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PARAMETRIC CONCEPTUAL DESIGN OF A UAV FOR SUPERFICIAL VOLCANO MONITORING.

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Abstract. *The unmanned aerial vehicles UAV have a Wide variety of applications, such as monitoring of wildfires, energy lines, human agglomerations, as well as to be used in military operations. Gas emission and geographical deformations in volcanoes are warnings of possible eruption; responsible entities in monitoring volcanoes have different methods to make accurate monitoring inside and outside the craters. One of these is done by continuous flights over the craters, making real-time videos to watch geomorphological changes; this is made with the help of manned aircraft, risking the live of pilots and technical specialists in volcanoes. The aim of this work is the parametric conceptual design of an UAV for superficial volcano monitoring. Parametric study is done using statistical entropy. Seeking for the geometrical, inertial, aerodynamics and performance characteristics which allow the UAV accomplish the project requirements, applying constraint analysis, together with fuzzy algebra.*

Keywords: *Conceptual Design, UAV, Volcano Monitoring, Statistical entropy, Constraint analysis, fuzzy algebra.*

1. INTRODUCTION.

In the last years unmanned aerial vehicles (UAVs) technology has improved. Enabling military organizations to be successful in the world. On the other hand, civil and commercial sector are in the early stages. Identifying a range of potential applications, the available technology offers the opportunity to replace existing solutions FAS (2007).

Unmanned systems have ideal characteristics to recognize areas of difficult access, performing missions that could not be made with traditional aircraft.

As research proposal, it was thought in the design of low-cost UAV, for constant monitoring over volcanoes, avoiding damage in aircraft manned components and in case of an eruption to prevent the people most at risk near volcanoes.

The mission of the UAV is collect data, from geographical territory, low speeds are required in order to allow taking pictures and videos at real time over volcanoes.

Under these conditions, was designed a conceptual prototype of UAV. The parametric study was made to set some parameters, involving analysis and evaluation of aircraft design characteristics.

The aircraft conceptual design is a complex process and the most important design stages Kovacs (1986), due it implies the solution of many equations assessing multiple disciplines, such as power plant system, aerodynamics, stability and control and so on. As a result, the aircraft conceptual design takes a long time.

The aircraft conceptual design develops parameters that are used to determine the final project, these parameters are studied, compared and evaluated by the designer until the final concept is defined and studied in detail. The design details are presented in simplified forms, such as configuration, weights, motorization, and the main dimensions of the aircraft under consideration. The purpose of the conceptual phase is select a functional concept and optimize it as much as possible.

To establish the UAV conceptual design, this paper presents two techniques for parameters study:

1. Statistical Entropy: Is based on the probability allocation and produces acceptable results in studies of evolutionary phenomena at the level of any population of heterogeneous entities, Saviotti (1988). The methodology used for statistical entropy is described by Frenken and Leydesdorff (2000) in this stage the designer must gather problem data, helping to establish, which values should have the merit of measure and what constraints the problem can create. The UAVs characteristics are organized by the first operational flight, as reference date. The essential characteristics of the UAVs are file into a database.

2. Fuzzy Algebra: To select parameters to be optimized in the project using constraint analysis.

This paper explain the development of a multidisciplinary optimization methodology of aircraft conceptual design. The concept of optimized aircraft is based on the study of evolutionary characteristics of the immediate categories of UAVs, in this case, UAVs that accomplish military and civilian missions and eventually cover discontinuities between phases of mission, this in order to seek dimensions, wing loading, power loading, thrust-to-weight ratio, total weight, global configuration and lift coefficient to proceed to the development of a new aircraft with characteristics of existing conceptions. The aim of the proposed UAV is to have the initial parameters of size, weight and performance to execute the specified mission.

2. OBJECTIVE.

The conceptual design of an aircraft is carried out by the needs and opportunities of the future market. The definition of new product begins after market analysis indicating which are the opportunities for the new aircraft. From there will be specified the technical requirements of the aircraft, to begin the search of technology that best meet the flight conditions imposed. Finally the technology that accomplishes the purpose is selected for use in the aircraft, thus the project can be implement in several "loops" of project, reaching solution of the selected parameters.

3. METHODOLOGY.

3.1 Statistical Entropy - Application.

The methodology for this work stage is supported by (Frenken and Leydesdorff, 2000). The UAV interest characteristics are selected, it is evaluated a relationship between them and with characteristics of other UAVs, if there is no evident variation in relationships, the UAV is not innovative. The analysis is based on a chronologically ordered series of 20 UAVs features, the period chosen for analysis are 10 years.

The design variables selected for analysis are:

- Technical features variable: Can be directly controlled by the designer. For example, the length of the fuselage.
- Service feature variable: Directly influenced in making the aircraft purchase decision. For example, endurance and range.
- Technical parameters and service characteristics: Involve technical and service variables. For example, wing loading, where weight is a service variable and wing area is a technical variable.

The analysis and comparison of results was done for each UAV and the set of UAVs, using statistical entropy. The methodology used is supported by the computational tool done by Abdalla (2014).

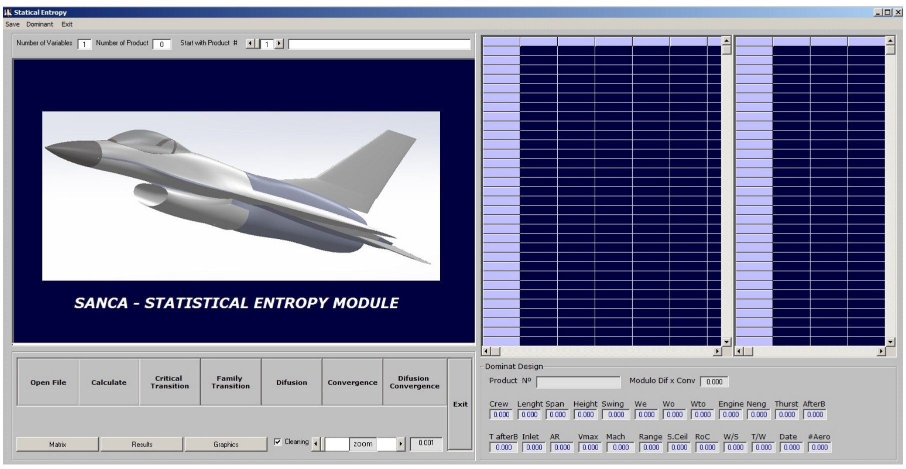

Figure 1. SANCA Statistical Entropy Module, A M Abdalla (2014)

This tool allows to know the changes between subsequent UAV designs, with the introduction of a new design in the market, classifying each UAV in four types of designs, in terms of their characteristics: Dominant designs, innovative designs, failed designs and monopolized designs, in order to select the dominant design that will be optimized to carry out volcanic monitoring.

3.2 The Database.

An extensive research in photographic UAVs was carried out. A database was done with 20 UAVs operating in the world, these were organized by the firts operational flight from $U1(UAV\#1)$ to $U20(UAV\#20)$. Table 1 present the technical specifications of UAVs whose characteristics became dominant at the industry level.

Table 1. UAVs Technical Specifications

UAVs	**U1**	**U2**	**U15**	**U19**
Year	2001	2002	2009	2012
Wo $[N]$	150,35	245,25	274,68	215,82
Bw $[m]$	2,6	2,9	2,6	3,3
Sw $[m^2]$	0,75	0,57	0,72	0,79
AR	12	14	9	13
HP	2,5	1,7	1,7	2,5
Vmax $[m/s]$	38,8	38,5	38,6	36
W/S $[N/m^2]$	200,46	430,26	382,85	273,19
Lmax $[m]$	1,6	1,7	1,9	2,2
$\mathbf{CL}_{Vmax}$	0,22	0,46	0,41	0,34
Ceiling $[m]$	4572	4500	4870	5000

Where:

- Wo: Total Weight.
- Bw: Span Wing.
- Sw: Wing Area.
- AR: Aspect Ratio.
- W/S: Wing Load.
- Lmax: Maximum Length

3.3 Deployment of Quality Function and Fuzzy Theory.

Deployment of quality function is a method to deploy the customer voice characteristics (quality, functional, cost and reliability) of product or service. By definition is a quality management system that seeks to achieve high customer satisfaction. A typical deployment of quality function system consist of 4 phases, Sullivan (1986).

Phase 1: Translates customer needs into technical measures, taking the customer requirements and transforming them into product specifications, this phase is also known as House of Quality. Phase 2: Translates important technical measures in parts of characteristics, product requirements are unfold in product components requirements. Phase 3: Translates the important parts characteristics in manufacturing process characteristics, the requirements generated in the previous step and the component requirements are transformed into parameters of process requirements. Phase 4: Translates basic manufacturing process characteristics in updated manufacturing requirements. With this approach, it ensures that every product specification, components, processes and operating standards are oriented to the customer's needs.

According to Chan (1999), the process of evaluate the customer opinion consists of 4 steps briefly described below.

- **Step 1**: Customer Needs: Determine which are the real customer requirements for the product in question. Customer needs can be express individually or in a group interview, sufficient to provide between 90 and 95% of the real customer needs.
- **Step 2**: Relative Importance Evaluation: Here the customer opinion assesses the degree of importance of customer needs. The customers are offered to give importance to every need, through review notes that can vary from 1 to 10 or other type of scale.
- **Step 3**: Competitive Analysis: The customer evaluates the companies performance and its main competitors. The knowledge of the strengths and weaknesses of competing products on the fundamental aspects, is paramount to achieve advantages.

- **Step 4**: Final Evaluation: Blending the relative importance perceived by customers in Step 2 and the priority of the company in 3rd Step, the final assessment can be made by classifying the items with higher scores indicating a high potential for business and greatest benefit for the company.

For practical implementation, the above steps can be represented according with:

$$\begin{bmatrix} \textbf{Step 1} \\ \textbf{Customer Needs} \\ W1 \\ W2 \\ \cdots \\ Wm \end{bmatrix} \rightarrow \begin{bmatrix} \textbf{Step 2} \\ \textbf{Relative Importance} \\ g1 \\ g2 \\ \cdots \\ gm \end{bmatrix} \rightarrow$$

$$\rightarrow \begin{bmatrix} \multicolumn{7}{c}{\textbf{Step 3}} \\ \multicolumn{3}{c}{\textbf{Performance Evaluation } (\boldsymbol{x})} & \multicolumn{4}{c}{\textbf{Evaluation of Properties } (\boldsymbol{e})} \\ \cdots & C1 & C2 & \cdots & Ck & \cdots & e1 \\ W1 & x11 & x12 & \cdots & x1k & \cdots & e2 \\ W2 & x21 & x22 & \cdots & x2k & \cdots & e3 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ Wm & xm1 & xm2 & xm3 & xmk & \cdots & em \end{bmatrix} \rightarrow$$

$$\rightarrow \begin{bmatrix} \textbf{Step 4} \\ \textbf{Final Evaluation} - \textbf{Importance } (\boldsymbol{f}) \\ f1 = g1\,x\,e1 \\ f2 = g1\,x\,e2 \\ \cdots \\ fm = gm\,x\,em \end{bmatrix}$$

Figure 2. Customer Opinion: Quantitative representation

Where:

- $W1...Wm$: Customer Needs.
- $g1...gm$: Relative importance of consumer needs.
- $C1...Cm$: Competitors that manufacture the same product. The company is identified as C1.
- $X11...Xm1$: Average values of corporate performance.
- $e1...em$: Assessment of priority needs of the customer are obtained based on X information According to:

$$X = \begin{matrix} W1 \\ W2 \\ \cdots \\ Wm \end{matrix} \begin{bmatrix} C1 & C2 & \cdots & Ck \\ x11 & x12 & \cdots & xk \\ \cdots & \cdots & \cdots & \cdots \\ xm1 & xm2 & \cdots & xmk \end{bmatrix}$$

Figure 3. Final evaluation of Customer Need Importance

Combining g in Step 2 and e in Step 3 the final evaluation of importance customer needs, $f = (f1, ..., fn)$ can be obtained for each $j = 1, ..., m$ by multiplying $fj = gj \times ej$ Paul and Ching-Lai (1995) or through average weight $f_j = w_g g_j + w_e e_j$ where $w_g \geq 0$ and $w_e \geq 0$, satisfying $w_g + w_e = 1$.

3.4 Fuzzy Theory.

Fuzzy theory was first introduced by Zadeh (1965), it was developed to solve problems where the description of the activities, observations and judgements are subjective and inaccurate. The "fuzzy" term is generally used to refer the situation where the boundary between action and trial is undefined.

Triangular Fuzzy Number.

A fuzzy number is a fuzzy set $\phi = \{(x, \mu_\phi(x)), x \in R^1\}$ where x receives the real value in a row $R^1 : -\infty < x < +\infty$ and $\mu_\phi(x)$ is continuous line of R^1 for closed interval $[0, 1]$, Dubois and Prade (1980). The fuzzy numbers are used to handle inaccurate numerical concepts. A triangular fuzzy number, denoted by $M = (a, b, c)$, where $a \leq b \leq c$, is a special fuzzy number represented in fuzzy form $M \approx b$, Kaufmann and Gupta (1985) has triangular shaped function according to:

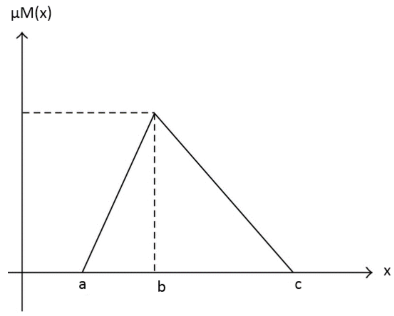

Figure 4. Triangular fuzzy number $M = (a, b, c)$

$$\mu_M(x) = \{0...............x \leq a...or...x \geq c\} \tag{1}$$

$$\mu_M(x) = \{(x-a)/(b-a)........a \leq x \leq b\} \tag{2}$$

$$\mu_M(x) = \{(c-x)/(c-b)........b \leq x \leq c\} \tag{3}$$

Representation Fuzzy Evaluation.

The evaluation of customer needs in accordance with the fuzzy model for a 9-point scale can be represented with the associated function $M1 \approx 1$ to $M9 \approx 9$ according to:

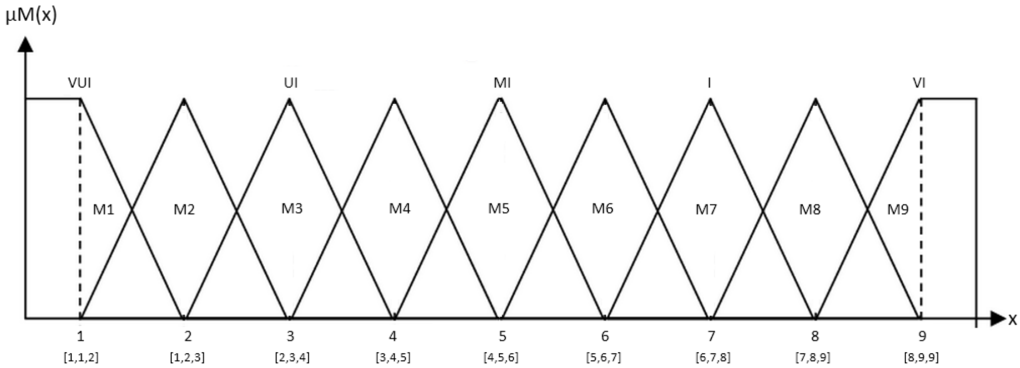

Figure 5. Fuzzy Function

Where:

- VUI: Very Unimportant.
- UI: Unimportant.
- MI: Medium Important.
- I: Important.
- VI: Very Important.

3.5 Fuzzy - Application.

According to (Chan, 1999), quality function has own methodology. The important classification of the requirements are obtained by triangular fuzzy numbers application.

A Fuzzy module program was developed for applying the methodology set. It makes up the deployment of customer requirements for the desired configuration and transforms these requirements into product specifications. These specifications are the variables for optimization.

The first condition to use the fuzzy module program is meet the customer needs in relation to the UAV design. The customer needs are transformed in technical measures and are classified in order of priority, to achieve the requirements that must be optimized for the UAV design. The needs may contain objective, subjective, technical or operational informations and are proposed by potential customers. The evaluation and classification of customer needs are made by the fuzzy module program using triangular fuzzy numbers. The selected design parameters for case study are: Wing Load, Thrust to weight ratio, Rate of climb and Take-off distance (Caltabiano *et al.*, 2005) in order to optimize the conceptual design phase of a UAV for superficial volcano monitoring using Constraint analysis.

3.6 Constraint Analysis.

Constraint Analysis is function of many aircraft operations, like take-off with a specific distance, flight with altitude and speed determined, turn with defined parameters and landing with airstrip specified, however it is important to note that this analysis provides a space for solutions and not just a well-defined solution.

The Constraint analysis allow to determine the minimum value of wing area and thrust required for the aircraft conceptual design.

Performance requirements imply a functional relationship between Thrust to Weight ratio T/W and Wing Loading W/S for each phase of flight.

The variables used to plot the constraint diagram were taken of the dominant UAV characteristics, into the statistical entropy analysis, with the aim of optimize the design parameters described in the fuzzy application.

The master equation (Mattingly, 2002) used to plot the constraint diagram for each phase of flight is:

$$\left(\frac{T}{W_{TO}}\right) = \frac{\beta}{\alpha}\left[\frac{qS}{\beta W_{TO}}\left[k_1\left(\frac{n\beta W_{TO}}{qS}\right)^2 + k_2\left(\frac{n\beta W_{TO}}{qS}\right) + C_{DO} + C_{DR}\right] + \frac{P_S}{V}\right] \tag{4}$$

Where:

- T: Thrust.
- W_{TO}: Take-off weight.
- α: Failure of installed thrust.
- β: Instant weight fraction.
- S: Wing area.
- C_{DO}: Drag Coefficient with zero lift.
- C_{DR}: Additional Drag Coefficient.
- $k_{1,2}$: Coefficient of lift-drag polar.
- q: Dynamic Pressure.
- n: Load Factor.
- P_S: Specific Power.
- V: Speed.

The master equation is simplified for each flight stage:

Take-off.

Adapting the master equation:

$$\left(\frac{T}{W_{TO}}\right) = \left[\frac{\beta^2 k_{TO}^2 \frac{W_{TO}}{S}}{\alpha S_G g \rho C_{Lmax}}\right] \tag{5}$$

where:

- ρ: Density.
- S_G: Runway length.
- C_{Lmax}: Lift coefficient.

For this case, it is considered that the thrust is greater than the drag force, there is no change in altitude and the values for density, maximum lift coefficient, runway length and take-off speed are known.

The speed is expressed in terms of the position derivative, to integrate the master equation and get the equation that relates thrust loading with wing loading and also the runway length.

Climb.

Adapting the master equation:

$$\left(\frac{T}{W_{TO}}\right) = \frac{\beta}{\alpha}\left[\frac{C_{DO}}{\frac{\beta}{q}\frac{W_{TO}}{S}} + k_1\frac{\beta}{q}\left(\frac{W_{TO}}{S}\right) + \frac{dh}{Vdt}\right] \tag{6}$$

Considering a rate of climb from 0 to 1000 meters and vertical speed of 4 m/s. In this stage the lift and thrust must overcome the aircraft weight.

Cruise.

Adapting the master equation:

$$\left(\frac{T}{W_{TO}}\right) = \frac{\beta}{\alpha}\left[\frac{C_{DO}}{\frac{\beta}{q}\frac{W_{TO}}{S}} + k_1\frac{\beta}{q}\left(\frac{W_{TO}}{S}\right)\right] \tag{7}$$

Considering the ceiling and cruise speed of the dominant UAV.

Turning.

Adapting the master equation:

$$\left(\frac{T}{W_{TO}}\right) = \frac{\beta}{\alpha}\left[k_1 n^2\frac{\beta}{q}\left(\frac{W_{TO}}{S}\right) + \frac{C_{DO}}{\frac{\beta}{q}\frac{W_{TO}}{S}}\right] \tag{8}$$

Landing.

Adapting the master equation:

$$S_L = \left[\frac{\beta k_{TO}^2\frac{W_{TO}}{S}}{\mu g\rho C_{Lmax}}\right] \tag{9}$$

In this case the value obtained for the wing loading is a constant number.

4. RESULTS.

4.1 Statistical Entropy.

Using SANCA Statistical Entropy Module, A M Abdalla (2014) was obtained the dominant design from the set of UAVs into the database.

Diffusion and Convergence.

On the X axis, the diffusion term means the subsequent classification of a particular product design. On the Y axis, the degree of convergence is defined as the distance between all the products of a population, that precedes a product by reference to the last product in the population study.

By analyzing Fig.6, it is possible to infer that $U1$ was dominant and conducted the design parameters of the category in study, in other words these UAV had a strong impact on industry.

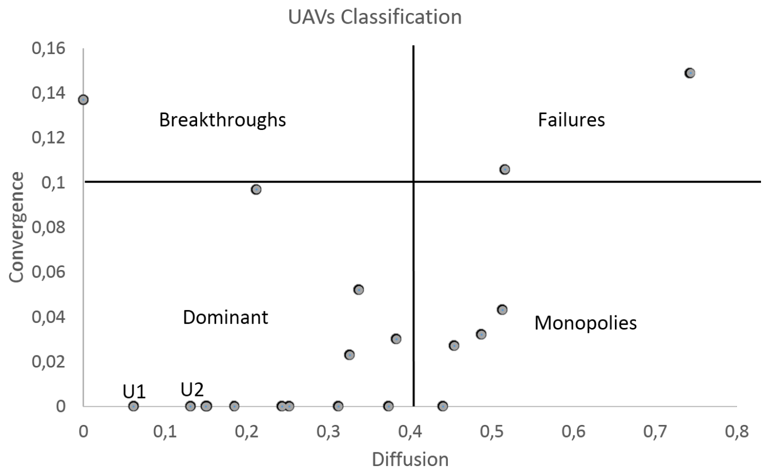

Figure 6. Diffusion and Convergence results

UAV 1 was selected to use its design parameters in the constraints analysis, applying the fuzzy theory to optimize it.

4.2 Fuzzy Application.

The maximum fuzzy number was select from each variable optimization, this means the evaluation of customer needs that are most important to optimize, in order that the UAV should perform a right mission.

Table 2. Fuzzy classification Requirements for Optimization

Needs Ranking	Minimum Fuzzy	Average Fuzzy	Maximum Fuzzy
Wing Loading	6,9	8,5	10
Thrust to weight ratio	4,3	6,0	7,4
Rate of Climb	6,7	8,3	9,7
Take-off Distance	5,3	6,9	8,4

4.3 Constraint diagram.

Constraint diagram shows the design points of the Dominant UAV.

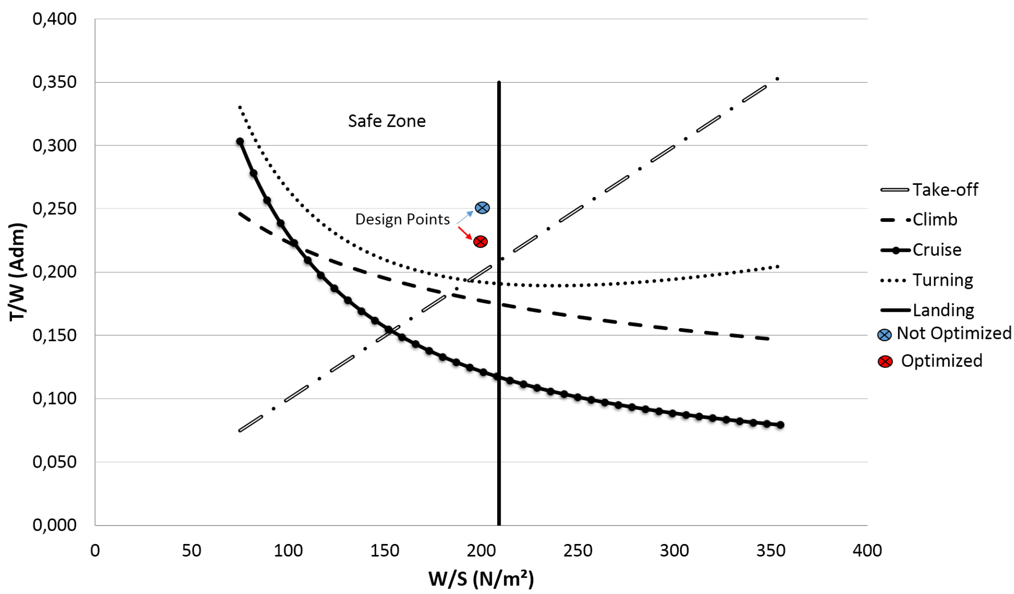

Figure 7. Constraint Analysis

Blue symbol represents the design point between wing load and thrust load of the UAV without optimization, whose coordinates are: $\frac{W}{S} = 200,46\frac{N}{m^2}$; $\frac{T}{W} = 0,25$.

Red symbol represents the design point between wing load and thrust load of the new UAV using the optimization variables of fuzzy application, whose coordinates are: $\frac{W}{S} = 198,46\frac{N}{m^2}$; $\frac{T}{W} = 0,22$.

In accordance with fuzzy classification requirements for optimization, wing load parameter is the most important variable to optimize, because the fuzzy number of this parameter meets the total customer needs in relation to the UAV design, represented by number 10 into the maximum fuzzy scale. This parameter serve to estimate the wing surface, it is calculated by dividing the aircraft take-off weight by wing loading, it represents how much load is held by each unit area of the wing.

By the Fig 7. The area allowed to respect all constraints for each flight phase is called Safe Zone. the UAV without optimization is within this area, however the UAV with optimization is located in the point that minimize the wing load and the specific power for each flight phase with a certain safety margin.

5. CONCLUSIONS.

The main contribution of this work is to get an initial parameters and configurations required for the production of aircraft conceptual design efficiently and in a short time compared to traditional methods of conceptual design.

The results indicate that, the methodology developed by the authors, leads to satisfactory parameters, in concordance to optimization of wing loading W/S and thrust loading T/W. Therefore, accomplish satisfactorily the requirements of design, based on customer needs.

As can be verify, the value found for optimized wing loading is not representative in terms of the wing area reduction. That means, with the reduction of $2,0N/m^2$ in wing loading, the wing area would decrease from $0,75m^2$ to $0,7421m^2$, in other words only $0.0079m^2$ of wing area will be decreased. However, with regard to power load, the optimized value obtained can be considered important, due the reduction of 12% in terms of power, which leads to choosing a new power plant system, with possible characteristics of: weight and adjacent structures, lower than original aircraft (without optimization). Besides reduction of specific fuel consumption and cost of acquisition.

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