Journal of Engineering and Technology for Industrial Applications

ITEGAM-JETIA

Manaus, v.7 n.31, p. 4-10. Sept/Oct, 2021
DOI: https://doi.org/10.5935/jetia.v7i31.775

ISSN ONLINE: 2447-0228

RESEARCH ARTICLE OPEN ACCESS

THE INTEGRATION OF DFMA (DESIGN FOR MANUFACTURING AND ASSEMBLY) AND REVERSE ENGINEERING (ER) APPLIED TO A LANDING GEAR REDESIGN

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ARTICLE INFO

Article History
Received: October 12th, 2021
Accepted: October 26th, 2021
Published: October 29th, 2021

Keywords:
DFMA,
Reverse engineering,
Integration,
Landing gear,
Aerodesign.

ABSTRACT

The article addresses the redesign of a landing gear for a light aircraft that suffered from manufacturing and assembly problems. Numerical parameters of design features are related to design guidelines for identifying fabrication and assembly issues within 3D model analysis. For this work, the Lucas method of the DFMA integrated with reverse engineering was used as a methodology for the redesign, and its evaluation parameters for resizing the assembly item. Subsequently, the geometry of the redesigned component was defined, where significant reductions were obtained for the evaluation rates of the method used. Reduction from 20 pieces to just 6, which corresponds to a gain of 42% for functional analysis, reductions of 72% for power analysis and 84% for assembly analysis.

I. INTRODUCTION

The product development process (PDP) is complex for its multidisciplinary knowledge [1]. A structured PDP is essential for an industry's competitiveness and survival and is composed of multifunctional activities influenced by many internal and external factors [2]. Many companies competing in today's international scenario consider the PDP an important factor to hold competitive advantages [3]. Product redesign can be seen as a means of executing companies' competitive strategies. This technique, when inserted in a methodology for implementing product improvements, takes as a starting point the technical specifications of a product already launched on the market, aiming at technological improvement and not the simple copy of the existing product [4].

Between this techniques related to PDP, the term design for manufacturing (DFM) refers to the design for easy manufacturing of parts that form the product after assembly, while design for assembly (DFA) is related to product design for easy assembly. Design for manufacturing and assembly (DFMA) is a combination of DFA and DFM [5].

The design for manufacture and assembly (DFMA) aims at making product design and production planning happen simultaneously, based on a set of principles. In the redesign, DFMA helps to adapt the product in the best way to the characteristics of production and assembly, seeking to improve quality and reduce the time of manufacture and assembly [5].

There are several DFMA and DFA methods or techniques for concurrent engineering development. The three best known are the Boothroyd–Dewhurst DFMA method, the Hitachi Assemblability Evaluation and the Lucas DFA [6]. The Lucas DFA method was developed by the University of Hull and has the same research base as Boothroyd–Dewhurst [5], so they present some common characteristics, such as the reduction of the number of parts and the analysis of the parts' geometry regarding the assembly process [7].

Conversely, reverse engineering and shape reconstruction play an important role in design and manufacturing through the increased use of shape acquisition and processing technologies in the product development process. Geometric reverse engineering relies on a set of generic methods inherited from the geometric modeling and processing fields. Those methods encompass mesh segmentation, surface reconstruction, and feature recognition. Moreover, geometric reverse engineering is nowadays supported by a digital thread from the raw acquired point cloud data to parametric feature-based cad models. [8]. Reverse engineering is used when you want to exchange or modify one part or software for another, with the same characteristics, but not all information about that part is available. Basically, it consists of a planned and organized attempt to obtain technology of product and process through the analysis of reference products (the best in that segment) [9]. The main application of the RE is in the redesign and improvement of existing parts, in which improvements are desired, such as cost reduction or even the inclusion of new features to the product.

The DFMA method is widely used as a support to improve the concept of projects or an existing project, in order to optimize the manufacturing and assembly steps. When integrated with RE, a more accurate and holistic assessment can be performed, obtaining greater gains.

Aircraft parts are complex precision-engineered products with tighter assembly tolerances produced by conventional and non-conventional manufacturing processes. Variations in these manufacturing processes have to be controlled, process risks mitigated, and managed effectively, to facilitate the ease of aero-engine assembly to reduce overall variation and improve the assembly quality [10].

In this regard, the main functions of an aircraft landing gear are to support the plane on the ground and to maneuver it during the taxiing, takeoff and landing processes. In most aircraft, the landing gear used has wheels, but there are cases where floats on seaplanes and skis are used for snow operation. The landing gear can be classified basically into two categories according to the arrangement of the wheels: tricycle or conventional [11].

An aircraft landing gear was selected in this case study, due to difficulties verified during the manufacturing and construction stages of the landing gear items to SAE aerodesign competitions, it took a long time to manufacture and assemble. In this way, was possible to analyze through the RE all the stages of manufacture and assembly, checking what can be changed.

The case study addresses on redesigning and formulating a methodology for stages of creating aircraft landing gear projects in order to reduce the amount of parts made, reduce assembly time and, consequently, increase the quality of the project. Concurrently DFMA integrated with RE, a more accurate and holistic assessment can be performed, obtaining greater gains.

II. METHODOLOGY

The work included an evaluation of the current design of the aircraft through reverse engineering method, it was carried in this way, to find possible failures and opportunities that through the DFMA method can be remedied and improved, aiming to optimize manufacturing, assembly and weight of the aircraft. The use of integrated methods between DFMA and ER will be addressed. Specifically between the DFMA methods, the Lucas method will be used, to evaluate the landing gear and to support a new concept to reformulate the current project.

Figure 1 is showed the operational sequence of the study development; it was summarized in a flowchart, which contains all the steps for analyzing an existing product and its redesign, in order to improve its assembly characteristics.

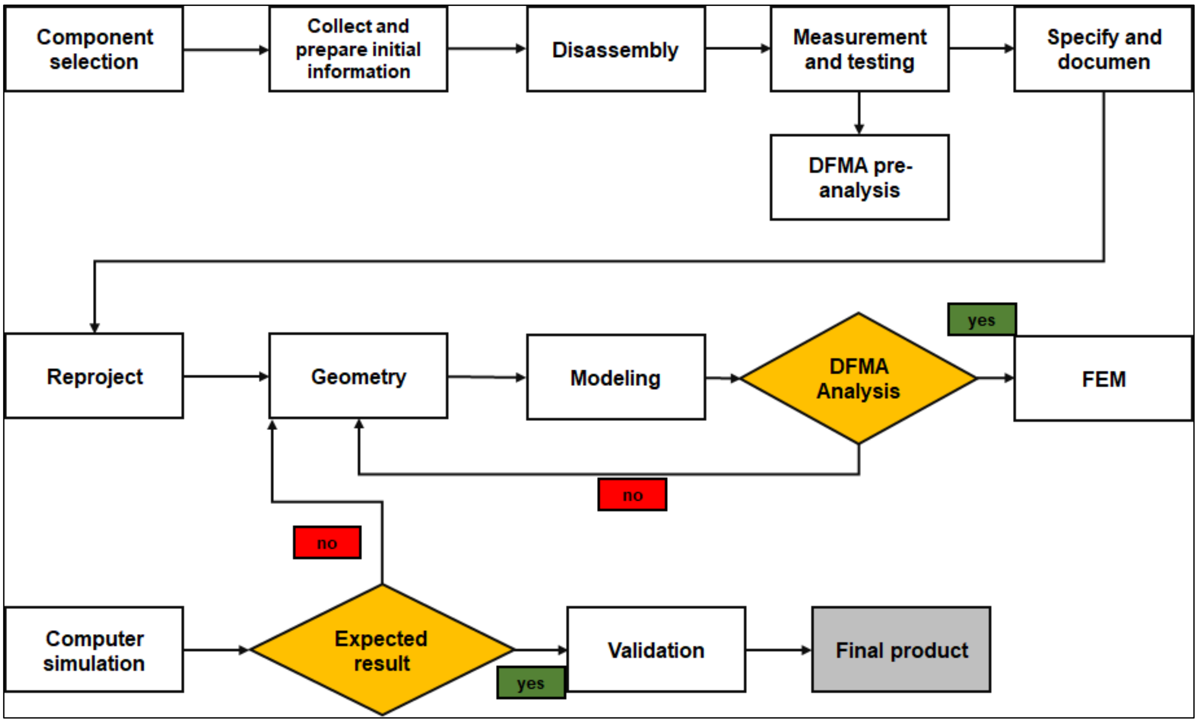

Figure 1: Study methodology applied to landing gear redesign.
Source: Authors, (2021).

The design geometry was redefined according to the evaluation carried out using the Lucas method. The method is based on standardized and tabulated parameters, which allows greater flexibility in input data and even in evaluation [2], aiming to improve assembly and manufacturing. The current landing gear material will not undergo major changes, as the purpose of the work is to improve the assembly and manufacturing criteria.

In this methodology is proposed that the new landing gear geometry is validated using DFMA tools. For its implementation, finite element analysis (FEM) through computer simulation was also used. After completing these steps, the landing gear design can be validated and suitable for use in aerodesign aircraft.

The reference model used as the basis for the redesign and reformulation was the landing gear of the Urutau Aerodesign team from Amazonas - Brazil, identified in Figure 2, participating in the national competition SAE Brazil AeroDesign.

Figure 2: Current landing gear.
Source: Authors, (2021).

To assess the current conditions of the landing gear it was necessary to disassemble it to collect information about the parts, check the quantity of items and thus apply the DFMA method of Lucas [2].

The landing gear was disassembled and its parts were listed to start the analysis process, as shown in Figure 3.

1.Sheet metal	6. Cable fixing screw
2. Plate screws	7. Wheel coating
3.Steel cable	8.Clips for cable
4.Showers	9. Nuts
5.Wheels	10. Bearing

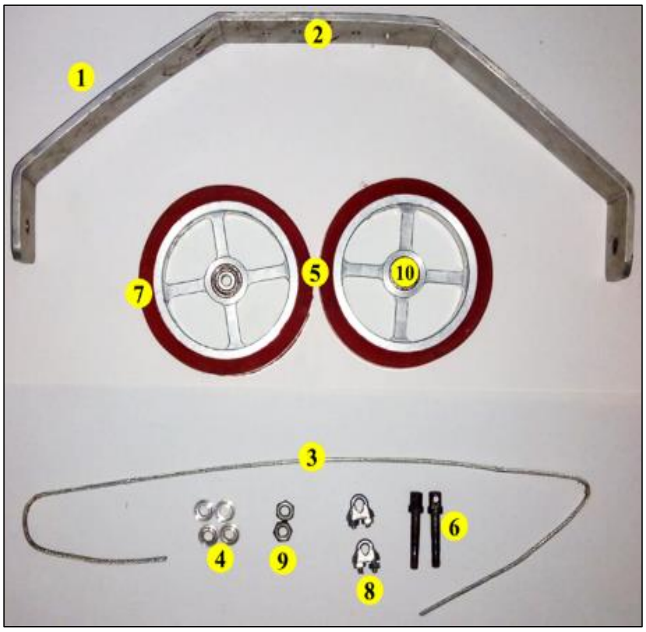

Figure 3: Classification of main landing gear items.
Source: Authors, (2021).

The evaluation of essentials items (α), are extremely important for the functioning of the product and also the non-essential items (β), it indicates even with the absence of the product functions can be performed normally.

The evaluation of essentials items (α), are extremely important for the functioning of the product and also the non-essential items (β), it indicates even with the absence of the product functions can be performed normally.

By obtaining these two variables, it is possible to carry out the analysis of the design functional efficiency index (Ed), feeding ratio and fitting ratio, according equations 1 to 3 used in Lucas method. In handling analysis, problems associated with handling the part are scored using an appropriate table. For each part, the individual feeding ratio is scored [12].

The equations to functional, handling and assembly analysis are employed as follows:

Functional analysis

$$Ed = \frac{\alpha}{(\alpha + \beta) * 100\%} \quad (1)$$

Handling analysis

$$Feeding\ Ratio = \frac{Total\ Feeding\ Ratio}{Number\ of\ essential\ components} \quad (2)$$

Assembly analysis

$$Fitting\ Ratio = \frac{Total\ Fitting\ Ratio}{Number\ of\ essential\ components} \quad (3)$$

Regarding competition requirements [13] says that the main types of loading on the landing gear are:

- Static loading on the ground;
- Dynamic loading on landing.

Loads can be tensile, compression, shear, torsion or bending loads.

The following conditions are evaluated: landing on three wheels, landing on two wheels and landing on a single wheel of the landing gear.

To validate the component, a drop test was performed with the physical prototype of the landing gear in accordance with the American standard for light aircraft [15].

To carry out the simulation of loading on the parts of the main landing gear, defined in the work, was used ©2002-2021 Dassault Systèmes SolidWorks Corporation software.

For the analyses, the tetrahedral mesh was used to obtain more accurate results accompanied by the Von Misses failure criterion, which can later be compared with the Tresca failure criteria.

III. RESULTS

III.1 ANALYSIS OF THE CURRENT LANDING TRAIN

The number of parts in this study was 15 functional and 5 non-functional. As reported in Table1 the efficiency rate of the current landing gear design is 25%. The Table1 data were processed by equation (4), according to [4].

$$Assembly\ metric\ design = \frac{Number\ of\ parts}{Theoretical\ minimum\ parts} \quad (4)$$

The efficiency index additionally informed in Table 1 it is lower than the 60% limit, it is not acceptable, requiring the elimination of some parts, until reaching the suggested efficiency.

Table 1: Functional analysis of the landing gear.

N	Part	Number of parts (Np)	Theoretical minimum parts
1	Sheet metal	1	1
2	Plate screws	2	0
3	Steel cable	1	0
4	Bushings	4	2
5	Wheels	2	2
6	Cable fixing screw	2	0
7	Wheel casing	2	0
8	Cable Clips	2	0
9	Nuts	2	0
10	Bearings	2	0
	Total	20	5
	Assembly metric design	25%	
	Goals	> 60%	

Source: Authors, (2021).

Parameters A, B, C, D, E and F shows in Table 2 are used to calculate feeding and fitting ratios, which provide values according to [14], involving information related to types of orientation, insertion and weight of parts for each situation in the analyzes.

Applying the corresponding values (19.9 to total feeting ratio and 5 to number of essential components in equation (2), a feeding ratio of 3.98 is reported in Table 2 related to handling analysis. Therefore, the feeding ratio is greater than 2.5, the project current cannot be considered acceptable, meaning that the items that are part of the assembly of the landing gear are not entirely suitable for handling, requiring a redesign.

Table 2: Result of landing gear handling analysis.

N	PART	A	B	C	D	TOTAL (A + B + C + D)
1	Sheet metal	1.0	0.6	0.1	0.0	1.7
2	Plate fixing screws	1.5	0.6	0.1	0.2	2.4
3	Steel cable	1.0	0.6	0.1	0.0	1.7
4	Bushings	1.0	0.6	0.5	0.4	2.5
5	Wheels	1.0	0.4	0.1	0.2	1.7
6	Cable fixing screws	1.5	0.6	0.1	0.2	2.4
7	Wheel casing	1.0	1.7	0.1	0.2	3.0
8	Steel cable clips	1.0	0.6	0.1	0.2	1.9
9	Nuts	1	0.2	0.1	0	1.3
10	Bearings	1	0.2	0.1	0	1.3
Total						19.9
Actual feed ratio						3.98
Optimal feeding ratio						<2.5

Source: Authors, (2021).

Substituting the values A, B, C, D, E and F according to [14], a fitting ratio of approximately 12.78 is obtained, Table 3, The adaptation rate for the design far exceeds the limit value of 2.5. Non-essential parts must be eliminated. From the current project, it must be redesigned using devices to redesign the component and establish new indices until satisfactory values are reached, such as the fitting ratio.

Table 3: Result of the landing gear assembly analysis.

N	PART	A	B	C	D	E	F	TOTAL (A + B + C + D + E + F)
1	Sheet metal	6	1.6	0.7	0	0	0	8.3
2	Plate screws	6	0	0	0	0	0.6	6.6
3	Steel cable	3.3	0.1	0	0	0.7	0	4.1
4	Bushings	3.3	0.1	1.2	0	0.7	0	5.3
5	Wheels	6	0.1	0	0	0.7	0	6.8
6	Cable fixing screw	6	0.1	0	0	0	0	6.1
7	Wheel casing	6	0.1	0	0	0.7	0.6	7.4
8	Cable Clips	6	1.6	1.2	1.5	0.7	0.6	11.6
9	Nuts	6	0	0	0	0	0	6
10	Bearings	1	0.1	0	0	0	0.6	1.7
Total								63.9
Actual fitting ratio								12.78
Optimal fitting ratio								<2.5

Source: Authors, (2021).

III.2 LANDING GEAR REDESIGN

Figure 4 is show a sketch of landing gear that was developed by Lucas method in relation to essential and non-essential items.

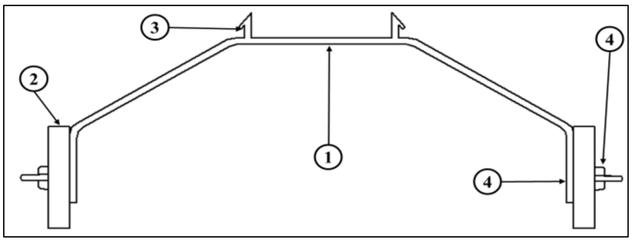

Figure 4: Sketch of the new landing gear.
Source: Authors, (2021).

Figure 5 shows image 3d of conceptual landing gear., it was modeled according to the idealization made with reverse engineering for modifications and improvements. Once the new geometry was established, the next step was the analysis of the conceptual landing gear, aiming to achieve results within the parameters of the Lucas method, both in efficiency and in the assembly.

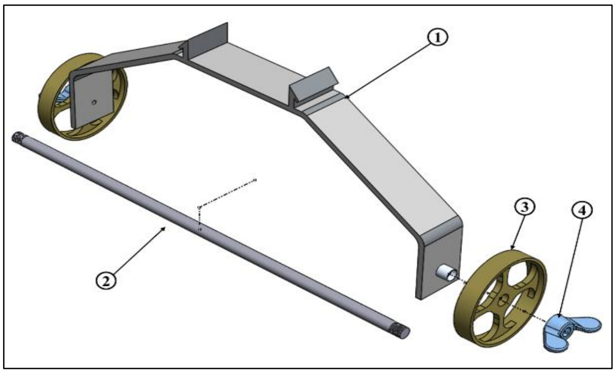

Figure 5: Conceptual landing gear.
Source: Authors, (2021).

III.3 CONCEPTUAL LANDING GEAR ANALYSIS

The number of parts for the new landing gear were, 4 functional and 2 non-functional.

The conceptual landing gear follow the initial design criteria, above 60% with a functional efficiency of 67%, shown in Table 4, as the project was carried out according to the premises of the DFMA.

Table 4: Functional conceptual landing gear analysis.

N	Part	Number of parts (Np)	Theoretical minimum parts
1	Main plate	1	1
2	Tube - shaft	1	1
3	Wheels	2	2
4	Nuts	2	0
	Total	6	4
	Assembly metric design	67%	
	Goals	> 60%	

Source: Authors, (2021).

After the redesign, the new value of the feed index decreased in relation to the previous one, now being 1.10, according to the parameters in Table 5, not only reducing the current but also meeting the criteria defined in the Lucas method.

Table 5: Result of the conceptual landing gear handling analysis.

N	PART	A	B	C	D	TOTAL (A + B + C + D)
1	Main plate	1	0.6	0.1	0	1.7
2	Tube - shaft	1	0.6	0.1	0	1.7
3	Wheels	1	0.4	0.1	0	1.5
4	Nuts	1	0.4	0.1	0.2	1.7
Total						6.6
Feed ratio						1.1
Optimal feeding ratio						<2.5

Source: Authors, (2021).

In the redesign, small fixing parts, such as screws and rivets, were avoided as much as possible to reduce insertion difficulties.

The index obtained for the current landing gear was 12.78, as already established in Table 3. After the redesign, this index decreased to 2.05, as can be evidenced in Table 6, for the conceptual landing gear, with an excellent design performance, as it not only reduced the value in relation to the previous project but also started to meet the criteria determined in the Lucas method, which indicates not to exceed the limit value of 2.5, the result being satisfactory for the redesign.

Table 6: Result of the analysis of the conceptual landing gear assembly.

N	PART	THE	B	Ç	D	AND	F	TOTAL (A + B + C + D + E + F)
1	Main plate	3.3	0.1	0.7	0	0	0	4.1
2	Tube - shaft	1	0	0	0	0	0	1
3	Wheels	6	0.1	0	0	0	0	6.1
4	Nuts	1	0.1	0	0	0	0	1.1
Total								12.3
Fitting ratio								2.05
Goals								<2.5

Source: Authors, (2021).

III.4 MATERIALS PROPERTIES AND SELECTION

Materials selection of landing gear in this study is shown in Table 7, were chosen observing the most used by teams participating in the aerodesign. Moreover, these materials are according to [15] and [16] similar works related to the construction of a landing gear.

Table 7: Materials and properties landing gear.

Properties /Materials	(1)	(2)	(3)	(4)	units
Elastic module (GPa)	2.6	8.3	69.0	70.0	N/m^2
Poisson's ratio	0.3	0.3	0.3	0.3	AT
Shear modulus (GPa)	1.0	3.2	26.0	5.0	N/m^2
Specific mass (x1000)	1.1	1.4	2.7	1.2	Kg/m^3
Tensile strength (MPa)	90.0	142.6	310	476.2	N/m^2
Flow limit (MPa)	103.6	139.0	275.	600.0	N/m^2

Legend Table 7: (1) PA Type 6; (2) Nylon 6/10; (3) Al 6061 T6; (4) Carbon fiber + resin.

Source: Adapted for authors, (2021).

III.5 LOAD ASSIGNMENT

Figure 6 shows the landing gear location under the aircraft. To carry out this project activity, the load distribution and previous work [13] and [17] were considered.

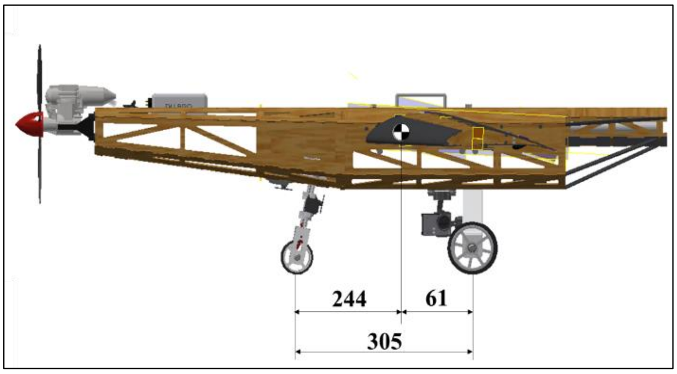

Figure 6: Landing gear location.
Source: Authors, (2021).

For the analysis criteria on the wheel, the most critical landing situation adopted were on a single wheel, in this way it makes the effort to be extreme. And for the main plate, the most critical situation is when it was supported on the two main wheels, that is, only on the main train, taking the plate to higher efforts. Therefore it is established:

- Maximum wheel load: Vg = 608 N vertical;
- Maximum load on the main plate: Vg = 304 N vertical.

Figure 7 shows the 3D simulation of the wheel following the Von Misses criteria, the location of the maximum and minimum stresses indicated by arrows and colors in the side legend can also be observed. The simulation it was considered, as already explained, the most critical situation.

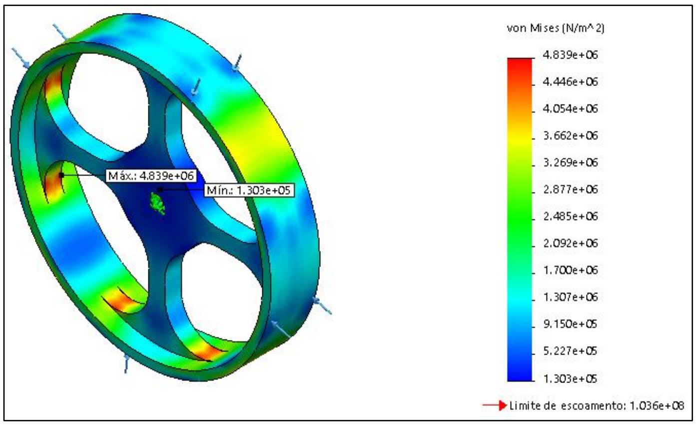

Figure 7: Result of Von Misses tension.
Source: Authors, (2021).

Table 8 summarizes the results related to wheel analysis comparing the materials used, it was possible to observe that all three situations established of material meet the analyzed criteria, thus they support the efforts and with minimum displacements. Furthermore a stress factor of 1.5 was used to compare the stresses and a, load factor of 3.8 was used to calculate the stresses, the design defined for the three materials is consistent with the real one. Therefore are within the criteria, the chosen materials one were according to lowest mass, since in the competition it is essential that the components have the least possible mass and maximum resistance, and then the wheel with PA Type 6 material was chosen to compose the redesign of landing gear conceptual.

Table 8: Result of the wheel analysis, with comparison between materials.

Material	Permissible stress (MPa)	Maximum stress (MPa)	Displacement (mm)	Deformation	Mass (kg)
PA TYPE 6	69.1	4.839	0.00583	0.000152	0.01796
Nylon 6/10	92.7	4,854	0.00184	0.000045	0.02245
Al 6061 - T6	183.3	4.841	0.00022	0.000006	0.04329

Source: Authors, (2021).

Figure 8 shows the 3D simulation of the landing gear following the von Misses criteria. The higher stresses were found on wheel supports, which have the first contact with the ground. This maximum stress value, which is 2.475 MPa, is much less than the allowable stress of 400 MPa, so there will be no concerns related to strength.

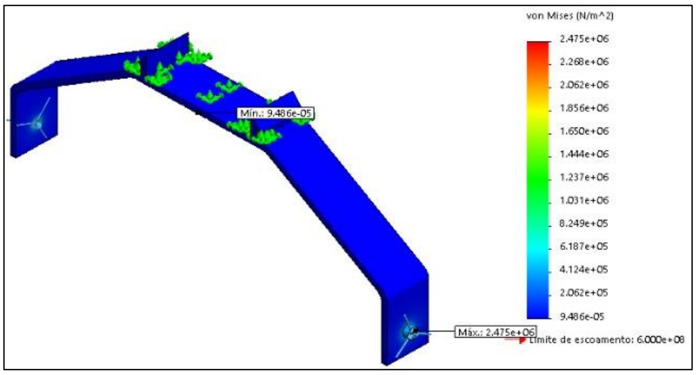

Figure 8: Result of stress analysis of the conceptual landing gear.
Source: Authors, (2021).

The latter analysis depicted in Figure 8, asses to certify that the conceptual landing gear can actually be used. Nevertheless, the most critical situation was considered, that is, with a simulation of the maximum load on the landing gear and a height above that established by Federal Aviation Administration [17], which is 230 mm, with this test being used 1000 mm.

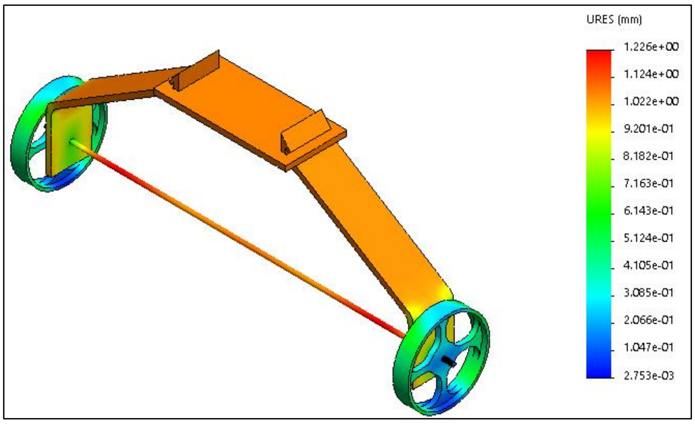

Figure 9: Result of the displacement analysis for the Drop test.
Source: Authors, (2021).

Figure 10 depicted drop test performed to a height of 1000 mm, this result report higher than the height required by the standard, for result certification.

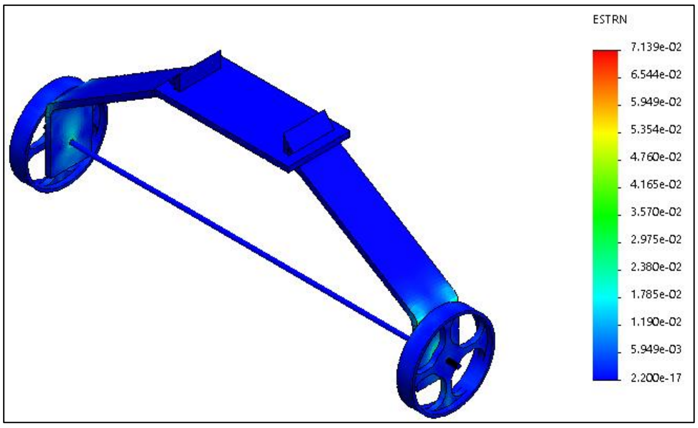

Figure 10: Result of deformation analysis in the Drop test.
Source: Authors, (2021).

After the Drop test simulation, it was observed that the results for displacement and deformation are favorable, with no major changes, enhance the integrity of the project, with this the conceptual landing gear will able to be used in the next competitions.

IV. DISCUSSION

Assembly efficiency values are of extreme importance for the validation of a good design. For the landing gear design, the results found were well below what was required for an acceptable design according to [14]. As well as the rates of feeding and adaptation, which also ran away from the satisfactory values required in [14]. These values justified the assembly difficulties encountered in the initial project of the proposed problem.

With the use of reverse engineering, to obtain data from the initial landing gear, as well as reported by [8] and with the use of CAD (computer-assisted design) technology, the new geometry was modeled, based on the principles of the Lucas method of DFMA, for modifications and improvements. Being possible to design the conceptual landing gear assertively, ensuring the visualization of the project to verify possible assembly errors, being effective in the design of the parts, bypassing the difficulties based on the principles of reverse engineering.

To confirm the project visualized with CAD technology and the principles of DFMA integration and reverse engineering, the methods of [14][2] and [5] were put back to the test. This time, with a landing gear project showing an increase in efficiency, meeting the criteria established in [14] for the Lucas method of DFMA. The feed and adaptation indexes also changed, both meeting the expected expectations of results in [14], with reductions compared to the initial landing gear.

To complement CAD technology, the use of CAE (computer aided engineering) technology integrated into the finite element method contributed to the design and analysis of the projected parts, showing all the points of concentration of stress and deformations, ensuring that the redesign has reliability in its use. Confirming that the method adopted for the structuring of the new landing gear was effective.

The methodology aligned with the integration of reverse engineering, DFMA, CAD and CAE, proved to be efficient for the redesign of new components. Getting the challenge of redesign a complete aircraft, in order to, achieve greater assembly and construction efficiency.

V. CONCLUSION

The analyzes performed with Lucas DFMA method for the landing gear were very relevant and their results were significant, presenting a gain of 42% for the functional analysis, and reductions for the feed analysis and assembly analysis, these being respectively 72% and 84%, a fact that proves that the method used was efficient for the redesign of the landing gear, ensuring greater efficiencies.

The simulations carried out help to analyze the behavior of the parts that make up the landing gear in functional situations, helping to prevent possible design failures before its construction. Through the simulations it was possible to define the PA TYPE 6 as the material to be used in the wheels, and to prove that the materials defined for the other parts supported all loads.

The Drop Test, being one of the main tests to validate the landing gear, was performed by computational method, proving that the landing gear was fit for its functionality, presenting good parameters of stress and deformation.

It is expected that with this work, new project development techniques will be used to maximize the efficiency of assembling and manufacturing new items, as well as improving existing products.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Sanches Ismael de Oliveira and Marcos Dantas dos Santos.
Methodology: Sanches Ismael de Oliveira, Marcos Dantas dos Santos and Antonio Claudio Kieling.
Investigation: Sanches Ismael de Oliveira.
Discussion of results: Sanches Ismael de Oliveira and Marcos Dantas dos Santos.
Writing – Original draft: Sanches Ismael de Oliveira.
Writing – Review and editing: Marcos Dantas dos Santos and Antonio Claudio Kieling.
Resources: Marcos Dantas dos Santos and Antonio Claudio Kieling.
Supervision: Marcos Dantas dos Santos and Antonio Claudio Kieling.
Approval of the final text: Sanches Ismael de Oliveira, Marcos Dantas dos Santos and Antonio Claudio Kieling.

VII. ACKNOWLEDGMENTS

The authors thank the Urutau aerodesign team, the Amazonas State University and FAPEAM.

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