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ANALYSIS OF THE STRUCTURAL CHARACTERISTICS OF 4- AND 5-DIGIT NACA AIRFOILS FROM A MDO PERSPECTIVE

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Abstract. The present work proposes to comparatively analyze the influence of thickness and curvature of airfoils on the structural parameters and weight of wing sections, comparing the changes on aerodynamic efficiency these changes bring to the structural efficiency of an optimal wing section of a given airfoil shape. For that, different families of 4- and 5-digit NACA airfoil are used as the basic shape for the torque box of semi-monocoque metallic wing structures; then these wing structures weights are optimized by varying the number and shape of stringers, using predetermined T, Z, J, and hat cross sections, and the thickness of each panel, bounded by the maximum buckling stresses for that geometry, using a genetic-algorithm pre-implemented within Python libraries. The stresses are taken from the bending and shear of the wing structure and are calculated using a classic analytical model, automated in Python language, for asymmetric bending and shear flow in thin reinforced closed beams based on the aerodynamic and inertial loads calculated for each airfoil using XFOIL. Although the aerodynamic efficiency is linked to the thickness and curvature of the airfoils, this analysis aims to compare the influence of the aerodynamic efficiency gain on the weight, since the change of airfoil directly influences the position of the shear center and the distribution of bending shear loads, which can lead to a neutral or even negative net gain in drag/weight ratio. First, results regarding the impact of different genetic algorithm parameters and models such as mutation, crossover, and elitism ratio over the convergence of the model are shown. Finally, an analysis of the influence of thickness and curvature of the airfoils through comparing the results for the different members of the chosen NACA families by comparing different aerodynamic metrics such as efficiency, max lift coefficient, and performance metrics to the structural efficiency metrics of the optimized structure like weight, number of stringers, maximum stresses, and overall safety margins.

Keywords: optimization, genetic algorithm, wing structures, multidisciplinary design optimization

1. INTRODUCTION

The increase in demand for the solution of more complex problems, without compromising the economic and environmental aspect, boosted the collaboration of different areas of knowledge to make the production and operation of projects that meet these demands viable. The aeronautical industry, as well as the aerospace, naval, oil and railway industries, can be framed in this context since their focus is on lightweight structures that have requirements, such as high levels of safety, efficiency, and structural redundancy (Raymer, 2006). For modern aeronautical structural design, particularly wing structures, aspects besides safety, minimum weight and guaranteed structural integrity, related to other areas of aircraft design need to be considered, such as: pre-established aerodynamic shapes, housing of different systems, proper weight distribution due to stability constraints, and economical and manufacture viability (Niu, 1988).

Structural optimization results in skins with thicknesses of the order of magnitude of millimeters, thus being subject to fatigue and structural instability phenomena not common in other engineering applications, such as: aeroelastic phenomena (divergence and flutter), local buckling in reinforcements and panels, buckling caused by semi-diagonal tensions and crippling, which are very present in the structures of the aircraft wing region (Niu, 1997).

The design of modern aircraft wings uses a semimonocoque type of structure called a torque box, which is a basic structure that supports the wing, formed by reinforced panels in the shape of the aerodynamic profile (airfoil) (Niu, 1988). The position, amount, and shape of these reinforcement beams, called stringers, are usually made using a trial-and-error approach during the earlier stages of wing structure design. This approach is usually based on past design experiences and parametric analysis to justify the choice of positioning and structural characteristics of the components, so that in a later phase, these characteristics are in fact optimized, due to the lack of quantitative knowledge of the influence of these different parameters. (Roskam, 2000). Among the main structural aspects to be considered, the following stand out: number of ribs, spars, and stringers, positioning, shape, and choice of materials for each of these components.

Structural characteristics are directly impacted by the choice of the airfoil profile, which, in most design philosophies occurs in early stages due being bounded by basic mission requirements and being input for several subsequential analysis. The curvature and thickness of the airfoil profiles, related to its aerodynamic efficiency, significantly alters the distribution of the bending and shear loads supported by the wing section, highlighting the need to comparatively analyze the benefits of choosing a profile in relation to its aerodynamic and structural aspects during the conceptual design phase of an aircraft. (Mandorin, 2021). This type of wing structural optimization analysis was performed in different contexts for projects with different approaches such as Grossman (1988), Livne (1990), Dubreuil (2020) and Vankan (2021).

MDO (Multidisciplinary design optimization) is an engineering field that studies the use of numerical optimization methodologies in systems that involve different disciplines and subsystems. The main objective of this type of analysis is to find the optimal design of a multidisciplinary system, based on the premise that this can only be obtained when all interactions between the different subsystems are considered (Martins et al., 2013). The choice of representative models of subsystems, solution strategies and coupling of different variables is called multidisciplinary design optimization architecture. From this, it is possible to estimate the computational times needed to solve each step of the problem, as well as define the objective functions, restrictions and variables of interest that will be used to solve the problem completely. Thus, the motivation for the development of a methodology that compares these aspects and studies their relationship consists in its direct application to the early stages of aircraft design, enabling the fulfillment of the project requirements as the influence of the choice of each parameter becomes clearer. Furthermore, as it is an optimization problem, it is possible to approach it in a multidisciplinary way, using computational algorithms to model and solve the problem more efficiently.

The present work aims to analyze the influence on the optimal weight of a structural section of a semimonocoque bi-spar aluminum wing, considering the variation in the number and shape of equally spaced stringers and the variation in the thickness of each panel present in the structure, on the aerodynamical efficiency in different families of airfoils NACA 4 and 5 digits. The choice of 4- and 5-digits NACA airfoils is due its simple generation of different airfoil families with increasing curvature and thicknesses, maintaining the same overall behavior. This way, correlations between the aerodynamic and structural metrics can be made as different characteristics of the airfoil profile is changed. Thus, objective of this work is to study the trade-off between aerodynamic and structural efficiency in relation to the weight of this type of wing structure, using genetic algorithms pre-implemented in libraries along with the Python programming language, exploring its various parameters such as rate of mutation, crossover, and population size, and to obtain possible conclusions about the impact of the geometric parameters of the airfoils in the wing structural design.

2. METHODOLOGY

Given the objectives of the paper, the first step of the analysis is defining a wing section and how to optimize its weight. For this study, for simplicity, given an airfoil profile, the structural wing section is separated into three areas: the upper surface, leading edge, and lower surface. Over each of these areas a random number of uniformly distributed reinforcements is considered, respectively quantified by triplet of integer numbers (m, n, o) . Given these number of reinforcements $m + n + o + 5$ panels are defined, $m + 1, n + 1, o + 1$ for each region, respectively, plus two spar webs, each with an individual float thickness. This assembly is given Figure 1. The reinforcements cross sections are variable, being able to be taken from six fixed possibilities: T, J, hat, and three Z with different heights, defined by series of integer arrays S_m, S_n and S_o , these shapes are found on Figures 2a to 2f.

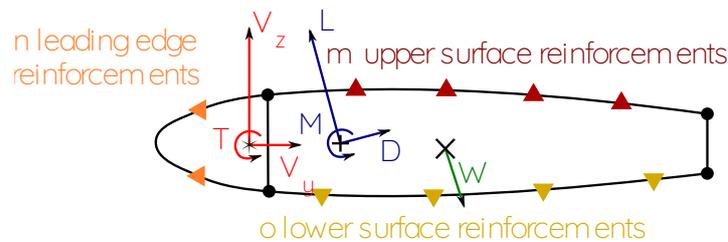
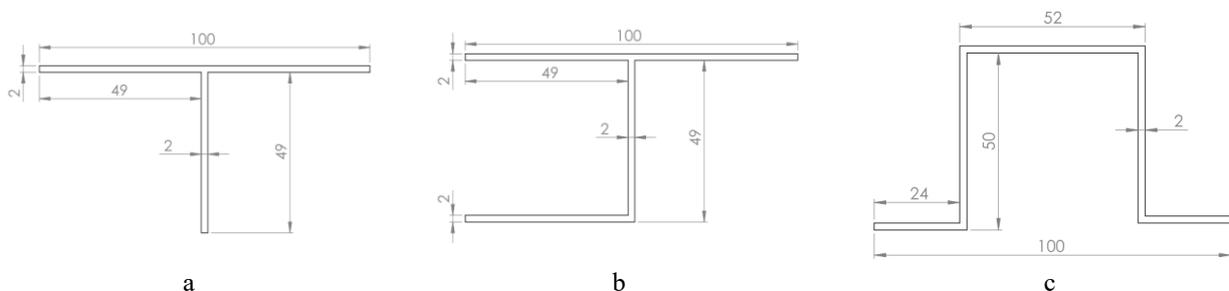


Figure 1 – Proposed wing section and loads



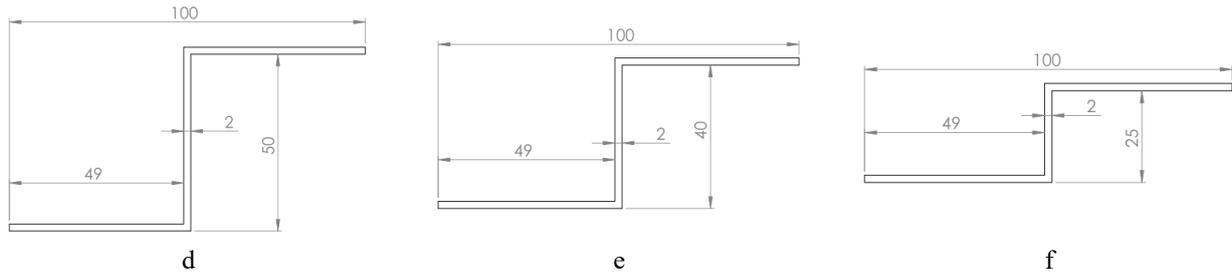


Figure 2 – Possible stringer cross sections

Given these variables and wing structure definition, the weight can be optimized through the optimization problem found in Eq. (1), bounded by the population space given by Table 1, organized in an array as per Figure 3:

$$\begin{aligned} & \text{Minimize } f(t, m, n, o, S_m, S_n, S_o) = \rho \sum_i^{m+n+o} A_i + \rho \sum_i^{m+n+o+5} t_i l_i \\ & \text{subject to } \begin{cases} \sigma_c^i \leq \frac{E\pi^2 t_i}{A_i l_i^2}, & \text{for every } i\text{th stringer} \\ \sigma_{b_{max}}^i \leq \sigma_y, & \text{for every } i\text{th stringer} \\ \sigma_{b_{min}}^i \leq K_b \frac{E\pi^2}{12(1-\nu^2)} \left(\frac{2}{b}\right)^2, & \text{for every } i\text{th stringer} \\ \sigma_{s_{max}}^i \leq K_s \frac{E\pi^2}{12(1-\nu^2)} \left(\frac{t_i}{l_i}\right)^2, & \text{for every } i\text{th skin} \end{cases} \end{aligned} \quad (1)$$

where σ_c are the compressive stresses on the stringers caused by the bending of the wing for a given load case; σ_b are the average bending stresses over the flanges of a given stringer and σ_s are the shearing stresses over the panels.

Table 1 – Population space

Parameters	Boundaries	Type of variable
Number of stringers*	$n \geq 1$	Integer
Number of skins*	$n \geq 2$	Integer
Skin thickness [mm]	$n \geq 0.8$	Float
Stringer cross section	$0 < n < 7$	Integer

* Per region

Skin thicknesses

1.23	1.51	0.97	1.14	1.28	1.15	2.51	2.50	1	3	5	5	4	5	1	2
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Cross sections of the upper surface stringers

Cross sections of the leading edge stringers

Cross sections of the lower surface stringers

Figure 3 – Representation of the population space organized as sequence of arrays

The boundaries for these are given by classic buckling theories for beams and plates (Jean-Claude, 1997). The acting stresses are calculated using classic analytical theories for thin beams for both asymmetric bending and torsion (Donaldson, 2008; Peery, 2011; Megson, 2016) as per Eq. (2) to (4):

$$\sigma_c^i = -\frac{V_y I_{yy} - V_z I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} \frac{A_i}{t_i} \bar{y}_i - \frac{V_z I_{zz} - V_y I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} \frac{A_i}{t_i} \bar{z}_i \quad (2)$$

$$\sigma_b^i = -\frac{M_z I_{yy} - M_y I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} (y - \bar{y}_i) - \frac{M_y I_{zz} - M_z I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} (z - \bar{z}_i) \quad (3)$$

$$\sigma_s^j = \max_{s \in [0, l_j]} \left\{ -\frac{V_y I_{yy} - V_z I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} \int_0^s y ds - \frac{V_z I_{zz} - V_y I_{yz}}{I_{yy} I_{zz} - I_{yz}^2} \int_0^s z ds + q_0 + q_T \right\} \quad (4)$$

where q_0 is the shear flow for closed sections caused by shear forces and q_T is the Bredt-Batho torsion shear. I_{yy} , I_{zz} , I_{yz} are the wing sections second moments of area, A_i is the area of the i -th stringer and \bar{y}_i and \bar{z}_i are the horizontal and vertical distance of the centroids of the i -th stringer to the wing section centroid, respectively. These stresses are caused by the equivalent system of the V_y , V_z and T equivalent efforts acting over the shear center, created from the aerodynamic forces of lift, drag and pitching moment L , D , and M , applied over the aerodynamic center and the section weight W applied over the mass center of the section, as seen in Figure 1. The aerodynamic efforts are calculated for each profile from the dimensionless constants and polar drag curve obtained using the XFOIL software (Drela, 2001) as per Eq. (5) and (6) (Lomax, 1996), by equating the vertical resultant in the Z direction of the lift and drag to 1.5 times 2.5 times an estimated weight for a given aircraft, following the minimum critical load for symmetrical cruise maneuvers the 14-CFR Part 25 defines on §25.303 and §25.321 to §25.351 (Federal Aviation Administration, 2020). The material properties and conditions for the aerodynamic simulations used for the calculations are found on Table 2.

Table 2 – Material properties and aerodynamic simulations conditions

Properties of the Al-7075 (Callister, 2020)					Flight condition			
E [GPa]	ν []	σ_u [MPa]	σ_y [MPa]	τ_u [MPa]	h [m]	ρ [kg/m ³]	ν [kg ² /s]	T [C]
71.0	0.330	570	502	330	1200	1.100	13.94e-6	7.470

$$\begin{cases} L = \frac{1}{2} \rho V^2 c (C_{L_0} + C_{L_\alpha} \alpha) \\ D = \frac{1}{2} \rho V^2 c (\kappa_0 + \kappa_1 (C_{L_0} + C_{L_\alpha} \alpha)^2) \\ M = \frac{1}{2} \rho V^2 c^2 C_M \end{cases} \quad (5)$$

$$\begin{cases} V_x = -L \sin \alpha + D \cos \alpha - W \sin \theta \\ V_z = +L \cos \alpha + D \sin \alpha - W \cos \theta \\ T = M - W \cos \theta (mc - sc) + (L \cos \alpha + D \sin \alpha)(ac - sc) \end{cases} \quad (6)$$

Given the stresses of the boundaries of the optimization problem σ_c , σ_b and σ_s depend not only on the section weight, but on the second moment of areas, shear center and center of mass, all of which depend on the number of stringers, choice of cross section and thicknesses of the skins, the optimization problem is clearly non-linear and NP-incomplete (Mitchel, 1998; Cormen, 2009; Du Ding-Zhu, 2011). NP problems have the characteristic of having several local minimums, add to the fact they propose an integer choice make it hard to use classical gradient based algorithms such as BFGS as it creates a mixed discrete/continuous problem; given the difficulties of solving these kinds of problems with gradient methods, initially it was proposed to use a genetic algorithm (Rao, 2019). Genetical algorithms have several advantages over classic gradient-based algorithms such as: it makes the search from a population of points instead of a single points, with some implementations having a varying size population or multiple populations; it only uses the objective function information and not its derivatives which can be hard to obtain; it supports multi-objective optimization, including calculation of Pareto fronts; it uses probabilistic transition rules, which lead to a stochastic solution; by the use of the right crossover techniques and randomness such as mutation it is robust with respect to local minima; it is easily parallelized given its multiple population. Some of its limitations are: the difficulty in obtaining the right hyperparameters for the best convergence; the difficulty in designing an objective function, the information of each individual; its implementation is more complex than classic algorithms; it is more computationally expensive and time-consuming than most gradient based algorithms.

As such, due to the difficulty of genetic algorithms dealing of a variable number of parameters per individual, which would be needed given the number of panels and cross section choices vary according to the number (m, n, o) of reinforcements, which are variables themselves a two-pronged approach is proposed, summarized on Figure 3: first, a greedy algorithm is implemented within inhouse Python 3.x scripts within the reduced population space, by setting the number of reinforcements on the upper and lower surfaces to be less than 25 and the number of reinforcements of the leading edge to be less than 10; then a genetic algorithm was implemented using pre-implemented PyPI Python 3.x to find the ideal cross section shapes, given the choices previously shown. Before further implementing the procedure studies for the computer time estimation and most fit hyperparameters were made.

For studying the different aerodynamic characteristics, the whole procedure was repeated for several 4- and 5-digit NACA airfoils, with different curvatures and increasing maximum thickness. The 4-digit families chosen with increasing curvature were 00xx, 13xx, 24xx, and 44xx and can be seen on Figure 4a to 4d; the 5-digit families chosen with increasing curvature were 230xx, 250xx, and 251xx and can be seen on Figure 4e to 4g. The thicknesses were taken to be 10%, 12%, 15% and 18%.

3. RESULTS

3.1 Genetic algorithm hyperparameters studies and time estimates

The execution time of scripts written in Python 3.x programming language were estimated to evaluate the number of parameters that make the analysis viable. The estimated computational time to obtain all the desired results depends mainly on the execution time of the objective function, which is requested whenever it is necessary to evaluate a different individual. Considering that the calculation methodology can be divided into two parts: the greedy algorithm, and the genetic algorithm, and using the Eq. (7), which list the main variables of each algorithm that were used, it is possible to estimate the computational time needed to complete the optimization and check if it is feasible. Table 3 considers the main values used and the initial estimate of computational time. The setup used for testing was a simple notebook with an Intel Core i5-6200U CPU @ 2.30GHz processor.

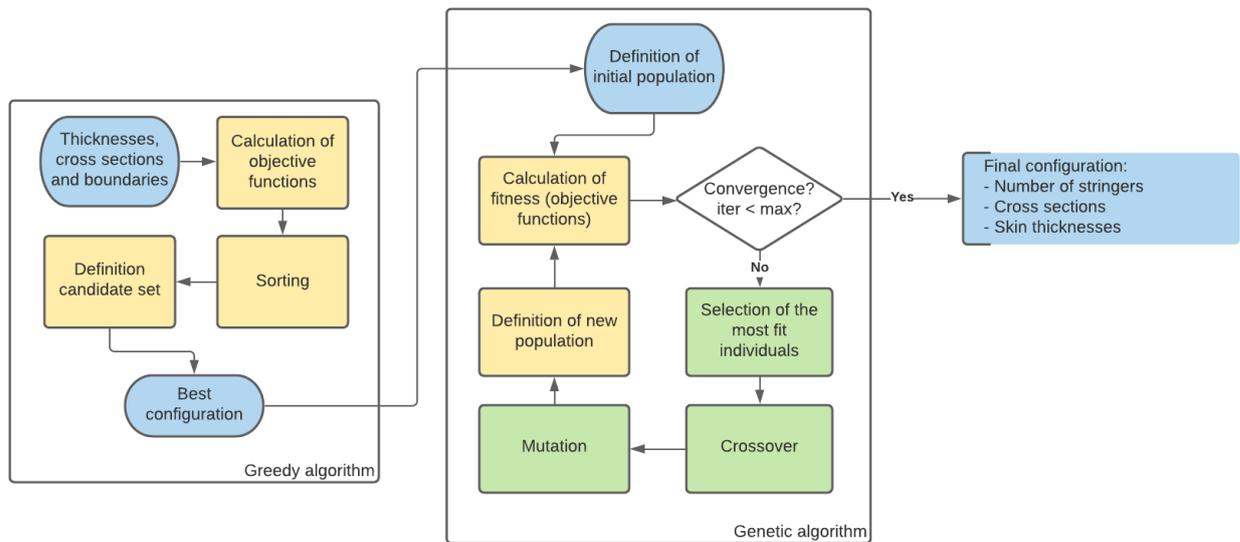


Figure 3 – Proposed methodology for wing section structure optimization

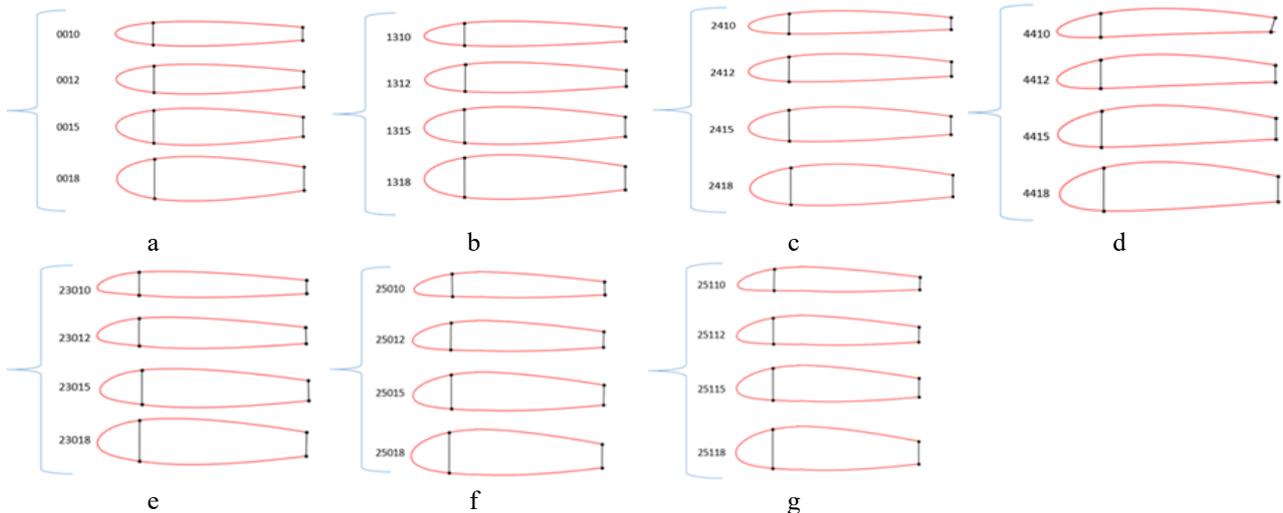


Figure 4 – Chosen airfoils for study

$$\begin{cases} t_{gen.alg.} = t_{objective\ function} * N_{individuals} * N_{generations} * N_{airfoils} \\ t_{gred.alg.} = t_{objective\ function} * \max\{m\} * \max\{n\} * \max\{o\} * N_{airfoils} \\ t_{total} = t_{gen.alg.} + t_{gred.alg.}, \end{cases} \quad (7)$$

Table 3 – Execution time estimates

Greedy algorithm		Genetic algorithm	
Objective function calculation [s]	1 - 1.5	Objective function calculation [s]	1 - 1.5
Number of stringers on the lower surface	21	Number of individuals per population	20
Number of stringers on the upper surface	21	Number of generations	500
Number of stringers on the leading edge	5	Number of airfoils	28
Number of airfoils	28	Total [h]	78 - 116
Total [h]	18 - 25		

In the steps of the methodology in which the genetic algorithm was used, it was necessary to establish a criterion for choosing the parameters inherent to the algorithm (hyperparameters) that would efficiently return the results. The hyperparameters studied in this analysis were: mutation rate, number of individuals per population, crossover rate and number of generations calculated. The mutation rate represents the probability of an individual suffering random change in one of its characteristics and the crossover rate is the probability that new individuals are generated from the recombination of characteristics from previous individuals. The number of individuals per generation and the number of generations are characteristics that directly impact the number of times the objective function will be needed; therefore, it has a great influence on the computational time of the algorithm. Together with the other parameters, the aim is to determine the best way to combine them to obtain a satisfactory result in the shortest possible time.

Following the methodology proposed in Section 2, convergence curves were generated for each of the possible combinations of hyperparameters, based on values commonly found in the literature (Deb,2012; Kramer, 2017). Table 4 shows the values used for each of these variables. Through this table a matrix of computational experiments was performed for one of the airfoils. By establishing an equal random number generation parameter in all permutations of hyperparameters by setting the generation seed of the Python libraries, it was possible to generate the convergence curves represented by Figure 5a. It is possible to observe that the parameters of 5% mutation, 50% crossover and 20 individuals per population, obtained the best result. The maximum number of generations was then tested, using the best result found in the first test, obtaining Figure 5b. The percentage difference from the double of iterations was 3.2% in the final weight result, however, the computational time was 2.3 times higher, not being convenient for the number of times the algorithm would be used in the methodology.

Table 4 – Hyperparameter test range

Number of individuals per generation	Number of generations	Mutation	Crossover
10 to 20	500 to 1000	5% to 15%	33% to 50%

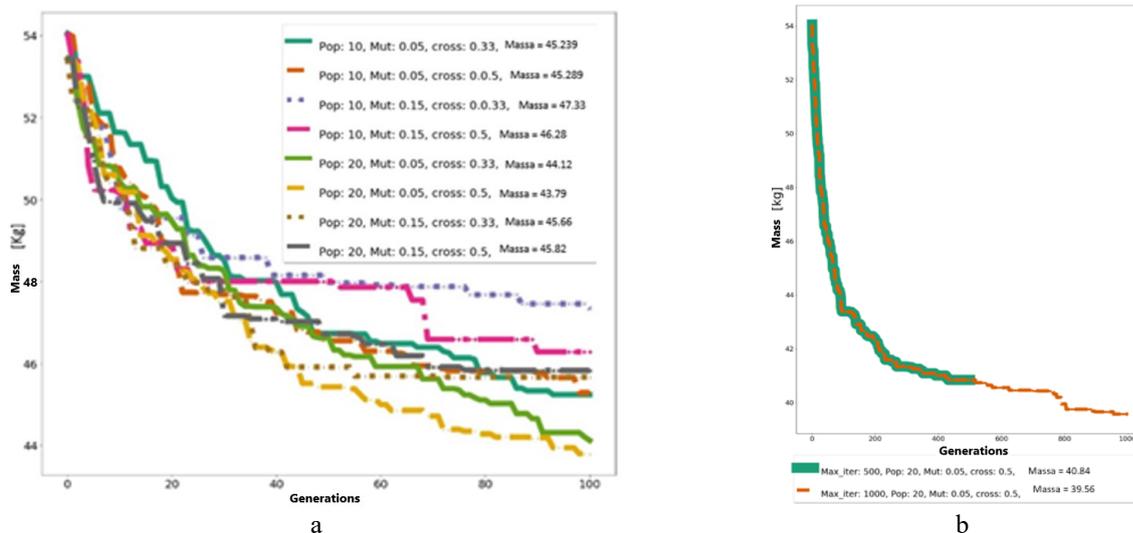


Figure 5 – Convergence and hyperparameters tests

Table 5 - Average number of stringers per airfoil family

Airfoil families	00xx	13xx	24xx	44xx	230xx	250xx	251xx
Average of number of stringers	27.75	23.75	26.50	31.25	21.50	22.00	22.50

3.2 Greedy algorithm results for number of stringers optimization

Figure 6 shows the results obtained from models with panels of fixed thickness equal to 2mm and the Z1 cross section for all reinforcements. The choice of these parameters was based on historical data normally used for this type of structure. The figure indicates the number of reinforcers by region and by aerodynamic profile, and it is possible to observe that in almost all profiles, the ideal amount found in the lower surface is slightly higher than in the upper surface, agreed with known results (Niu, 2008). The number of reinforcements in the leading-edge region remained small and constant.

Looking at Tables 5, the total amount of reinforcers for each profile within its family, it is possible to observe an increase in the number of reinforcers for most cases, except for the 13xx family which obtained a considerable decrease in the amount in relation to the 00xx family. Table 6 indicates the average amount of reinforcers by thickness and follows the same trend.

Table 6 - Average number of stringers per thicknesses sets

Thicknesses	xx10	xx12	xx15	xx18
Number of stringers	18	18	25	36

Number of Stringers per Region per NACA Foil - Thickness = 2mm

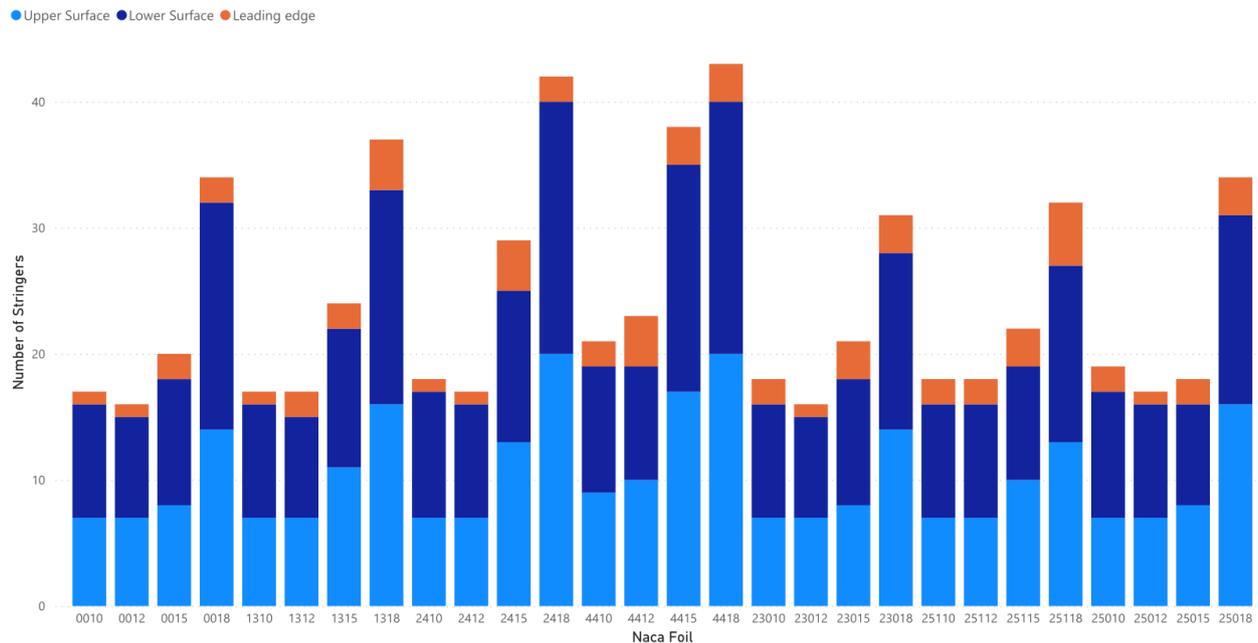


Figure 5 – Results of the greedy algorithm

3.3 Stringers cross section shape optimization

From the ideal quantities of reinforcers found in the previous analysis, the average values of the quantity of reinforcers per region were used to carry out the analysis of models with variable thickness. The amounts of stringers used in each region are found in Table 7, as well as the final average thickness value. The highest average thickness was found on upper surface region, indicating a greater demand for the panels in this region, inverting the behavior of the number of stringers, which is higher on the lower surface, showing the most restrictive boundary for the panels was shearing buckling, while for the stringers was probably the static stresses. Figures 7 and 8 presents the thickness distributions found for each profile in each region separately, while Figure 6 presents the mean thickness values of each region for each airfoil studied. It is observed that the average thickness for each profile was smaller than that used in the previous analysis, indicating the importance of optimizing this variable. Regarding the shape of the cross section of the reinforcers, Figure 6, indicates that the most suitable shape in all cases is the Z3. Regarding the analysis of the number of reinforcers, the result obtained reflects the expected, to demonstrate an increase in the number of reinforcers as the profile thickness increases in all airfoil families. Another aspect of this analysis was that the number of reinforcers per study region reflected an adequate amount for this type of wing, in addition to indicating a greater need in the soffit region, a fact also presents in observations of real projects.

Table 7 – Results for the type of stringer and thickness optimization

Average number of stringers per region		Average skin thickness per region	
Upper surface	10	Upper surface	1.05
Leading edge	2	Leading edge	1.01
Lower surface	11	Lower surface	1.07

Airfoil	0010	0012	0015	0018	1310	1312	1315	1318	2410	2412	2415	2418	4410	4412	4415	4418	23010	23012	23015	23018	25110	25112	25115	25118	25010	25012	25015	25018
T	0	0	1	2	1	0	1	0	1	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	1	1	2
J	1	0	0	1	1	3	2	0	0	0	3	2	0	0	0	5	0	1	2	2	0	0	0	1	2	4	1	
Hat	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Z1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Z2	2	7	7	4	3	5	3	4	6	2	6	2	5	5	5	4	5	4	4	5	2	7	5	3	3	5	5	1
Z3	24	20	19	20	22	19	21	23	20	25	18	23	22	22	22	21	17	23	22	20	23	19	22	24	23	19	17	23

Figure 6 – Results of the genetic algorithm for stringer shape

Perfil	Upper surface										Leading edge			Lower surface														
	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27
0010	1.37	1.05	1.05	0.85	1.44	0.82	1.20	1.05	1.23	1.22	0.94	1.01	0.91	1.14	0.90	1.50	0.82	0.81	0.87	1.21	0.83	0.87	1.52	1.12	0.83	1.40	1.03	1.57
0012	0.87	0.99	0.95	1.42	1.49	0.99	0.81	0.81	1.08	0.84	0.97	0.89	1.09	0.81	0.95	1.15	0.91	0.85	1.12	0.99	1.19	0.84	0.96	1.43	1.07	1.62	1.25	1.70
0015	1.01	1.01	0.83	0.80	1.28	0.84	0.91	1.07	1.38	1.01	0.84	1.13	1.29	1.24	0.90	0.80	1.06	1.23	1.89	0.83	0.91	0.92	0.92	1.28	0.85	1.27	0.88	1.59
0018	0.83	1.24	0.81	0.90	1.15	1.14	0.96	0.95	0.96	0.81	1.38	0.87	0.91	1.08	0.97	0.99	0.97	0.86	0.80	0.81	0.93	0.80	0.87	1.28	0.92	1.10	1.08	1.83
1310	0.94	0.88	0.98	1.15	0.87	1.44	1.24	0.93	1.20	0.96	0.95	1.02	1.18	1.04	0.82	0.90	0.91	1.31	1.44	0.90	1.19	0.95	0.98	0.83	1.03	1.43	1.18	1.70
1312	1.19	0.99	0.81	0.94	1.06	0.81	1.13	0.97	1.21	1.01	0.96	1.02	0.97	1.17	0.82	1.02	0.81	1.21	0.80	0.83	0.99	0.95	1.05	1.30	0.94	1.41	1.11	1.58
1315	1.00	0.93	0.85	0.80	1.58	0.84	0.99	0.95	0.89	1.01	1.04	0.84	0.99	0.93	0.81	0.92	0.94	0.86	1.16	1.18	1.00	0.83	0.92	1.20	0.81	1.35	0.90	1.65
1318	1.00	0.83	1.29	1.11	0.89	0.89	1.08	0.93	0.92	0.97	0.83	1.38	0.91	0.82	0.96	1.11	1.95	0.81	0.85	0.85	1.02	1.84	0.88	1.42	0.88	2.52	0.99	1.69
2410	0.98	1.67	1.06	1.13	0.95	1.27	0.87	1.06	0.91	0.85	1.09	0.94	1.16	0.94	1.58	0.85	1.08	1.33	1.44	0.93	0.84	0.95	0.88	1.46	1.04	1.78	1.05	1.78
2412	1.03	0.84	1.01	1.31	0.94	0.93	1.26	1.01	1.20	1.09	1.17	1.08	0.95	0.84	1.11	1.11	1.34	0.85	1.30	0.82	0.87	0.84	0.94	0.92	0.84	1.34	0.97	1.65
2415	1.16	0.89	0.96	0.80	1.39	0.87	1.01	0.91	0.85	0.82	0.85	1.15	1.09	0.86	0.91	0.88	0.90	0.87	0.87	1.24	1.00	0.84	0.92	1.16	0.98	1.39	0.91	1.78
2418	1.05	1.42	0.95	0.97	0.82	1.18	0.88	0.95	1.31	0.81	1.03	0.91	0.95	0.86	1.36	1.02	1.09	0.86	1.17	1.17	0.93	1.45	0.92	1.35	1.22	1.04	0.89	1.62
4410	1.29	1.27	0.98	0.93	1.28	0.83	1.01	0.95	1.06	1.07	0.86	1.21	0.97	0.97	0.81	0.85	0.87	0.89	1.09	0.97	0.87	0.96	0.92	1.04	0.88	1.46	0.89	1.53
4412	1.09	0.89	0.81	1.07	0.89	0.84	1.07	0.89	0.85	1.01	1.09	0.91	0.89	0.83	0.85	0.90	0.82	1.08	1.15	0.89	0.95	1.23	1.18	0.90	0.97	1.42	1.08	1.67
4415	1.27	1.24	0.87	0.82	0.89	0.87	0.86	0.81	1.15	0.83	0.92	1.11	0.93	0.86	1.00	1.22	1.06	0.93	1.05	1.39	1.06	0.84	1.05	1.04	0.92	1.31	1.01	2.14
4418	0.81	0.84	0.97	0.82	0.94	0.87	1.04	0.98	1.35	1.12	1.25	0.81	1.14	0.86	0.88	1.15	0.88	1.00	1.34	0.82	0.90	0.84	1.08	1.28	0.91	1.55	0.85	2.17
23010	0.85	0.96	1.25	0.93	0.83	0.98	0.86	0.95	2.73	1.07	0.94	1.24	0.89	0.90	1.36	1.64	1.37	0.86	1.96	1.41	1.10	0.83	0.86	0.91	0.88	1.71	1.13	1.44
23012	1.49	1.06	0.83	1.30	0.97	1.29	1.01	1.05	1.50	1.03	1.21	0.89	0.83	1.02	1.14	1.32	1.37	0.88	1.00	0.94	1.17	0.83	0.95	1.51	0.84	1.55	0.88	1.39
23015	0.88	1.34	1.32	1.12	1.14	0.84	1.16	0.91	0.95	0.91	0.81	1.01	1.07	1.31	1.13	0.85	1.06	1.47	0.80	0.83	0.97	0.98	0.92	0.96	0.84	1.56	1.13	1.64
23018	1.00	0.81	0.82	1.39	1.18	0.87	0.81	0.93	1.15	0.97	1.22	0.89	0.92	0.86	0.87	1.12	1.28	1.07	0.83	0.92	0.89	0.89	0.96	1.17	1.08	0.98	0.81	1.78
25110	0.96	1.01	0.83	0.83	1.04	0.89	1.23	1.37	2.51	1.07	1.60	0.81	0.93	1.26	1.82	1.15	1.04	1.08	1.49	0.89	1.03	0.83	1.00	1.41	1.12	1.44	0.95	1.40
25112	1.20	0.99	0.88	0.83	1.21	0.83	1.20	0.87	1.19	0.93	0.81	1.17	0.85	0.94	1.37	0.96	0.88	1.12	1.80	0.87	1.20	0.83	0.97	0.99	0.85	1.69	1.13	1.70
25115	1.15	0.83	1.29	1.39	1.39	0.84	1.07	0.91	0.99	0.92	1.06	1.08	1.12	0.83	0.82	0.85	0.87	1.50	0.99	0.82	0.97	0.83	0.92	1.39	0.84	1.29	1.10	2.01
25118	0.96	1.27	0.81	1.17	0.94	1.12	1.10	1.77	1.12	0.97	0.81	0.89	1.10	0.93	0.88	1.12	1.50	1.00	1.41	0.83	0.97	0.84	0.84	0.91	1.44	1.14	0.91	1.71
25010	1.16	0.95	1.03	0.83	0.89	1.38	1.53	1.20	1.30	0.84	0.84	1.59	1.65	0.82	1.11	0.82	1.31	1.67	0.98	0.89	0.92	1.03	0.96	0.96	1.05	1.52	1.13	1.99
25012	1.16	0.89	0.89	1.02	1.24	0.83	0.85	1.30	1.08	1.27	0.97	1.28	0.85	0.94	1.09	0.91	1.13	0.92	1.35	0.90	0.80	0.83	0.97	1.24	0.84	1.34	1.13	1.70
25015	0.98	1.23	1.06	0.86	1.04	1.74	1.26	1.14	1.17	0.91	1.07	1.59	0.99	1.10	0.86	1.02	1.39	0.97	0.88	1.31	1.36	0.92	0.98	0.94	1.35	1.01	0.81	1.38
25018	0.88	0.90	1.06	0.86	0.84	1.03	0.86	1.25	0.86	1.34	1.76	0.93	0.93	0.96	0.82	0.86	0.92	1.27	0.94	1.16	0.91	0.83	1.05	0.84	1.13	1.71	0.91	1.68

Figure 7 – Results of the genetic algorithm for panel thicknesses

3.4 Aerodynamics and structural efficiency comparison

The study as a function of families was carried out to establish a relationship between the final weight of the airfoil and the drag produced by it. Figure 9 presents the results found for this type of analysis, indicating the weight x drag value per profile studied.

Analyzing the airfoil families separately, it is observed that for the symmetrical profiles (00xx family), the increase in the profile thickness resulted in a significant increase in the weight/drag value only for the largest thickness value studied. In non-symmetrical 4-digit families, with lower curvatures (13xx and 24xx families) and 5-digit families, the behavior of the study variable decreased with increasing thickness, while the 44xx family presented a more similar behavior to the profiles symmetrical.

Analyzing the study variable as a function of the thickness of the profiles, this same downward trend is observed with the increase in thickness for the isolated analysis of the 4- and 5-digit families and for the total average of the study, as indicated in Table 8.

Therefore, regarding the use of the genetic algorithm, it was necessary to study the different hyperparameters of the algorithm to find better results more efficiently. However, the consideration of a greater number of test variables for this type of analysis, as well as the repeated execution of the algorithm more times with the same set of hyperparameters, can help to ensure the convergence of the results obtained. In this work, we considered a set of hyperparameters large enough to represent the influence of the analysis of this characteristic, while allowing a viable computational execution time for the type of analysis performed. The analysis focusing on the drag/weight ratio and drag x weight metric as a function of each airfoil demonstrated the main aspects of considering the subsystems that make up the design of a wing from the result that the choice of the aerodynamic profile directly impacted the structural variables. In general, from the perspective of aircraft design, it was possible to conclude that for the chosen metric, the increase in the thickness of the profiles leads to a tendency to decrease the drag/weight value for non-symmetrical airfoils, justifying the analysis made to quantify this difference and consider it with other aspects of aeronautical design.

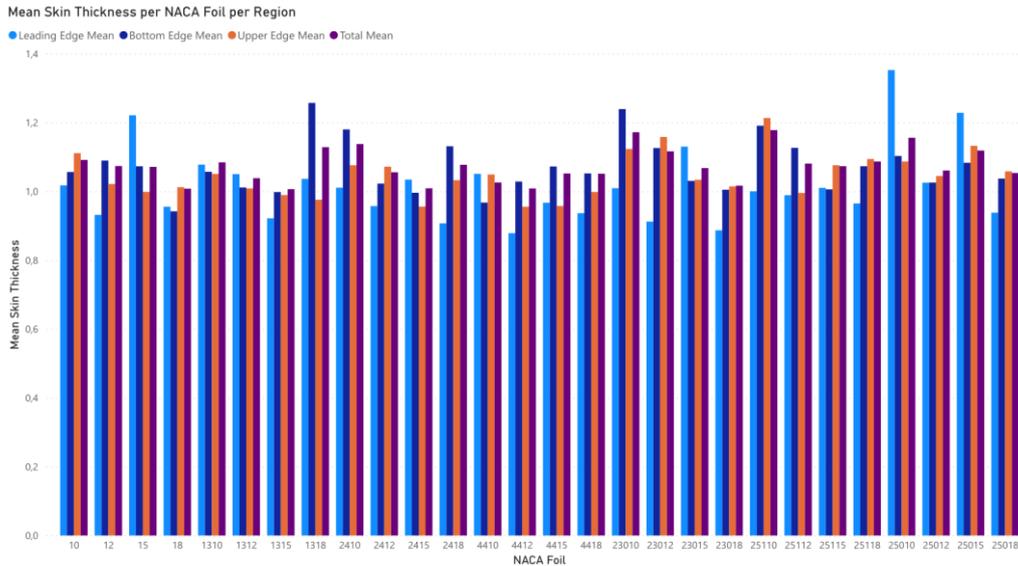


Figure 8 – Results of the genetic algorithm for stringer shape

Drag/Weight - Foil - NACA Group

NACA Group ● 00 ● 13 ● 230 ● 24 ● 250 ● 251 ● 44

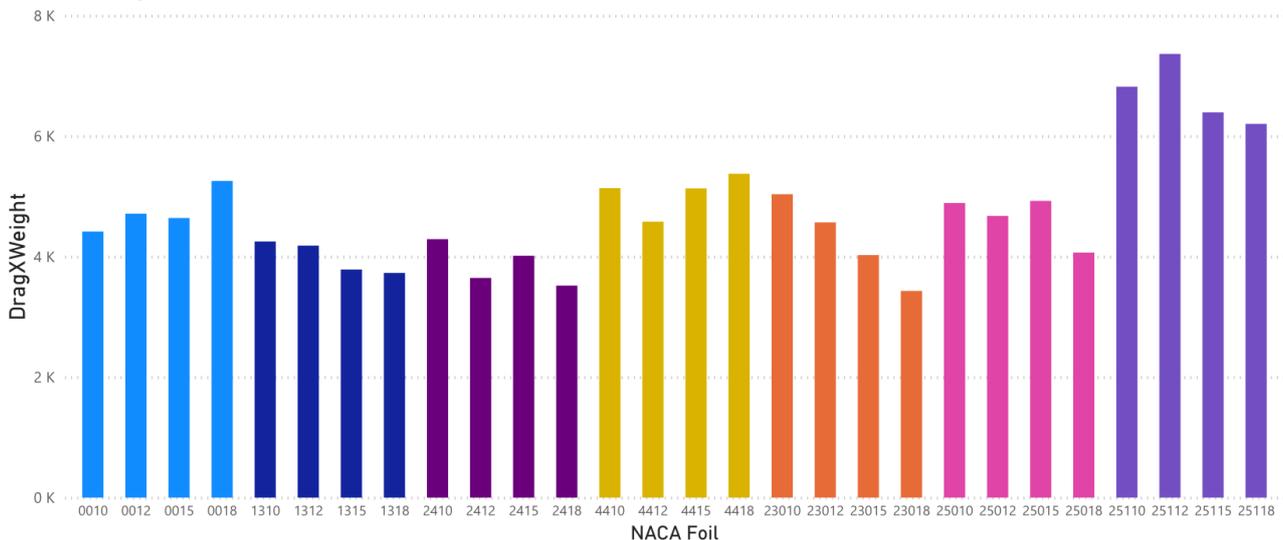


Figure 9 – Drag x weight per optimal wing structure for the studied airfoils

Table 8 – Average Drag/Weight for different thicknesses families

Thickness	xx10	xx12	xx15	xx18
4-digit NACA airfoils	7.3	6.9	6.9	6.8
5-digit NACA airfoils	8.5	8.6	7.7	7.1
Average	7.8	7.6	7.2	6.9

4. CONCLUSIONS

The main objective of the present work was to analyze the influence of structural and aerodynamic parameters of wing design from the point of view of MDO, specifically aerodynamic, weight and structural characteristics, to concomitantly consider the variables that define these areas of study in a single analysis. Specifically, this work proposed to study the trade-off between aerodynamic and structural efficiency in relation to the weight of this type of structure, using computational programming tools and analytical formulations that model the physics of the problem. Thus, according to the results presented, it was possible to conclude that the developed methodology fulfilled these proposed objectives, since it determined steps that allowed the analysis of numerous wing models and the choice of the most optimized characteristics within the sampling space of variables, considering a satisfactory computational time and the restrictions arising from both areas of study.

It is important to emphasize that the methodology used can include more aerodynamic profiles and different structural aspects of the wing design, in addition to the analysis of other relevant metrics of aeronautical design. Therefore, it would be necessary to adapt the analytical equation that dictates the structural and aerodynamic behavior of the model. Among the possible changes beyond the modeling steps, there is the possibility of using other optimization methods, such as machine learning and other heuristic algorithms and the use of restriction conditions that reflect the flight behavior of aircraft with another type missions, such as commercial and military aviation.

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6. RESPONSIBILITY NOTICE

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