in the dimensional representation. An extrusion constraint was applied to the D-space (burgundy) to translate the 3D calculation case into a 2D calculation case and simplify the optimization process obtaining results that can later be translated into the hybrid structure made up of profiles and elements that can be manufactured through milling. Since it is desired to perform an optimization from a 3D volume, the only type of optimization that can be applied in this case is topological optimization. The optimization parameter, response type, was chosen was volume, and the objective was minimizing response. The same calculation case was considered in the case of two mesh sizes, 10 mm and 20 mm, in order to see the influence of the mesh dimension on the results obtained and to be able to compare them later with those obtained by applying another software application.

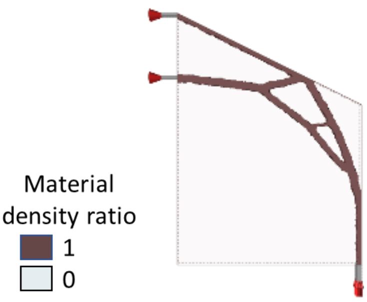



Fig. 46 Mesh 20 mm resulting mass 0.9 Kg (Munteanu & Cismilianu, 2016) [OWN CONTRIBUTION]

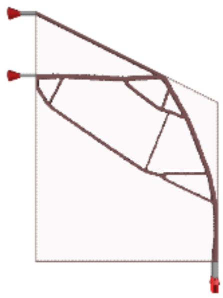


Fig. 47 Mesh 10 mm resulting mass 0,88 Kg (Munteanu & Cismilianu, 2016) [OWN CONTRIBUTION]

The variation of mesh size was used in this case to influence the direction of distribution of the material, thus giving the user options in choosing the ideal concept.

**Optimization made with Patran/Nastran**

The case presented above represents my own contribution, in parallel, in INCAS, the structural optimization was carried out in identical conditions in the optimization module of Patran/Nastran. The optimization carried out in Patran/Nastran does not represent an own contribution, and in the current subchapter only a few figures are presented that will be considered the source of INCAS.

Starting from the same input data, using the geometric dimensions of the considered design space, a surface was generated and subsequently discretized, with elements of size 20 mm.

Since conceptual optimization is desired, the only type of optimization that can be applied in this case is topological optimization. The response chosen was volume, and the objective was to minimize response. The same calculation case was considered in the case of two meshes, 10 mm and 20 mm to see the influence of meshing in the results and to find an ideal variant.

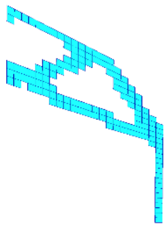


Fig. 48 Mesh 20 mm (Munteanu & Cismilianu, 2016)

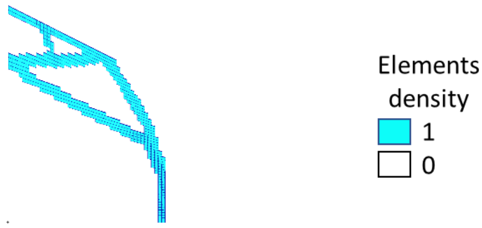



Fig. 49 Mesh 10 mm (Munteanu & Cismilianu, 2016)

The variation of mesh size was also used in this case to influence the direction of distribution of the material, thus giving the user options in choosing the ideal concept.

**Optimization made with Matlab**

Starting from the input data presented in the introduction, Fig. 45 was used to define the dimensions of the design space allocated for optimization for the landing gear of a turbojet-powered vertical take-off and vertical landing vehicle (VTVL).

The optimization was performed using the code (Sigmund, 2001), code that was modified, according to the comments in the code in ANNEX 1, for the specific needs of the current study case. The code is made according to a standard case of topological optimization. The parameters of the calculation case are entered as numerical values in the main program by the command below, writing numerical values instead of each parameter represented:

```
top(nelx, nely, volfrac, penal, rmin)
```

where, nelx – represents the number of elements horizontally (along the x axis); nely – represents the number of elements vertically (along the y axis); volfrac – represents the volume fraction imposed in optimization; penal – represents the penalization factor imposed in optimization on the result; RMIN – represents the filter size applied to eliminate the checker board effect. When choosing a numeric value less than 1, the filter is inactivated.

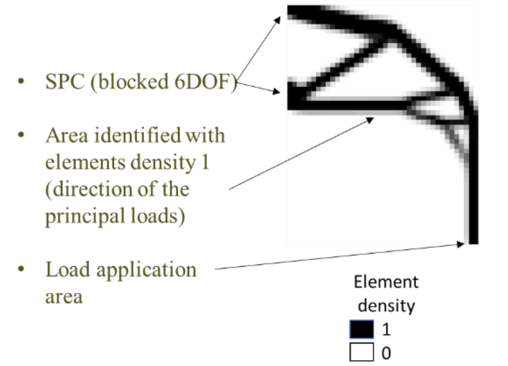
In order to be able to perform the optimization calculation in Matlab, we adapted the code described above to define the design range according to Fig. 45

A sensitivity analysis was performed first on the penalization factor and the second time on the filter factor, determining the ideal numerical values for the mentioned parameters.

Nelx, the number of elements horizontally, is imposed at 40, and nely, the number of elements vertically, 55, so the size of each element is 10mm, size identical to case 2 of optimization analyzed, both in Inspire and in Nastran/Patran. Volfrac is imposed at 0.2, thus, the optimization program has the constraint of using only 20% of the volume of the total design range to generate the direction of the main loads.

By entering all the above variables into the modified code, running it generated the result from **Error! Not a valid bookmark self-reference.**

Tab. 10 Result obtained with Matlab code using the first set of parameters (mesh size 10 mm)

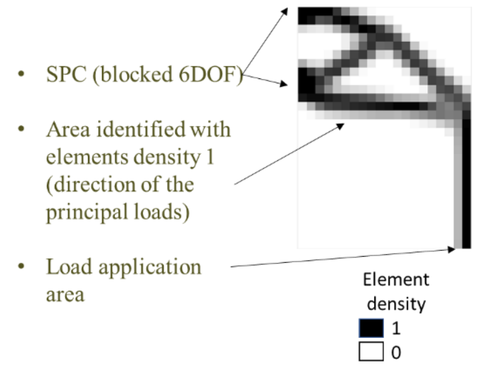



A low number of thick components (strings of density 1 elements) can be identified, implying a low number of assembly areas and thus a low degree of complexity of the related parts and the overall assembly. At the same time, the result is continuous from a structural point of view, and in the structural evaluation the continuity of a structure brings a major structural contribution.

| Initial | top | (nelx, | nely, | volfrac, | penal, | rmin) |
|---|---|---|---|---|---|---|
| Set 1 of parameters | top | (40, | 55, | 0.2, | 4.0, | 1.5) |
| *all of the above parameters are dimensionless | | | | | | |

For reasons of similarity with the optimization cases made in Inspire and Nastran/Patran, a new run is required to have an optimized variant with 20 mm elements as well. Thus, the values of the horizontal elements, nelx, and the values of the vertical elements, nely, used in parameter set 1 are divided by 2, resulting in an element size of 20 mm.

Tab. 11 Result obtained with Matlab code using the second set of parameters (mesh size 20 mm)




We can identify a small number of thick components, but at the same time a vague structure defined by the presence of some diffuse elements near the directions of the main stresses.
At the same time, it is observed that we obtained 2 thick components that end in a vertical component (string of density elements 1) forming an angle of ~90 degrees at the intersection between the horizontal components and the vertical component (strings of density elements 1). Thus, much of the impact demand is taken up concentrated by that junction.

| Initial | top | (nelx, | nely, | volfrac, | penal, | rmin) |
|---|---|---|---|---|---|---|
| Set 2 of parameters | top | (20, | 28, | 0.2, | 4.0, | 1.5) |
| *all of the above parameters are dimensionless | | | | | | |

**Comparison of results**

All optimization calculations were performed under identical boundary conditions according to  Fig. 45 The results (see Fig. 50) for each software application are divided according to the size of the discretized elements into two categories:

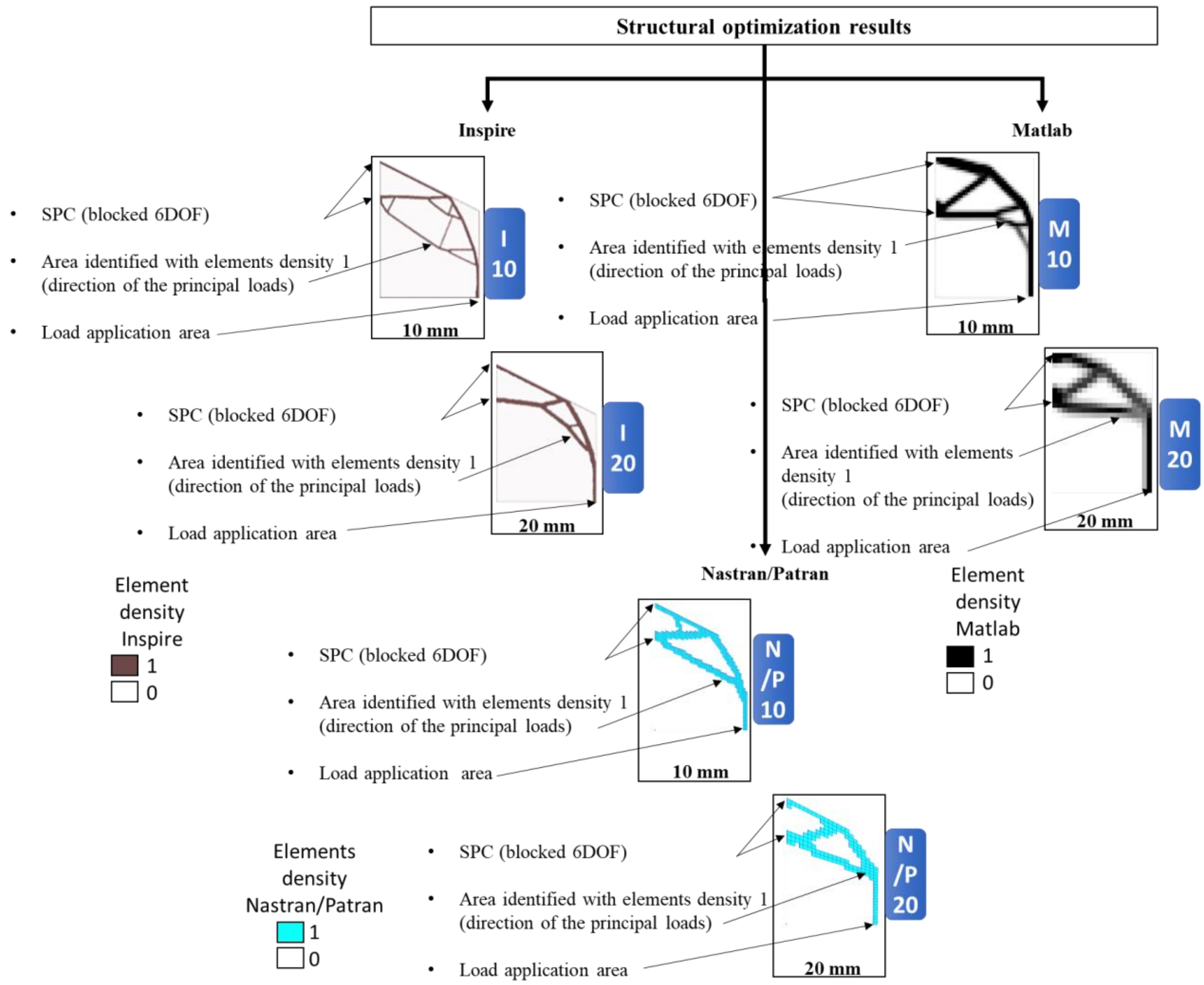



Fig. 50 Structural optimization results in Inspire, Nastran/Patran, Matlab

A ranking was made from the point of view of the main loads distribution (visualized in the results by density 1 of the elements) in the resulting structure: 1. I20 and M10; 2. N/A 10; 3. N/P 20 and M20; 4. I10. A comparison was made (see Fig. 51) between the results obtained by the 3 methods and two dimensions of element discretization by using a free online software application (onlinejpgtools, 2022) through which the average colors were extracted from the results of the optimizations carried out in Inspire, Nastran/Patran and Matlab.

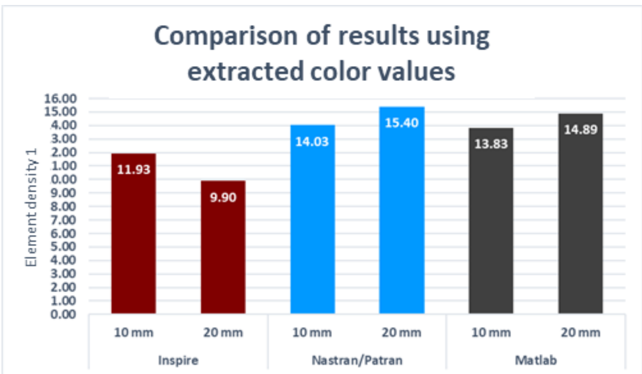



Fig. 51 Comparison of results Inspire, Nastran/Patran, Matlab

In Fig. 51 it is observed that, for the mesh performed with elements of 10 mm and 20 mm, respectively, in the case of Nastran/Patran and Matlab software applications, in terms of surface area of elements with density 1 extracted, the 4 results are similar. A ~1% difference is identified in the case of Nastran/Patran and Matlab software applications for results where 10 mm element mesh size was used and a ~3% difference in the case of 20 mm element mesh size. In the case of Inspire, it can be seen that for the mesh size of 10mm elements and for the mesh size of 20mm elements, the results are ~15% better and ~36% better than competing optimization methods.

The Altair suite consists of two software applications that can be used for structural optimization, Inspire and Hypermesh. Both are based on the same solver, Optistruct. Thus, regarding the common solver, both software applications are advantaged by this study.

### 12.2. Optimization for a VTVL vehicle with a rocket engine ADAMP

**Context**

A study was conducted for a damped landing gear for a reusable octagonal structure vehicle with vertical take-off and landing and rocket engine. The study was conducted using structural optimization methods with the aim of developing a landing gear concept. This study was used in pre-design steps of the ADAMP Project (see ANNEX 3.4) led by INCAS under the tutelage of the European Space Agency.

**Study**

The vehicle on which the study was performed consists of 4 landing gear arranged axially equidistant and has a mass of approximately 800 Kg. It starts from the same premise, as from 1 m distance the engine traction is cut and the vehicle falls first on one of the legs.

We started from an initial concept created in INCAS and generated a design volume D only in the area that is considered fixed (see Fig. 52). In the area not included in the D space, it is considered to introduce shock absorbers so that the area resulting from optimization oscillates on the hinges to allow damping (see Fig. 52).

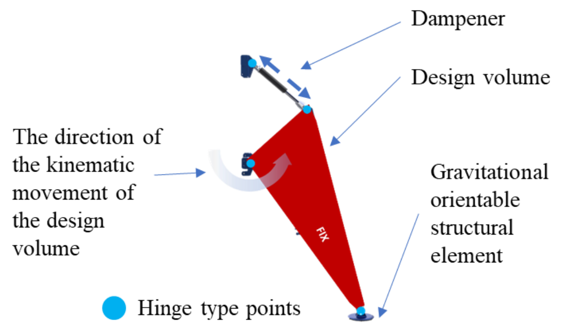



Fig. 52 Design space considered as fixed component marked in **red** (Own contribution. Source: INCAS - ADAMP PROJECT. More information in ANNEX 3.4)

Since it is desired to achieve conceptual optimization from a 3D volume, the only type of optimization that can be applied in this case is topological optimization. For the current optimization, the INSPIRE Solidthinking software application was used as it can perform a multitude of different optimizations and provides the means to analyze and to verify the results.

Next, only the area marked in the previous figure will be considered in optimization. Points of constraint and application of force were also imposed when presenting geometric dimensions. Points have been converted into non-design (ND) volumes outside the design space to be able to apply forces and constraints to ND spaces (gray). A symmetry constraint was also introduced in the middle area of the landing gear.

The force values imposed in the current study case are confidential, which is why they are not mentioned.

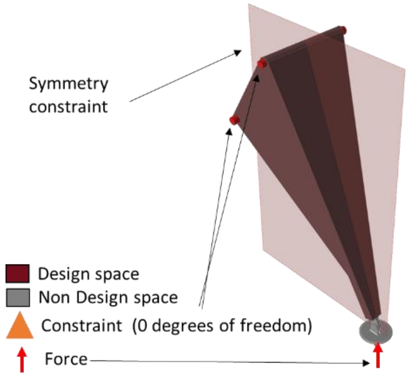



Fig. 53 Spaces of **D** and ND + Applied symmetry in the middle area (Own contribution. Source: INCAS - ADAMP PROJECT. More information in ANNEX 3.4)

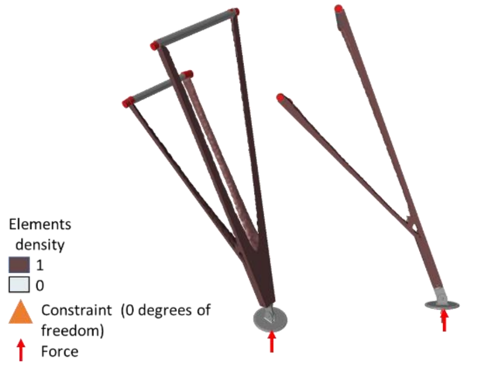



Fig. 54 Optimization results (Own contribution. Source: INCAS - ADAMP PROJECT. More information in ANNEX 3.4)

The chosen response was the volume, and the objective was the minimization of the response. Volume D was discretized with 20 mm elements. The results tell us the placement area of circular profiles, which should be maximally extended into the design volume space. The indicated direction was respected in the lower area, and in the upper area the area allocated to the 2 structural elements generated by optimization was considered and they were replaced by a single centrally arranged profile. The junction areas were replaced with milled elements to connect the circular profiles, and shock absorber elements were introduced into the upper zone.

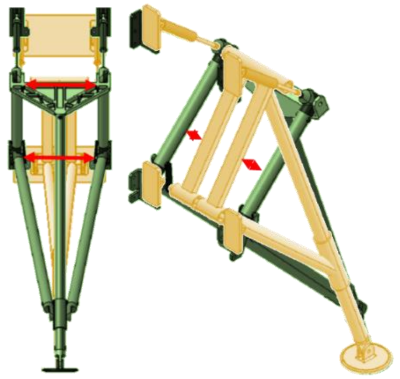


Fig. 55 Overlapping of optimization and design result (**New Model** Old Model) (Own contribution. Source: INCAS - ADAMP PROJECT. More information in ANNEX 3.4)

The results have been redesigned as an assembly of EN AW 6082 aluminum pipes and milled parts made from EN AW 7075. Over the initial concept (Fig. 66 Fig. 55Fig. 66Fig. 55 green) to notice the differences between them. The new concept, the green one in Fig. 55, has the structural elements extended to the maximum width allowed by the fasteners. Thus, the structural performance of the optimized landing gear is superior to the original model.

**Conclusions**

The overall structural optimization methodology is validated once again, demonstrating that it is robust regardless of the calculation case to which it applies.

The size of the mesh has a direct impact on the optimization results (see Fig. 50), especially if optimization is used to obtain a concept. Varying the size of discretized elements can be done to obtain several variants of concept in order to identify the feasible one for the desired manufacturing method.

In case of conceptual optimization of a planar landing gear (single plane) that is intended to be manufactured from standard profiles and milled elements at the junctions, the extrusion constraint will be introduced for optimization achieved in Inspire. This is imposed on the design space.

In case of conceptual optimization of a non-planar landing gear (2 angled planes) that is intended to be made of standard profiles and milled elements at the junctions, the symmetry constraint centered in the volume of space D will be introduced.

In the case of optimization in Nastran/Patran, the smaller the size of the elements in the mesh, the more clearly defined the results are, as shown in Fig. 50

In the case of optimization in Matlab, special attention should be paid to the numerical value of the penalization factor and the numerical value of the factor to be filtered. For each parameter, it is recommended to perform a sensitivity analysis before considering the results of the desired optimization calculation.

A comparative analysis was made between the results obtained in Inspire, Nastran/Patran and Matlab having identical boundary conditions and discretization sizes of the elements. The comparative analysis was done in terms of structural continuity and the percentage of elements with density 1 in the results from which it was observed that the result for the discretization performed in Inspire with 20 mm elements is ~36% better than the competing optimization methods.

# Chapter 13. Conclusions, own contributions and future research directions

## 13.1. General conclusions

The thesis addressed a topic not documented in detail, that of a robust structural optimization methodology and variations thereof where the structural optimization can be customized for pre-selected manufacturing technology. This methodology has been applied in real cases, either starting from scratch or starting from already existing models. The paper begins with the state of the art in additive manufacturing and structural optimization and is divided into 13 chapters.

**The general conclusions resulting from the research are:**

- The introduction of topological optimization on the path between design and structural analysis drastically reduces the number of iterations between these steps, but does not completely eliminate them, because the optimization itself can represent an iterative process of optimizing and re-designing the results in CAD, also optimizing the remodeled result until fulfill the constraints and the desired objective function;
- There are very advanced commercial design software applications that eliminate the need to develop a proprietary software application of this kind at the moment;
- Structural optimization can be performed for a specific technology (welding, casting, extrusion, CNC milling, additive manufacturing, etc.). When the technology is known from the beginning, the possibility of reducing the time to obtain a relevant and subsequently adapted result for that technology decreases dramatically. Each customized result must be adapted from a technological point of view in the step of redesigning a CAD model based on the results obtained from the structural optimization;
- The optimization methodology was tested on the study cases covered through this paper. Given the variety between cases and the fact that the methodology has remained constant, being necessary to vary them in individual cases only by multiplying some steps, it follows that the resulting optimization methodology is robust;
- Based on the case studies in chapters 5-8, the steps that must be followed and the parameters that can be varied were studied and three sets of rules for achieving topological optimization were created;
- Parts with cavities require a dedicated powder evacuation procedure;
- In the case of parts with cavities, necessary steps that must be added or modified in production to obtain such a part have been presented.
- Based on the topics addressed in the thesis, a rapid method of interpretation and understanding of the results obtained in various analyzes was achieved;
- In the case of the conceptual optimization of a non-planar landing gear (two planes at an angle) which is to be manufactured from standard profiles and milled elements at the junctions, the symmetry constraint centered in the volume of space D will be introduced. The results obtained in following the concept optimization for a landing gear can be later modified to include a shock absorber and the kinematics necessary to engage it upon landing.

### 13.2. Own contributions

The results obtained in the current thesis are represented by results currently used in practice or of practical importance primarily in the field of parts made by additive manufacturing with metal powders that have cavities in their composition from the point of view of the development of design rules, additional steps required in production and methods of qualification/validation of parts made for space. Second, it is of practical importance in customizing structural optimization and developing a structural optimization methodology. The main contributions were:

- Elaboration of a robust structural optimization methodology that has been applied and validated on all study cases in the paper;
- Demonstration of the use of a robust methodology easily adaptable in specific cases;
- Evaluation of the topological optimization methodology developed in terms of applicability by applying them in an increased number of case studies;
- Elaboration and presentation of a set of case studies in order to demonstrate the possibility of customizing the methodology for different technologies, including additive manufacturing technologies with metal powders;
- Demonstration of how topological optimization can be customized for the desired manufacturing technology, be it additive manufacturing or classic variants such as parts obtained by welding, milling on CNC centers, etc.;
- Presentation, explanation and documentation of the current state of topological optimization algorithms in the literature;
- Highlighting general errors in structural optimization and methods for their prevention;
- Development of design rules for cavities and powder evacuation rules in case of their introduction in case of manufacturing by PBF additive technologies;
- Achieving a quick method of interpretation and understanding of the results obtained in structural optimization and various structural analyzes;
- Establishing sets of optimization rules correlating the results obtained for each case study from chapters 5-8;
- Development of concept rules in the case of additive manufacturing with metal powders for parts with cavities and their tabular synthesis.

### 13.3. Future research directions

The developed structural optimization methodology, but also the methods for customizing the optimization results for pre-selected manufacturing technologies require a thorough research and development activity, which must be continued by:

- Testing custom components under real working conditions. Part of the components, those produced, are used as component flight parts of each assembly presented in the context of each case study (DTV, Euclid) and have successfully passed the test step in relevant environments carried out either by INCAS (in the case of DTV) or by European Space Agency (in the case of EUCLID);
- Analyzing their evolution over time and tracking possible defects and tracing them to identify if optimization customization could be done preventively. The components already produced have been used as flight parts for about 3 years, and up to this point they have no defects;
- Evaluation of the resistance over time and in mechanical working conditions of part of the structural components obtained by customizing the structural optimization. The components already produced have been used as flight parts for about 3 years, and up to this point they have no defects.

## BIBLIOGRAPHY (extract)


[WOS1] **A.M. Cismilianu**, I. Chirita, A.G. Persinaru, A. Marin, C.E. Munteanu, A.M. Neculaescu, C. Dragoman, „Re-entry Vehicle Structural Optimization for Mass Minimization”. In: Machado, J., Soares, F., Trojanowska, J., Ottaviano, E. (eds) Innovations in Mechanical Engineering. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-030-79165-0_9, 2021

[WOS2] T.P. Afilipoae, A.M. Neculaescu, A.I. Onel, M. V. Pricop, A. Marin, A.G. Persinaru, **A.M. Cismilianu**, C.E. Munteanu, A. Toader, A. Sirbi, S. Bennani, T.V. Chelaru, "LV-MDO în the development of a Microlauncher"", Transportation Research Procedia, 2352-1465 © 2017 The Authors. Published by Elsevier B.V., Peer-review under responsibility of the scientific committee of the 6th CEAS Air & Space Conference Aerospace Europe 2017;"

[WOS3] Frunzulica, **A.M. Cișmilianu**, A. Boros, A. Dumitrache, and B. Suatean, University POLITEHNICA of Bucharest, Professor, "A new Vertical Axis Wind Turbine Design for Urban Areas", AIP Conference Proceedings 1738, 410008 (2016); doi: http://dx.doi.org/10.1063/1.4952209, 13th edition of International Conference of Numerical Analysis and Applied Mathematics, ICNAAM 2015, Rodos Greece;

[SCOPUS1] Nenciu, A.R. Petre, **A.M. Cișmilianu,** C.E. Munteanu, “VTVL Engine Attachment Structural Optimization”, NMAS 2022, Romania.

[SCOPUS2] **A.M. Cișmilianu**, I. Chirita, A.G. Persinaru, A. Marin, C.E. Munteanu, A.M. Neculaescu, C. Dragoman, "Re-entry vehicle structural optimization for mass minimization", ICIE 2020, Portugal;

[SCOPUS3] **A.M. Cișmilianu**, M. Năstase, I.C Oncescu, "Research on the optimal shape of high pressure tanks for vehicles with vertical take-off and landing", U.P.B. Sci. Bull., Series D, Vol. 83, Iss. 2, 2021

[SCOPUS4] Toader, A.M. Neculăescu, A.G. Perșinaru, **A.M. Cișmilianu**, A. Marin, C.E: Munteanu, " GNC algorithms numerical and testing validation for VTVL demonstrator ", International Workshop on Numerical Modelling în Aerospace Sciences, NMAS 2019, Bucharest Romania;

[SCOPUS5] C.E. Munteanu, **A.M. Cismilianu**, A.I. Chira & D. Baran – " Structural optimization of space components adapted for 3D printing ", DAAAM Proceedings, 28th Danube Adria Association for Automation & Manufacturing, DAAAM 2017, Zadar Croatia;

[BDI1] **A.M. Cișmilianu**, C.E. Munteanu, I.C. Oncescu, R.P. Bibire, V. Stoenescu, M.V. Pricop de la INCAS; E. Rey, S. Eyrignoux de la LISI Aerospace Additive Manufacturing, "End to end process of hollow spacecraft structures with high frequency and low mass obtained with in-house structural optimization tool and additive manufacturing", INCAS BULLETIN, Volume 9, Issue 3, pag. 13, ISSN 2247-4528 (online), ISSN 2066-8201 (print), 5th International Workshop on Numerical Modelling în Aerospace Sciences, NMAS 2017, Bucharest Romania;

[BDI2] **A.M. Cișmilianu**, A.R. Petre, C.D. Liliceanu, R.P. Bibire, "Topology optimization of a payload adapter for a launcher" Book of Abstracts NMAS 2017 and DVD, ISSN 2360–1809, 5th International Workshop on Numerical Modelling în Aerospace Sciences, NMAS 2017, Bucharest Romania;