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Multidisciplinary Design and Optimization (MDO) Methodology for the Aircraft Conceptual Design

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An integrated design and optimization methodology has been developed for the conceptual design of an aircraft. The methodology brings higher fidelity Computer Aided Design, Engineering and Manufacturing (CAD, CAE and CAM) Tools such as CATIA, FLUENT, ANSYS and SURFCAM into the conceptual design by utilizing Excel as the integrator and controller. The approach is also demonstrated to integrate with many of the existing low to medium fidelity codes such as the aerodynamic panel code called CMARC and sizing and constraint analysis codes, thus providing the multi-fidelity capabilities to the aircraft designers. The higher fidelity tools bring the quantitative aspects of a design such as precise measurements of weight, volume, surface areas, center of gravity (CG) location, lift over drag ratio, and structural weight as well as the qualitative aspects such as external geometry definition, internal layout, and coloring scheme early in the design process. The performance and safety risks involved with the new technologies can be reduced by modeling and assessing their impact more accurately on the performance of the aircraft. The methodology also enables the design and evaluation of the novel concepts such as the blended and the hybrid wing bodies (BWB and HWB). Higher fidelity computational fluid dynamics (CFD) and finite element analysis (FEA) allow verification of the claims for the performance gains in aerodynamics while ascertaining risks of structural failure due to different pressure distribution in the fuselage as compared with the tube and wing designs. The approach is shown to eliminate the traditional boundary between the conceptual and the preliminary design stages, combining them into one consolidated preliminary design phase. Several examples for the validation and utilization of the Multidisciplinary Design and Optimization (MDO) Tool are presented using mission for the Medium Altitude Long Range/Endurance Unmanned Aerial Vehicles.

Nomenclature

AR	=	Aspect Ratio
CAD	=	Computer Aided Design
CAE	=	Computer Aided Engineering
CAM	=	Computer Aided Manufacturing
CFD	=	Computational Fluid Dynamics
COTS	=	Commercial off the Shelf
FEA	=	Finite Element Analysis
MALE	=	Medium Altitude Long Endurance
MDO	=	Multi Disciplinary Optimization
MO	=	Multi-objective
OML	=	Outer Mold Line
TOGW	=	Take Off Gross Weight
UAV	=	Unmanned Aerial Vehicle

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I. Introduction

The aerospace industry has completed 100 years of astounding achievements in air as well as in space and the design community has been tremendously challenged throughout due to the technological, economical, and geographical factors. As the products underwent changes to meet these challenges, so did the processes that created such products. Given the advancements in computational technologies, the aircraft design process has received much attention in the recent past. The conceptual design of a new aircraft is focused on the analysis of the given customer requirements to synthesize possible configurations. Sizing codes, empirical relationships, statistical data, and proprietary legacy codes are deployed to evaluate different concepts and configurations as depicted in Figure 1. Since the aircraft design is multidisciplinary in nature, characterized by a wide variety of disciplines that often compete with each other for the best performance, the approach works well for the time tested and widely manufactured tube and wing designs due to availability of sizable statistical data; however, when it comes to some of the revolutionary concepts as depicted in Figure 2, this approach suffers from several limitations due to inadequacy either, in modeling of such concepts or capturing the true impact of a given technology leap such as the composite materials and fuel / solar cells propulsion systems[1].

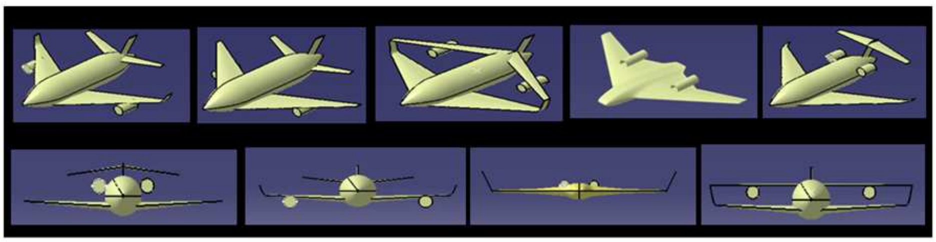


Figure 1. Configuration level decisions to be made during the Conceptual Design phase

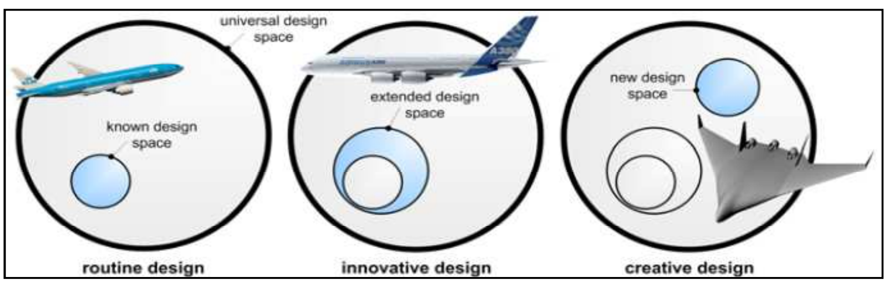


Figure 2 Evolutionary to revolutionary frontiers for the design innovation [2]

In order to provide the aircraft designer with such design tools that are not limited to any particular aircraft configuration, size or mission, an integrated design methodology has been developed that brings the high fidelity CAD and CAE tools and the multi-objective optimization (MO) in the conceptual design phase. The methodology is modular and flexible that allows inclusion of new disciplines and seamlessly integrates with existing low or medium fidelity sizing and analysis tools. The approach aims at providing *adequate fidelity tools* for any design task where the aircraft designer can sketch the concepts in CAD right from the beginning and embark on FEA and CFD analysis whenever needed. The approach utilizes only the commercial-off-the-shelf (COTS) design tools for the purpose of making it accessible to the entire design community. The methodology eliminates file transfer and translation that usually consumes 60-70% of the engineers' time. The approach aims at reducing the design cycle time and cost, improving the design and enabling the designs of novel concepts with the application the multi-fidelity tools.

Another reason for bringing the higher fidelity design tools in the conceptual design phase lies in the way the entire product design proceeds as depicted in Figure 3 [3]; the early part of the design lifecycle provides opportunity to consider many configurations and make wider design selections, thus permitting largest freedom to the designer. This freedom reduces sharply as the designer proceeds with the product design, making design changes prohibitively expensive. Therefore, the most suitable and viable time to make the configuration level decisions and major changes in the design lies in the conceptual design phase. When the conceptual phase is past, changing the configuration could easily cost the aerospace company its very existence. Substantial cost savings can be realized by employing better design processes that comprehensively and accurately include all factors affecting the lifecycle of a new product [3].

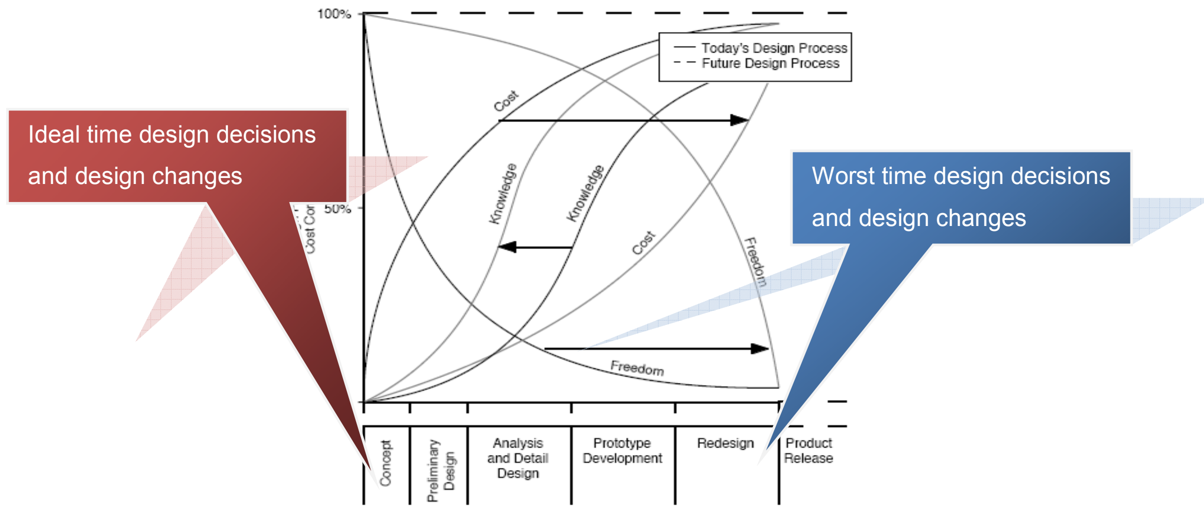
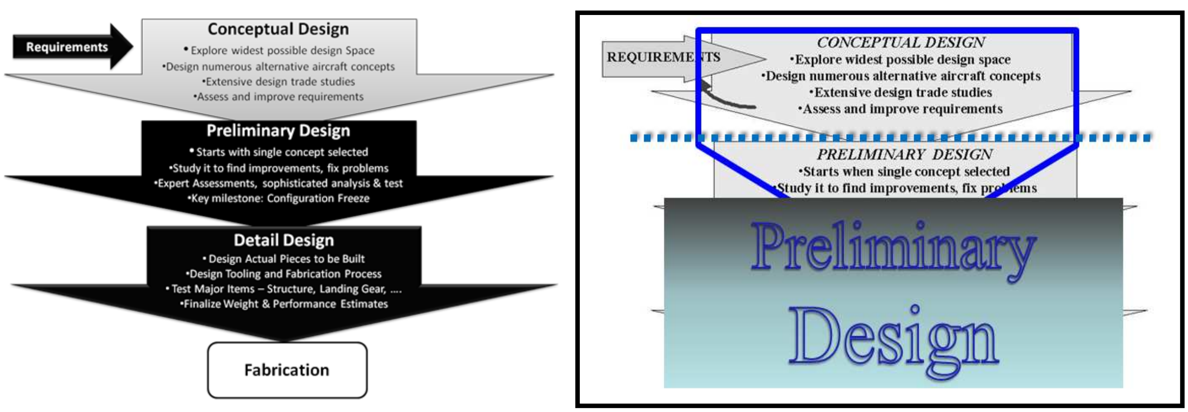


Figure 3. Current and desired trends in the design process [3]

A. Impact on the Design Methodology

The aircraft design process usually comprises three phases namely Conceptual Design, Preliminary Design and Detail Design. Figure 4(a) gives a summary of various activities that take place during each phase [4]. Several design activities including requirements' analysis, sizing, design trade off analysis and configuration studies take place during the Conceptual Design Phase and many critical decisions at the configuration level are made during this phase. The breakdown of the activities given in Figure 4(a) serves as the distinct boundaries between three design phases. The reason such boundaries have always existed is the way design process has been traditionally conducted. With the current methodology, these boundaries can be eliminated so that two separate conceptual and preliminary design phases can be merged into a single Preliminary Design phase as the CAD and CAE tools are made integral part of the design process from the very beginning. The illustration of this effect appears in Figure 4(b).



(a) (b)

Figure 4. (a) Aircraft design phases, reconstructed after [4] (b) redefining the boundaries of phases in the aircraft design

Furthermore, the start of the Detail Design is a far more smoother from this *merged Preliminary Design Phase* as compared with the traditional model; for example, with the position, geometry and dimensions of the ribs and spars already worked out, when it is the time to include holes and connectors for control surfaces and high lift devices, one can right away start to do the detailed analysis and design of these minor details as the FEA and CAD models are already setup for overall geometry.

II. Overview of the MDO Methodology

A vision for an integrated MDO Methodology that incorporates all of the disciplines involved in aircraft design was formulated. The overall model as appears in Figure 5 serves the purpose of a roadmap for this vision. The disciplines that have been successfully integrated in the MDO methodology presented in this paper appear in Figure 6.

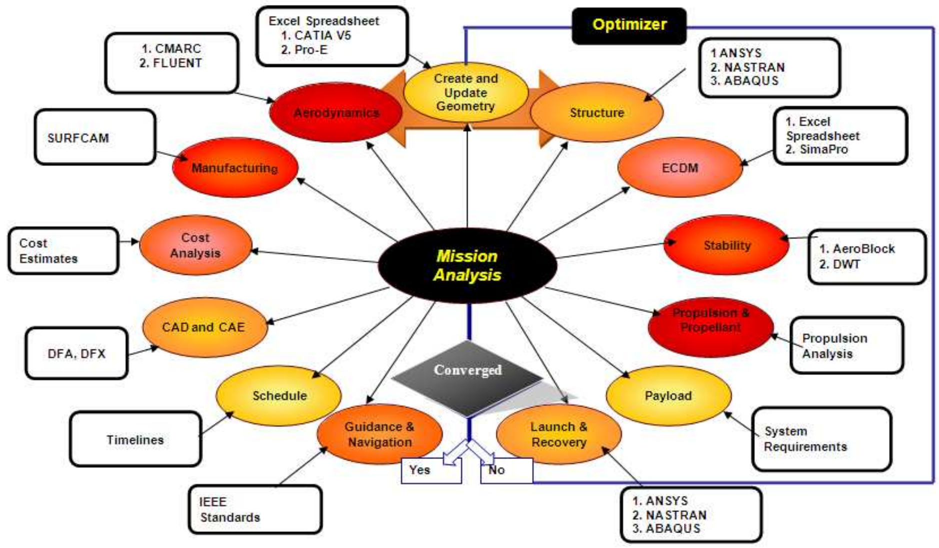


Figure 5. Envisioned framework for the design integration from the lifecycle point of view

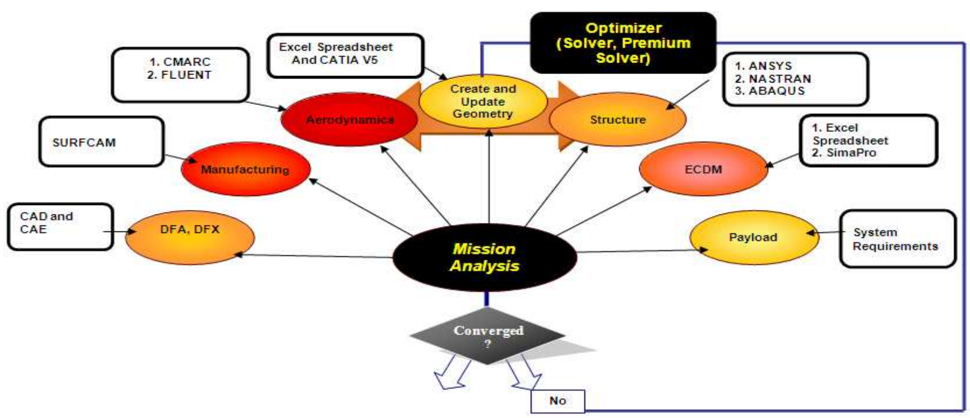


Figure 6. Subset of the disciplines implemented in the MDO Methodology

The approach [5, 6] builds on the strengths of Excel spreadsheet [7] to create necessary links and hence design integration across vital CAD and CAE tools. The multidisciplinary optimization is also carried out in the original optimization tool in MS Excel called Solver [8] along with its advanced version called Premium Solver [9]. *The idea is to layout the complete input files for the design tools in spreadsheets where data entry and visualization is simple and convenient & control and execute all computations and design optimization from Excel using its* native programming language called VBA.

Sizing methodologies from Raymer [10] and Brandt [11] are implemented in doing the Mission and Constraint Analysis for computing initial TOGW, T/W_o and W_o/S and the wing reference area (S_{ref}) in order to *start the design process*. After the initial sizing, design information from CAD and CAE tools is utilized instead of continuing with the sizing and lofting methods described in Raymer based on the empirical data and statistical relationships. The schematic of this approach appears in Figure 7. The user enters familiar wing geometry parameters such Aspect Ratio (AR), Sweep (Λ), Dihedral, Twist Angles and Taper Ratio (λ) along with the fuselage dimensions and shape parameters in the first spreadsheet. This spreadsheet is shown in Figure 8.

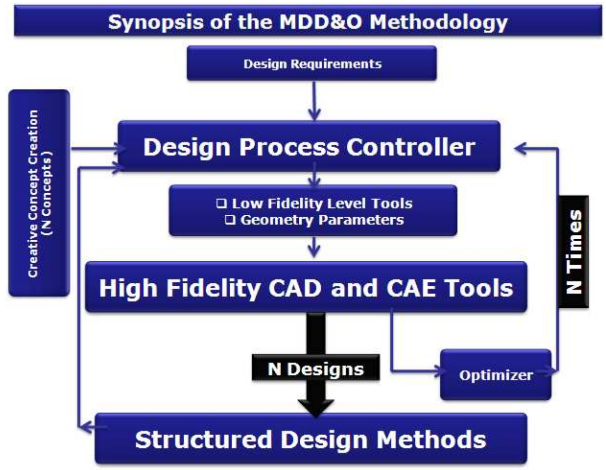


Figure 7. Schematic of the MDO Methodology

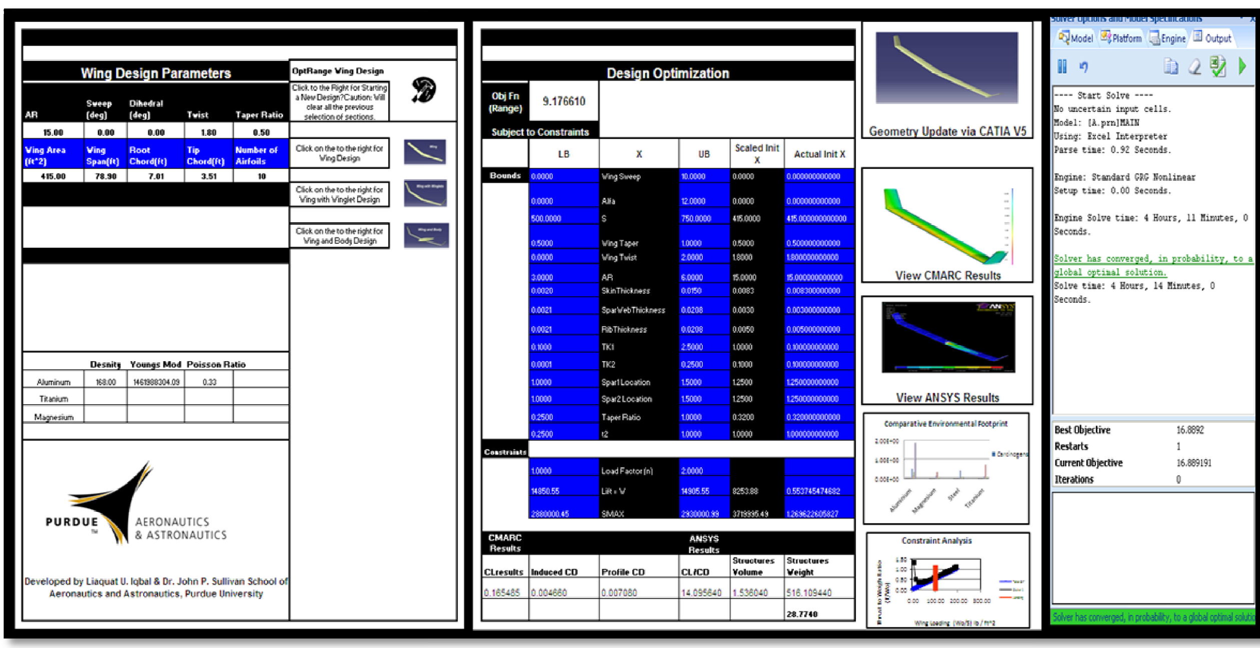


Figure 8. First spreadsheet for the master control of the MDO

III. Validation of the Computational Model

Validating the computational model that uses numerical methods such as the CFD and FEA for performing design and analysis is considered among the most challenging and essential parts of the current research. Given below is an outline of the validation process;

(1) As a first step, the relevant aero-structural theory is developed along with the analytical solutions and the charts. Several scenarios are developed to consider various structural weight ratios for wings and rest of the aircraft. The charts help in *identifying the beneficial tradeoffs and their limitations.*

(2) In next step, the computational model is used to design, analyze and optimize the same problem as done in the analytical case. The accuracy and limitations of the integrated MDO tool is then checked in the following manner;

   a. Computational model is fully tested in optimizing the wing's outer mold line (OML) as well as structural boxbeam to meet strength and performance criteria.

   b. The optimized solution from computational model is compared with the analytical solution.

c. Plots of displacement and bending stresses are generated to get further validation of the locations of maximum and minimum displacements and stresses as known from the well established Beam theory.

d. The validity of the optimizer is further checked *by changing the initial design values* to ensure that the optimizer is not sensitive to any particular starting value. This was further tested by choosing the *initial design values from the infeasible design space* i.e. the ones that violated one or both constraints at the onset of the optimization process.

All these steps are critical in ensuring validity of the computational results and correct functioning of the optimizer.

A. Analytical Formulation of the Possible Tradeoffs Involving the Drag and Weight Reduction

The famous Breguet Range Equation provides three major contributors that affect aircraft range. These include aerodynamic, propulsion and the structural efficiencies, as outlined in the following Eq. 1;

$$Range = V\ x \left[\frac{L}{D}\right]_{Aero\ Eff} x \left[I_{sp}\right]_{Prop\ Eff} x \left[\ln\left(\frac{W_i}{W_f}\right)\right]_{Struc\ Eff} \tag{1}$$

Two of these major contributors i.e. aerodynamics and structures are highly coupled and completely opposed to each other; improving one usually leads to the detriment of the other.

Historically span (b) has been used for reducing the induced drag along with the elliptic spanload distribution to enhance aerodynamic efficiency. This is done because induced drag varies with square of span (b^2), leading to sharp reduction in the induced drag for even a smaller increase in b [12]. This however leads to a greater loss when the structural weight is taken into account as a result of such a span increase. From the structural point of view however, the "bending wing weight" varies according to the following relationship [13];

$$W = W_o + k_2 W_o b^3 \tag{2}$$

The *direct cubic* relationship of span with weight vs. *inverse quadratic* relationship between span and the induced drag pose the overall study of impact of span on aircraft total weight as a classic MDO problem and investigated by RT Jones [13]. In order to *correctly understand the tradeoffs* between increase in the structural weight and reduction in the induced drag leading to an overall advantage/disadvantage at the system's level, several analytical solutions are developed from the Breguet Range Equation using a simplified boxbeam model shown in Figure 9. These solutions give an insight into the tradeoffs that would suggest how far the above formulation is correct, what design space would benefit from it and what kind of designs would deteriorate from the span increase at the system level.

B. Example Problem: Wing Design for an Unmanned Surveillance Aircraft

A notional long range surveillance UAV mission is considered as a test case with an objective to design the *minimum* weight wing for the Unmanned Surveillance Aircraft capable of flying the given mission profile;

(1) Range 10,000 miles at 40,000 ft at 0.6 Mach number
(2) Turbine powered with TSFC = 0.5 (1/hr)
(3) Rectangular wing planform to minimize construction cost
(4) Payload = 5000 lbs of instruments

C. Mission and Constraint Analysis

The mission and constraint analysis are performed to get an initial takeoff weight (W_o) and wing reference area (S_{ref}). The solution space in the constraint diagram gives the designer a wider range of thrust to weight (T/W_O) ratios and wing loadings (W_O/S) to choose from. Traditionally, the aircraft designer would hand pick a manageable number of such ratios and generate carpet plots to refine the design that fulfills the mission while being light weight. Since the current approach has MDO capabilities, it can solve the sizing problem to the mission requirements as an optimization problem. The mission and constraint analysis for the Unmanned Surveillance Aircraft lead to the takeoff weight (W_o) of 14860 lbs and wing reference area (S_{ref}) equal to 415 ft^2.

D. Analytical Solution

An average C_L value is selected based on the takeoff weight calculated from the mission analysis to begin the analytical solution. The maximum span efficiency can be empirically computed from the following relationship for different span loadings [13];

$$\frac{1}{e_{max}} = \frac{9}{2}\pi^2\beta_c^{\ 2} - 12\pi\beta_c + 9 \tag{3}$$

where β_c is the location of the centroid for different span loadings and e_{max} is the maximum span efficiency factor. The structural weight is calculated given the simplified boxbeam model shown in Figure 9 by varying the skin thickness to meet the allowed stress constraint. Four cases of varying wing structure to rest of the airplane structural weight ratios (Ws_{wing}/Ws_{rest}) are considered to develop deeper understanding of the tradeoffs involved. This was done in order to identify the weight ratios within the aircraft structures group that would benefit from the induced drag reduction due to span increase and change in the spanload distribution. Four cases included;

(1) Structural weight of the wing being same as compared with the rest of the airplane's *structural weight* to simulate flying wing type airplanes.
(2) Structural weight of the wing being ½ as compared with the rest of the airplane's *structural weight* to simulate BWB type airplanes.
(3) Structural weight of the wing being ¼ as compared with the rest of the airplane's *structural weight* to simulate HWB type airplanes.
(4) Structural weight of the wing being $^1/_{10}$ as compared with the rest of the airplane's *structural weight* to simulate transport type airplanes.

Drag is calculated by analytically computing induced drag [12] and estimating the profile drag from the equivalent skin friction relationships [10,11]. Given the flight range, cruise Mach/Altitude information, TSFC value, and the structures weight from the boxbeam, the Breguet Range Equation was used to compute the fuel weight. Sum of the empty weight (structures and fixed systems), payload and the fuel weight gives TOGW;

$$TOGW = W_e + W_p + W_f \tag{4}$$

A baseline wing was thus obtained that would meet the mission requirements as stated in the beginning. The baseline wing was then changed in terms of span (by varying the Aspect ratio, while maintaining a fixed wing area) and the spanload distribution, to generate different wings. A total of 4 analytical solution sets, one for each of the W_{swing}/W_{srest} ratio were generated. Each of these solutions, comprising of four spanload distributions over a range of aspect ratios, was plotted on the same graph to see which AR and Spanload Distribution has the lowest TOGW.

E. Boxbeam Structural Model

The boxbeam is modeled as an idealization for the actual wing structure that is designed to take all of the bending stresses. This is a reasonable approximation to perform hand calculations during the conceptual design Stage. The boxbeam extends in length along the wingspan and symbol 'b' is used to denote its length. Width of the beam is aligned with the wing chord and is taken as a certain fixed length to leave room for the LE Slats, TE Flaps and ailerons. Height of the beam is denoted by 'h' and is taken with due consideration to the viscous drag that is a result of the airfoil thickness leading to transition to turbulent flow and separation. On the other hand, 'h' is very effective in reducing the allowable stresses from mechanics of structures; larger it is, lighter the structure would be due to high area moment of inertia. To have a reasonable compromise between the viscous drag and the area moment of inertia, 'h' is fixed at 15%.

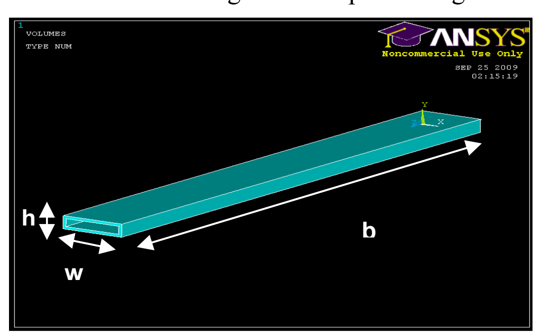


Figure 9. Boxbeam for structural weight calculation

F. Analytical Solution Results

The four cases are given in Figure 10 and Figure 11 where effect of changing the wingspan and the spanload distribution on takeoff gross weight can be studied. Although the tradeoffs are usually focused on seeing effect of span increase on overall weight, by classic belief that Elliptic loading is best for design, it turns out that other spanload distributions may offer more benefits when considered from the systems level benefit of TOGW rather than restrictive view of induced drag (that is minimum for elliptic load distribution). These tradeoffs based on AR and spanload distribution are explained in the following;

(1) **Tradeoffs based on AR.** It can be concluded that;

  a. **A**lthough the span increase has some advantage in reducing the induced drag due to the inverse quadratic relationship, the range of AR for which this happens is quite narrow since the span increase beyond some limit starts to incur more penalty in TOGW (due higher bending stresses) than can be balanced by reduction in induced drag.

  b. The overall best case applies to the designs where wing weight is closer to the rest of the airplane's structural weight (Figure 10 (a)). This case is usually far from majority of the real airplanes as it applies to the flying wing type designs.

(2) **Tradeoffs based on Spanload distribution.** The tradeoff that seems more promising for the higher AR designs (AR 8-12) and wider in application is the one based on departing from the elliptic load distribution to triangular one.

All in all, four scenarios contain a great deal of information and insight over a broad range of airplanes and the aircraft design team can consult these charts based on the design problem at hand to identify the *advantageous region* in terms of the span increase. The *triangular load distribution* offers *clear advantage for the higher AR* applications where the prohibitive penalties due to sharp rise in the bending moment quickly outweighs the benefits of induced drag reduction by the elliptic load distribution. This results in an overall increase in the TOGW due to structural weight penalty. On the other hand, the elliptic load distribution remains the best choice for designs with AR less than seven for the flying wing type designs.

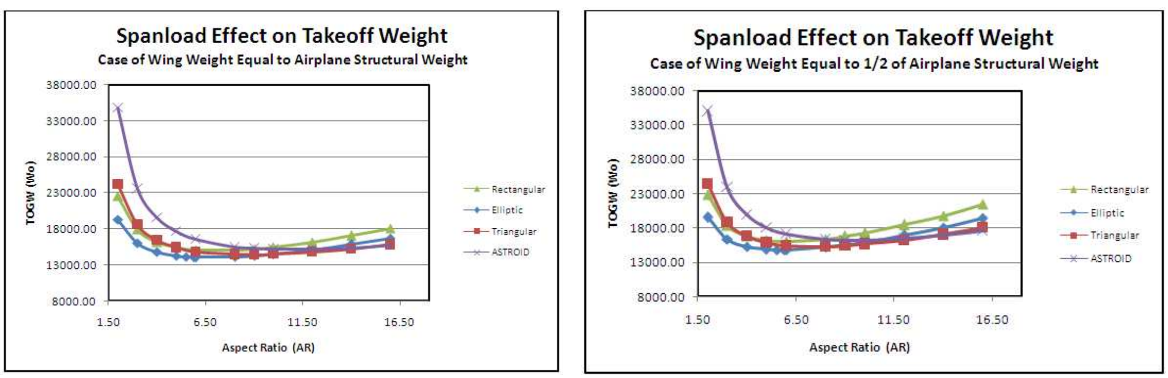


Figure 10. (a) Case 1 and (b) Case 2 of the analytical solution

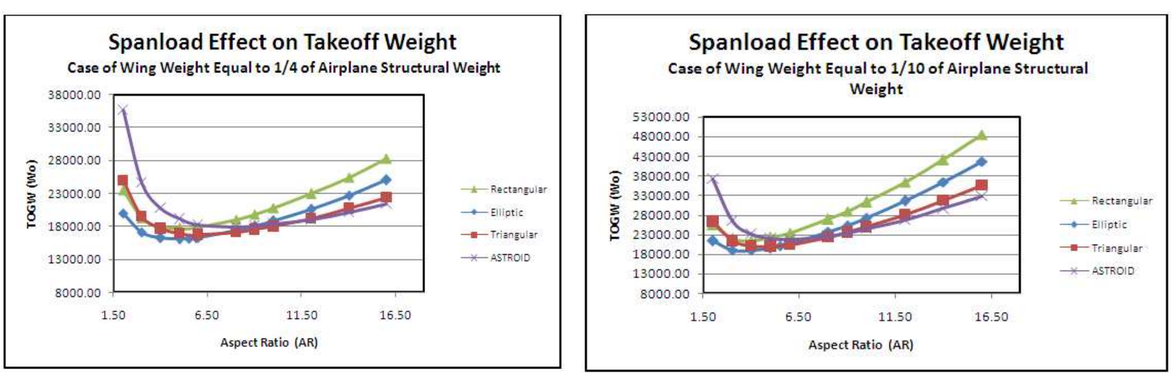


Figure 11. (a) Case 3 and (b) Case 4 of the analytical solution

G. MDO Solution

As stated earlier, the wing structural geometry is approximated or idealized from the actual wing box into a rectangular boxbeam. Figure 12 illustrates the progression from the actual structural layout to the idealized one along with the arrows pointing in the direction of change, terminating at the FE model of boxbeam in FEA code ANSYS [14].

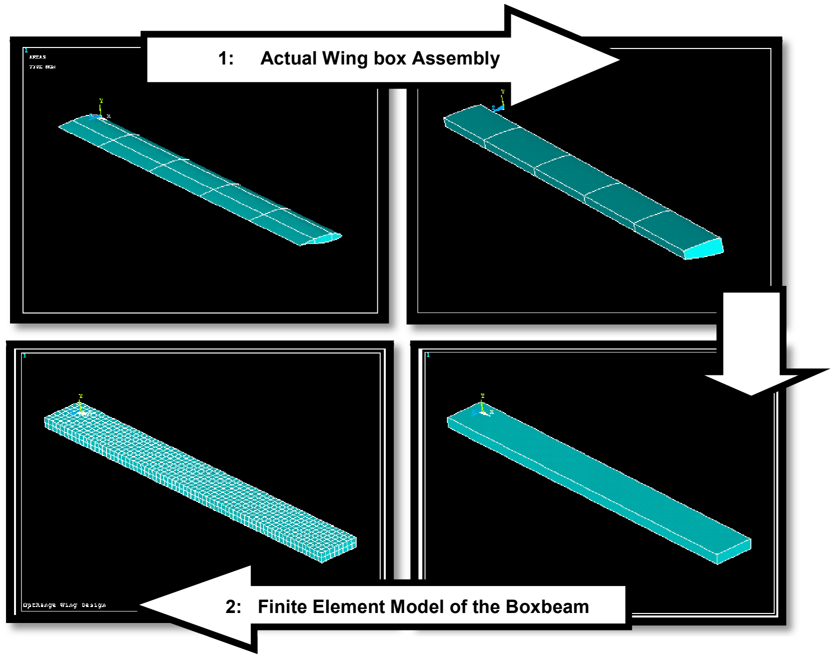


Figure 12. Idealization of the actual wing box into rectangular boxbeam

H. Aero-Structural Design and Optimization

Having defined the initial geometry, the next step is to perform design optimization. Having ascertained the correctness of input and calculated parameters through single design run, the next step is to optimize the design for the range mission with the minimum weight UAV. For this, a set of suitable design variables are defined as a range of parameters that the optimizer takes on for generating, analyzing, evaluating and optimizing new design candidates until arriving at the best one. The optimization problem is set up as described in detail below.

J. Objective Function

Weighted Objective Sum approach is used to formulate the overall objective function in such a way that when the overall objective function is optimized, L/D is maximized while the structural weight is minimized. It is important to assign the weighting coefficients to L/D and structural weight in the pseudo objective function (referred to as objective function from here on) in such a way that the optimizer does not get “biased” in the favor of one or the other. At times, more than one set of weighting coefficients have to be tried before arriving at such values that work well for a given problem. The second but equally important aspect is the selection of the initial design points (set of starting values for the design variables) for starting the optimization process. These can be best known values based on the problem, experimental data, personal experience or simply the best guess. As the optimization proceeds, one would notice several design candidates would emerge that may not pass the optimizer’s test for optimality but serve a great deal in choosing the next starting point.

$$\emptyset_{Range} = \alpha\left(\frac{L}{D}\right) + \beta\left(\frac{1}{W_s}\right) \tag{5}$$

Φ_{Range} is the pseudo objective function, α is the weighting coefficient for $-$ and β is the weighting coefficient for the structural weight.

K. Multiobjective Optimization Problem Setup and Solution

In order to compare the best analytical solution with the computational best solution (or ability of the optimizer to find such a solution), the case of wing weight equal to ½ of the rest of the airplane's structural weight was chosen as a validation example. This corresponds to the tradeoffs shown in Figure 10 (b). The optimum solution for this case occurs at an Aspect Ratio of 6 with the elliptic spanload distribution and a TOGW of 14810 lbs. In order to validate the ability of MDO tool to find this optimum solution, the TOGW was posed as an equality constraint on lift (Lift = Weight = 14810 lbs). The maximum allowable stress constraint was applied as the inequality constraint ($S_{max} \leq 20000$ psi). Lower and upper bounds were defined for the design variables i.e the skin thickness (t_s), wing aspect ratio (AR) and the twist distribution (γ) to change the spanload distribution. The multiobjective optimization was executed using the MDO tool to find the optimal solution and the results were compared. Table 1 gives the optimization problem statement with the multiobjective function subject to inequality and equality constraints and lower and upper bounds on the design variables.

The coefficients for the weighted objective approach were chosen to pose the L/D ratio and the structural weight with equal importance. This was accomplished by multiplying the two parts of the objective function with such values that would bring them equal to each other in magnitude. Next, the optimization was carried out with α and β values to be equal and the results were still quite close to the ones obtained with different values for α and β. Given this observation, the multiobjective function for the actual design examples was chosen to maximize L/D and minimize structural weight, without any weighting coefficients and it seemed to work well as no convergence issues were encountered.

Table 1. Validation Optimization Problem

Maximize $\Phi_{Range} = \alpha\left(\frac{L}{D}\right) + \beta\left(\frac{1}{Ws}\right)$

Subject to : $S_{max} \leq 20000$ *psi*

$L = 14810$ *lbs*

$0.002 \leq \ t_s \geq 0.015$ *ft*

$4 \leq \ AR \geq 10$

$0.5 \leq \ \gamma \geq 5$*deg*

Where t_s *= Skin Thickness*

AR = Aspect Ratio

γ *= Twist Angle*

In all of the cases given in Table 2 to Table 7, the *Global Optimization* capability of the Premium Solver was utilized that helps in searching through the entire design space. The *Global Optimization* option in solver looks at the range of each of the design variables and systematically divides it into segments to choose several initial design points for optimizations runs. Next, it sweeps through each of this subdivided domain one after the other by going through fresh starts. In each restart, it refreshes the starting point based on the sub-domain under evaluation. This significantly increases the prospects of finding a global optimum as opposed to a local optimum solution. The design optimization cases were run for the UAV wing design with a set of key design variables and constraints such as aspect ratio, boxbeam thickness, spanload distribution and maximum stress etc. The results of the fully converged solution are summarized in Table 2 to Table 7. It is very encouraging to see that the calculations performed by the MDO computational tool are very close to the analytical results. It is pertinent to mention here that extra significant digits under MDO column are only *shown to illustrate small changes* from one set to the other and *not the accuracy of the answers*.

All of the five solutions summarized in Table 2 to Table 6 were carried out with *narrow constraint boundaries* on the design variables in order *to save computational time*. This was possible because of the known optimal solution from the analytic solutions. However, in order to be more certain and confident about this solution being the global optimum design, the design limits on the AR, skin thickness and twist angle were made much larger. After longer computational time (6 hours, 43 minutes) as compared to the previous solution with narrower bounds on the design variables (2 hours, 42 minutes), the optimizer converged to the same solution. This was very encouraging for it not only verified the previous solution but also confirmed that the optimum solution at hand is indeed the best one.

L. Results and Conclusions of the Analytical and MDO Solutions

Table 2. Case 1: AR = 5.75, Skin Thickness = 0.0035 ft (0.042 in)

	Analytical Solution	MDO Solution	% Difference
Aspect Ratio (AR)	6.00	5.9157	-1.33
Boxbeam Thickness (in)	0.084	0.0864	+ 3.57
Wing Structural Weight (lbs)	470.28	500.3645	+ 6.39
Lift to Drag Ratio (L/D)	27.84	25.0397	-10.09

Table 3. Case 2: AR = 6.75, Skin Thickness = 0.0055 ft (0.06 in)

	Analytical Solution	MDO Solution	% Difference
Aspect Ratio (AR)	6.00	5.9154	- 1.33
Boxbeam Thickness (in)	0.084	0.0866	+ 3.10
Wing Structural Weight (lbs)	470.28	498.1301	+ 5.92
Lift to Drag Ratio (L/D)	27.84	25.0388	- 10.09

Table 4. Case 3: AR = 5.75 Skin Thickness = 0.0073ft (0.088 in)

	Analytical Solution	MDO Solution	% Difference
Aspect Ratio (AR)	6.00	5.9562	- 0.73
Boxbeam Thickness (in)	0.084	0.0870	+ 3.57
Wing Structural Weight (lbs)	470.28	501.5976	+ 6.66
Lift to Drag Ratio (L/D)	27.84	25.1122	- 9.79

Table 5. Case 4: AR = 5.99, Skin Thickness = 0.0073ft (0.088 in)

	Analytical Solution	MDO Solution	% Difference
Aspect Ratio (AR)	6.00	5.9900	- 0.167
Boxbeam Thickness (in)	0.084	0.0876	+ 4.29
Wing Structural Weight (lbs)	470.28	505.8278	+ 7.56
Lift to Drag Ratio (L/D)	27.84	25.1790	- 9.56

Table 6. Case 5: AR = 5.75, Skin Thickness = 0.0073ft (0.088 in)

	Analytical Solution	MDO Solution	% Difference
Aspect Ratio (AR)	6.00	5.8427	- 2.63
Boxbeam Thickness (in)	0.084	0.0870	+ 3.57
Wing Structural Weight (lbs)	470.28	498.4599	+ 5.99
Lift to Drag Ratio (L/D)	27.84	24.9189	- 10.49

Table 7. Case 6: Extended Variable Domains (AR = 4 -10, Twist =0.5 -5 deg)

	Analytical Solution	MDO Solution	% Difference
Aspect Ratio (AR)	6.00	5.8606	- 2.32
Boxbeam Thickness (in)	0.084	0.0870	+ 3.57
Wing Structural Weight (lbs)	470.28	498.8289	+ 6.07
Lift to Drag Ratio (L/D)	27.84	24.9567	- 10.36

M. Validation of the Results through Visualization Tools in ANSYS

There are several other ways to verify the FEA results and one of the most important ones is locations of maximum bending stresses and displacements. Beam theory is very well established based on the mathematical formulation, observation and experimental results. The maximum bending stress always occurs at the fixed or cantilevered end with minimum occurring at the free end. The case of displacement is opposite to this, with maximum displacement taking place at the free end and zero at the fixed end. In order to validate the bending stresses and displacement results, ANSYS post-processing ability was deployed to generate color contours of both kinds of outputs (stress and displacement distributions) for larger AR wings (AR = 10) for better visualization. The mapped displacement contours given in Figure 13 verify the theoretical maximum at the free end and minimum i.e. zero displacement at the cantilevered end with gradual increment towards maximum in between. Likewise, the bending stresses have a maximum at the fixed end and a minimum at the free end, as clearly seen by the color contours.

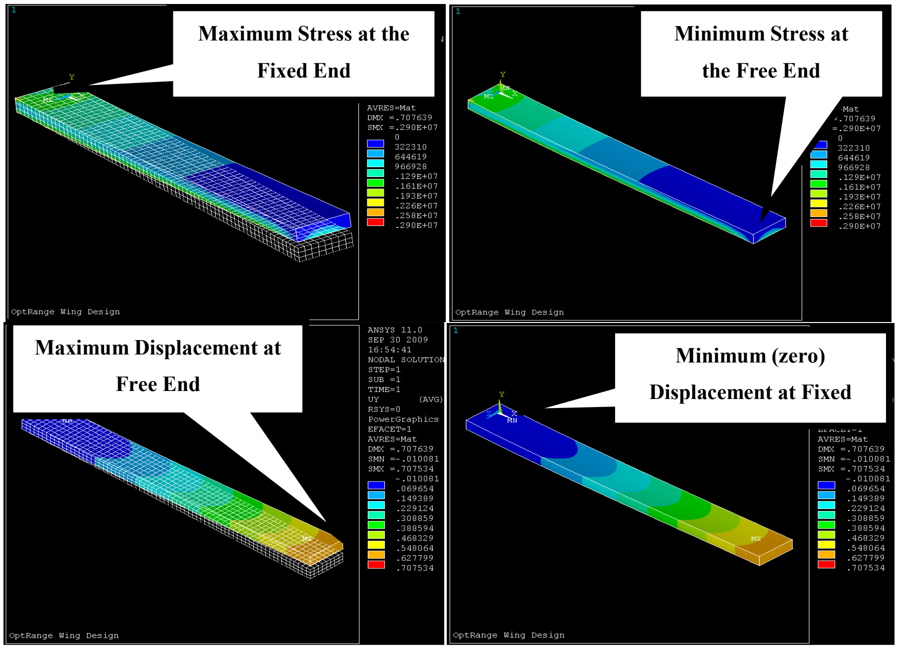


Figure 13. Minimum and maximum stress / displacement location as visual means of validation

IV. Design Examples

A. Application of the MDO tool by the AIAA DBF in 2007 Competition

The AIAA Design Build Fly (DBF) competition team was given access to the integrated design and analysis capabilities of the MDO tool for designing the 2007 competition aircraft [15]. The team was able to understand the computation of the geometry parameters in the spreadsheet fairly quickly and was able to effectively generate major concepts for the competition aircraft including a joined wing, BWB, and a conventional aircraft, shown in Figure 14;

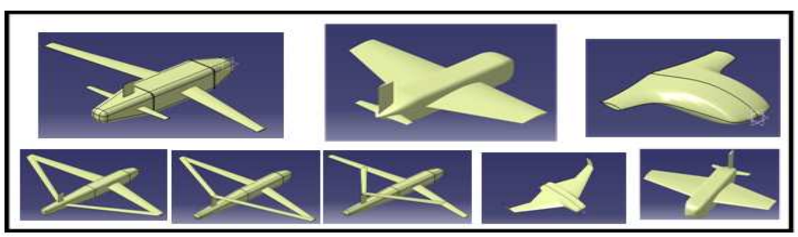


Figure 14. Conventional, BWB and Joined Wing concepts in CAD geometry

The team was able to accomplish a lot of wind tunnel testing on the two concepts chosen for further development i.e. the conventional and BWB aircraft This was made possible by the ability of readily converting the CAD geometry file into the Computer Aided Manufacturing (CAM) SURFCAM file.

This illustrates the ability of MDO methodology to lend itself quickly to the manufacturing for the wind tunnel testing or the rapid prototyping. Overall, it was observed that the team adopted the MDO tool easily, generated various concepts independently after the initial explanation of creating the geometry parameters in the spreadsheet, and explore various design concepts and ideas in CAD, FEA and the wind tunnel testing. The team was able to precisely manufacture the final concept given that the entire aircraft was already drawn in CATIA [16]. The final aircraft is sown in Figure 15.

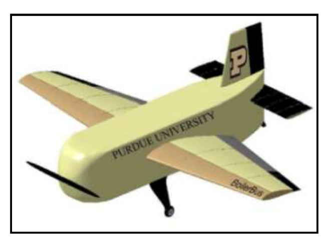


Figure 15. Final aircraft for the 2007 DBF competition [15]

B. MALE UAV Design

Medium Altitude Long Endurance (MALE) UAVs offer some of the most versatile applications in the civil as well as military sectors and were therefore chosen for the design example. In order to have a benchmark UAV concept to serve as datum as well as validation for the MDO Tool, the Tube and Wing conventional concept was designed based on the Predator UAV Mission and Geometry. The Predator UAV data is given in Table 8;

Table 8. Predator UAV published geometry and performance data [17, 18]

Dimensions and Operating Envelop	Wing AR	Wing Span (b) ft	Length (L) ft	Wing Area (S) ft^2	Air Speed (KIAS)	Operating Altitude ft	Endurance hrs
	17.5	64	34	234	270	45000	24
Power Plant	**Type**		**Weight lbs**		**Rated Thrust lbs**		**TSFC**
	William FJ44 Turbofan		520		2300		0.5
Weights (lbs)	**Payload Weight (Wp)**	**Fuel Weight (W_f)**	**Empty Weight (W_e)**		**TOGW**	**Empty Weight Fraction (W_e)**	
	750	3000	2650		6400	0.41	

The baseline UAV compares well with the Predator UAV as given in Table 9. The MALE_X1 structural weight was computed with the aluminum as construction material and is 14.98% higher than the composite material Predator UAV. This difference is likely to significantly reduce in case MALE_X1 is also designed with the composite material. Likewise, all of the structural members such as ribs and spars have been modeled here as whole sections whereas the Topology Optimization during the detail design would remove material where not needed thus further reducing the weight.

Table 9. Comparison of MALE X1 UAV with Predator UAV [17, 18]

	Payload Weight (Wp) lbs	Fuel Weight (Wf) lbs	Empty Weight (We) lbs	TOGW lbs	Empty Weight Fraction (We)	L/D Ratio
Predator	750	3000	2650	6400	0.41	
MALE_X1	750	4017.71	3172	7353	0.43	28.54

Having developed the baseline tube and wing MALE UAV, several design concepts were sketched. Some of these concepts are shown in Figure 16; two major groups of concepts i.e. BWB/HWB and tube and wing are shown. The concepts can be increased to larger groups such as joined wing and all wing concepts as well.

The BWB concept was modeled in CATIA and ANSYS and initial design evaluations were carried out without starting the design optimization. The encouraging results for the considerably higher L/D ratio along with similar structural weight as that of the MALE_X1 for some of the chosen BWB concepts initiated the optimization process. The two spar and ribs concept was optimized in the MDO environment with the Global Optimum Solution search method of the Premium Solver. The 20 hours long optimization lead to the following results;

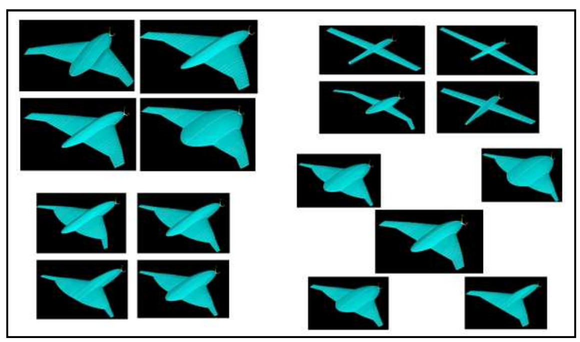


Figure 16. Conventional and BWB/HWB MALE UAV concepts

Table 10. Comparison of the optimized BWB MALE UAV design

	L/D	Structural Weight (lbs)
Baseline BWB Concept	38.50	1517.12
Optimized BWB	39.65	1462.52

The optimized concept has considerable aerodynamic as well as the structural advantage and would outperform even the Predator UAV due to considerably higher L/D ratio. The optimized concept is shown in Figure 17 with the two main spars and sixteen ribs. This geometry is taken from ANSYS and highlights the ability of ANSYS to model the geometry exactly as CAD. Figure 17 to Figure 20 have been shown to give the clear view of the CAD geometry, structural design results and aerodynamic design to illustrate that the design data could be displayed in the bigger size where one would very clearly see the design in CAD and CAE tools. CAE tools even provide the animation of stress and displacement development that can be very useful means to evaluate and change the design candidates.

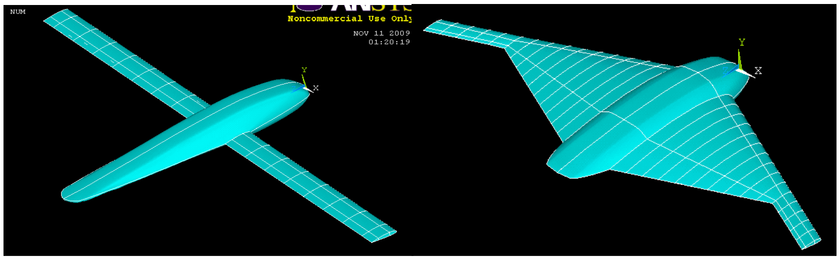


Figure 17. (a) Tube and Wing geometry (b) Optimized BWB concept

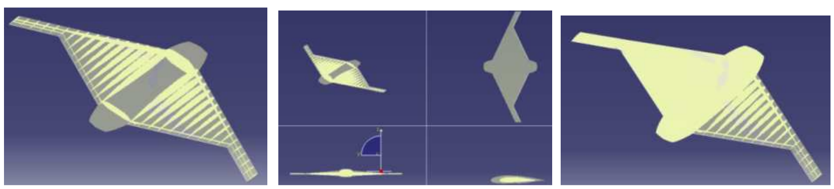


Figure 18. CAD geometry of the BWB concept with structural layout

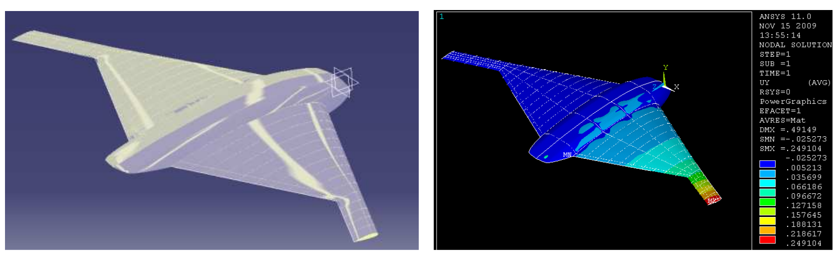


Figure 19. CAD geometry and displacement distribution for BWB concept

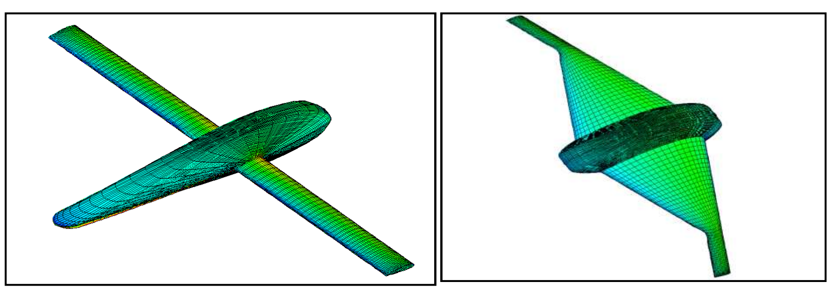


Figure 20. Cp Distribution for the tube and wing and BWB concepts

V. Conclusions and Recommendations

This research has developed an MDO Methodology that brings the higher fidelity CAD and CAE tools into the conceptual design phase. The MDO methodology is validated by comparing the computational results with the analytical solution for a high altitude long range UAV wing design. The methodology has been applied to design

MALE UAV similar to well tested Predator UAV. Predator UAV data provided the benchmark for the application of the design methodology as well as the validation of the design results. The TOGW results compared well given that the difference could be justified between an all metal conceptual design vs. an all composite fully tested operational design. Examples also included the utilization by the AIAA DBF Team for the design of 2007 competition aircraft. The generation of conventional and novel designs, quick fabrication for the wind tunnel testing, composite modeling for structural design and the rapid prototyping in CAM were all highlighted to illustrate major advantages realized by the team by virtue of the MDO tool. Given below are the major conclusions of the current research;

(1) The methodology enables the desired shifts in the current design process as envisioned by the NSF and shown in Figure 3. The knowledge about the design is moved upfront by bringing higher fidelity CAD and CAE Tools in the conceptual design phase. This allows making critical configuration level decisions with higher fidelity in the conceptual design phase leading to better designs in lesser time. The increased understanding of the design at hand by the designer enables better communication with the customer, leading to further improvements in the design and flow of knowledge about the design.
(2) The methodology removes the boundaries between the traditional conceptual and preliminary design phases, merging the two into a consolidated preliminary design phase, characterized by the multi-fidelity design tools and structured design methods.
(3) The methodology significantly reduces the wastage of the large amount of engineers' time in the file transfer, data transportation and formatting. This allows the designer to focus his/her time on the design rather than wasting it on the logistics of the design.
(4) Excel spreadsheet provides an effective and modular design control environment in which disciplines can be added, and the optimization sequence selected. The execution is flexible to allow disciplinary as well as the multidisciplinary design and optimization. The fact that majority of the engineers have working knowledge of Excel, the transfer of knowledge and training becomes easier as well.
(5) MDO Methodology provides ability to generate and evaluate larger number of design concepts and is practical and viable for the concept generation and evaluation as opposed to the prevailing viewpoint that CFD, FEA and CAD can be used mainly for a single concept in the detail design phase only.

The research has illustrated the development, validation and application of the MDO Methodology through several design examples. The application examples have provided key insight into the work that can be accomplished in the future. Some of the key tasks are recommended in the following;

(1) The multiobjective optimization was carried out in the conventional way by modeling and evaluating the actual geometry. This can be supplemented by the surrogate modeling and optimization through RSM as that has been shown to be efficient and helpful in saving time. The computational cost is considerably reduced by constructing a Response Surface based on the most important factors (design variables) and then optimizing the response surface instead of the actual objective function that might be computationally very expensive [19].
(2) FEA was conducted assuming all metal concepts for the MALE UAV design. However the tool has the ability to model composites and the AIAA DBF structural design work including hollow composite shells for the wing design is an example of the implementation. The same should be done for the MALE UAV design and in other applications.
(3) The Multiobjective optimization was carried out using one of the many techniques proposed for defining the multiobjective optimization problems. Several other approaches such as ε-Gaming, Min-Max and Goal Attainment can be utilized as well to ascertain which one works the best. It is recommended to formulate the MO problem at least with one more technique to compare which one works better.

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