Educational Methodology Applied to Aircraft Design

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Abstract

The purpose of this document is to evaluate and promote the methods of education in the STEM fields by reporting a particular overview of the results and accomplishments in an aeronautical vehicle design class project. In this experience, a development of individual effort and studies lead to a very important process of collaborative effort (an essential quality required in the industry). In aircraft design, a process is executed such that all the disciplinary studies of aeronautics are applied to produce together one single concept for a vehicle to be built followed by more detailed planning phases. The design is first of all achieved by creating a conceptual shape of the aircraft made by a convergence of variables that best fit the subjected mission requirements. The following seven steps give an overview of the conceptual design for an aircraft: 1) Analysis, 2) Integration, 3) Iteration, 4) Convergence, 5) Solution Space Screening, 6) Solution Space Visualization, and 7) Risk Assessment. Beginning with the mission requirements, an Analysis directed by all the disciplines provides values that contribute to the configuration of the vehicle as well as the specifications produced. Integration combines the findings and calculations in the analysis and assemblies it into one whole. Iteration recreates the process of analysis by reapplying the flight parameters in an iterative process. The Iteration process ends when these values arrive at Convergence and remain fixed for the rest of the design. This provides a visual Solution Space Screening, which provides the constraints of the vehicle in design. The Solution Space Visualization represents the available combination of parameters which provide an optimal design visually. This area is finally evaluated and any risks are assessed of the point chosen from the design space. Thus this paper will demonstrate the validation of this aircraft by recreating the design process to the World War II German Fighter, Messerschmitt Bf 109. Reverse engineering essentially serves as the first step in analysis where an initial set of parameters regarding the intentions of the plane are used. Parametric sizing, steps 2 to 6, essentially serves as a critical procedure of sizing the aircraft to the desired mission capabilities. The guideline for this sizing is

explained by Laurence Loftin's method of aircraft development documented in his work of *Subsonic Aircraft: Evolution and the Matching of Size to Performance*. This is important to any application of aircraft design where the knowledge gained by the Capstone students is utilized through combining the different elements during the years of study and is demonstrated in this collaborative work.

Introduction

Education in engineering has become a nation-wide concern against the rising global competition in the fields of Science, Technology, Engineering, and Mathematics (STEM) advancements. The concern is due to the forecasted inability of the United States to maintain economic leadership if the students, teachers, and professionals are not at the same stride of the international community in STEM education. Although the majority of these concerns should be targeted at the early stages of education that inspire and motivate the development of the STEM influence, the focus here lies on the existing undergraduate engineering university student. This student's academic course work, which was taken over the years, is applied not only to the capstone design project but also to the collaborative effort that will bring the best out of an organized group. This is one aspect in education that will generally not be initially taken into consideration in the educators' curriculum.

To accomplish a nation with strong STEM foundation, advanced levels of thinking must be achieved instead of following learned procedures in the classroom. A creative mind in conjunction of STEM initiatives will enable this nation to become an international leader in the scientific fields. This paper will present the overall procedure carried in the senior vehicle design project of reverse engineering of the World War II fighter planes by utilizing available historical resources and applying methods of group execution to arrive at a conceptual design of the aircraft. A method of aircraft design will be implemented to the aircraft based on the flight mission requirements that the fighter planes were required to maintain. The handling of the student group will also be evaluated. It is intended to showcase the strength of research of previous history to eliminate and understand the errors committed in the past and to demonstrate the necessity of effective team dynamics in the designing process.

Aircraft Design Procedure

In the aircraft design process, there are three main phases in which the creation of a flight vehicle is reached. These are generally considered to be the Conceptual Design, Preliminary Design, and Detailed Design. The analysis required in the designing of an aircraft implements a multi-disciplinary approach that integrates various elements involved.

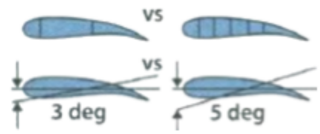
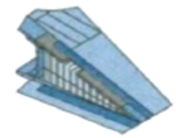
	Phase 1 Conceptual Design	Phase 2 Preliminary Design	Phase 3 Detailed Design
			
Known	Basic Mission Requirements Range, Altitude, & Speed Basic Material Properties σ/ρ E/ρ $\$/lb$	Aeroelastic Requirements Fatigue Requirements Flutter Requirements Overall Strength Requirements	Local Strength Requirements Producibility Functional Requirements
Results	**Geometry**: Airfoil Type, R, t/c, λ, Δ **Design Objectives**: Drag Level, Weight Goals, Cost Goals	Basic Internal Arrangement Complete External Configuration *Camber & Twist Distribution* *Local Flow Problems Solved* Major Loads, Stresses, Deflections	Detail Design *Mechanisms* *Joint Fittings and Attachments* Design Refinement as Result of Testing
Output	**Feasibility Design**	**Mature Design**	**Shop Designs**
TRL	**2-3**	**4-5**	**6-7**

Table 1. Three phases of aircraft design (Nicolai, 2010).

In the Conceptual Design phase, the initial configuration of the aircraft is made without scrutinizing on many of the details. Essentially the basic flight and mission requirements are addressed at this stage, such as if the plane being design is intended for certain cargo or payload requirement, high or low speed, and maneuverable capabilities. Such requirements allow determining the definition of wingspan, sweep, and basic dimensions of the aircraft that will fulfill the mission requirements. There no major constraints in this phase leading to generally making the design of a low Technology Readiness Level (TRL). However this TRL will increase with realistic implementations of available technology. Basic calculations are made in this phase to accomplish all general flight conditions.

Preliminary Design becomes more of a detailed analysis of the model created conceptually through the first phase of design. This stage will verify phase 1 as well as provide more detailed aspects of the flight vehicle. The engine and intake configurations are selected or confirmed at this point of stage. The structural overviews are assessed at this point such as aeroelastics, fatigue, and flutter analysis. Refined weight estimates are made and a more thorough performance analysis is conducted. Dynamic stability and control analysis influences are determined and six-degrees-of-freedom (6-DOF) rigid aircraft simulations are conducted to establish flight control requirements and handling quality levels. If the aircraft is highly flexible (such as a high aspect ratio wing, a high fineness ratio fuselage, low fuselage damping), the simulation might require consideration of more than six degrees of freedom in order to examine the coupling of the rigid aircraft modes and the flexible aircraft modes.

In the Detailed Design phase, the product reaches a fixed state in which no more modifications are made to the design of the aircraft. The modifications made in this phase are applied to the detailed components of the aircraft that do not necessarily contribute significantly to the design. Such components include mechanisms, joints, fittings, and attachments in the structure. It is important that from this point on the design changes be kept to a minimum because the cost of making a change is large once the drawing hits the shop floor (Nicolai 2010). Interior layout is detailed with respect to location and mounting of equipment, hydraulic lines, ducting, control cables, and wiring bundles.

For the scope of the assigned project, only the conceptual design phase is taken into consideration not only for the specifics of the assignment, but also to refrain from making ambiguous studies and analysis of the aircraft. To remain in a conceptual design approach, calculations can be made by using the general geometry and configuration of the aircraft. Any form of high-ordered detailed analysis by utilizing advanced computing tools is such as Computational Fluid Dynamics (CFD) viewed as over-ambitious, yet possible.

Team Methodology

The intended approach of the assembled team is to separate into groups in order to specialize in the main disciplines, to obtain concentrated data, and to efficiently master each criterion. The proposed subject criteria are accepted and agreed upon by the team, which include the following concentrations: Aerodynamics, Propulsion, Controls, Structure and Performance. In addition, two critical areas of interest that required detailed attention are studied: Aircraft Sizing (utilizing Loftin's method) and Risk/Certification. Assuming there will be enough documentation available, Risk will undertake any documented errors or maintenance necessities that will give understanding to the structure and function of the plane. Certification will analyze documentation regarding regulations for flight at the given era.

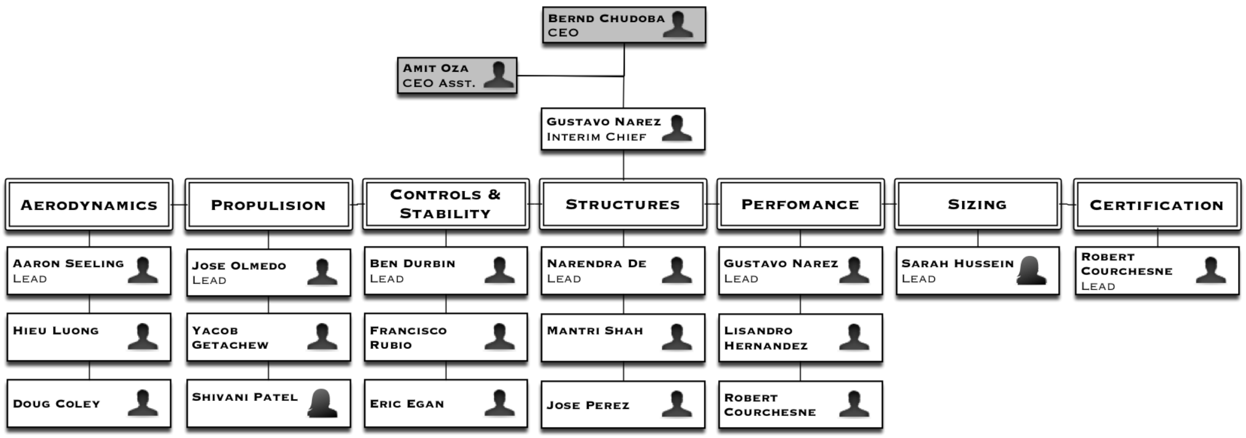


Figure 1. Design team diagram with team members and position within chosen criterion.

Aerodynamics

The aerodynamics group will specialize in tradition aerodynamic topics related to the results of normal and shear stress distributions applied to plane including coefficients of lift, drag, and moments applicable to any given dynamic pressure value. The group will decide on an implementation of measuring such values. Process possibilities include Thin Airfoil Theory, to find correlations in data, or advanced DATCOM programming.

Propulsion

The propulsion group will work to analyze the propulsion aspects surrounding mainly the propeller and power plant of the aircraft. Other topics of concern to be shared among performance are fuel consumption of the piston engine and temperature effects. Specifications of the engine must be considered as initial configuration elements of the aircraft, leaving not much room to change variables. Thus the available technology at the time must be correctly applied.

Controls

The controls group will overlook the control surfaces of the aircraft that operate the trim and flight maneuverability overall. Even though in the sizing approach in Loftin's procedure stability and controls are not included, this group will overlook the stability of flight in all the conditions (climb, cruise, combat, etc.)

Structure

The structure group will be dedicated to find structural information of the plane that dictate the force loads during flight and calculate the maximum forces and stress the aircraft can retain. This group will as well provide a CAD model to demonstrate stress distributions.

Performance

The performance group will examine the range and mission capabilities of the aircraft. Topics to be covered include lift-drag ratio, endurance, climb & descent, and flight envelope considering both optimal flight conditions as well as maximum capabilities. A great amount of collaboration with the other groups will be required to validate available information with the analytical approach of these values.

Mission Profile

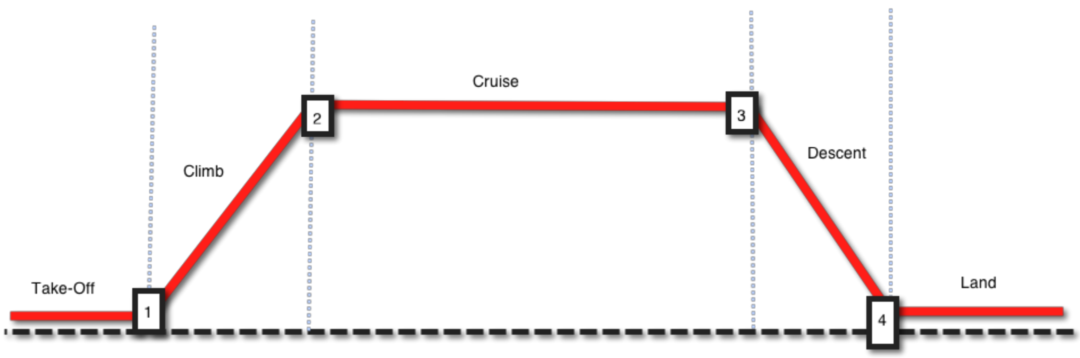


Figure 2. Mission profile requirements calculated for the Bf 109.

To begin with, a simple approach demonstrates the range of the Bf 109 and the specifications of a mission requiring a quick climb rate to cruising altitude and long range until fuel is out. This simple profile description will provide a demonstration for the endurance abilities for the aircraft in a simple manner of calculating several points in the path of the mission profile.

It is intended for the mission profile to be nice and simple by calculating the points for each segment of the profile (points 1, 2, 3, and 4).

A mission profile code is made to accommodate and organize these values in an input/output manner in order to facilitate the change in variables provided by other disciplines, or where different situations are to be investigated. This is not intended to substitute the Loftin sizing method, but merely to describe the instantaneous mission depiction.

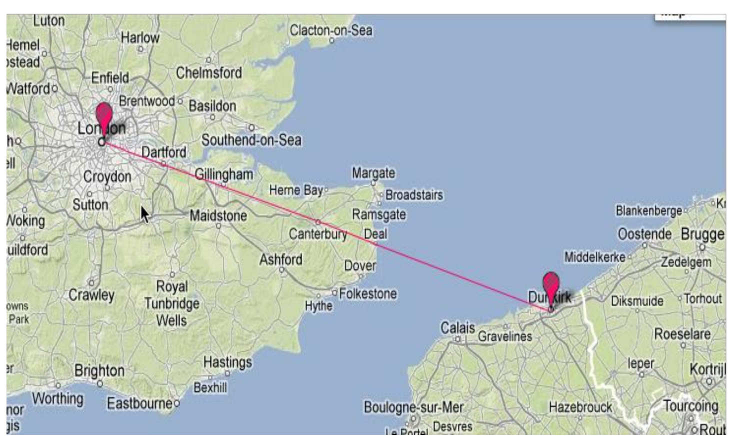


Figure 3. Mission example displaying Dunkirk to London capable by the Bf 109

An example to which this mission profile may be applied is the distance from Dunkirk, France to London. The values calculated for this mission profile demonstrated the capabilities in which this fighter aircraft is seen to be capable of accomplishing.

The distance between the two cities is approximately 182 kilometers (114 miles). While the Bf 109 E variations are documented as having a range capability of 650 kilometers (410 miles).

Project Overview

The instructions and description for this project are presented in this section. Four main objectives that are required for this assignment are

- Reverse-engineer three WWII Fighter missions and vehicles using design approach by Loftin.
- Validate individual missions segments using existing data.
- Develop a complete Conceptual-Design-Level study identifying the vehicle solution space for the mission selected.
- Produce a rendering of the vehicle.

The overall purpose of this project for MAE 4350 Vehicle Design Course is to execute a literature overview and analyze, based on calculations and historical data, the military aircraft in World War II era. An emphasis is made on applying the information of the past as well as becoming completely knowledgeable of the aircraft. The aircrafts used in combat at the time were regarded as vehicles of high performance. Due to the nature of military information, all data available were not accessible or public. Yet, in the past 70 years, much documentation has been made accessible to the public through intensive research on the Internet and in printed books from libraries.

The three aircrafts that will be studied by the MAE 4350 Vehicle Design class are the German *Messerschmitt Bf 109*, the British *Supermarine Spitfire*, and the United States' *P-51 Mustang*. The students in the senior design course are divided into three groups and each organization focuses on one of the three aircrafts assigned for the project; each organization consisting of about 13-16 individuals per group.

It is intended for the aircraft to be analyzed and evaluated through gathered data, essentially to conceptually reverse engineer the aircraft. A historical overview is required to fully comprehend the design and expectations of the assigned aircraft. Modifications or design enhancements of the aircraft will demonstrate the ability of the appointed senior design group to take a capstone approach and apply the acquired knowledge to the collected information of the designated aircraft.

This project will provide the senior design capstone student with the ability to specialize in a criterion of the aircraft presented and, through a collaborative effort, demonstrate the ability to analyze an aircraft numerically (all specifications and extremities of the original design) as well as understand the primary conceptual functions of the aircraft.

Figure 4. World War II era fighter planes, in this picture from left to right are the Messerschmitt Bf 109, British Spitfire, and P-51 Mustang.

Loftin's Parametric Approach

It is intended to implement a design approach by following the procedure outlined by Laurence Loftin in his publication *Subsonic Aircraft: Evolution and the Matching of size to Performance.* Loftin's guided procedure in the parameterizing and development of aircraft arrives at a solution space that visually demonstrates the optimal design configurations for the mission and operation of interest. This information found in his documentations is to be applied through the original available data from the aircraft to make an analysis based on the configurations. This will be seen through the outcome of the process and the change of the fighter plane's configuration. The differences between the iterated outcome values from Loftin and the original specs available of the aircraft will be an error that is intended to be analyzed. The result of this error will be explained as either due to optimization of the aircraft or true error in the initial input values used of the known aircraft data.

Chapters II, III, and IV in Loftin's document focus on the development of Jet Engine Propulsion aircraft while the following chapters V, VI, and VII are designated for the development of the Propeller-Driven aircraft. Although many subjects are generally the same, such as aerodynamics and structural forces, Loftin takes this into account in regards to the propulsion system and provides a procedure in the parameterization of the propeller blade.

Literature Review

The intention of the Messerschmitt Bf 109 is to replace the current line of fighter planes at the time in the 1930's, which for the German nation at the time included the Arado Ar 68 and the Heinkel He 51 as shown in Figure 3. The Arado Ar 80 design was a relatively conservative open-cockpit monoplane, with the characteristic (Nicolai 2010) forward-set vertical fin. On the other hand, the Heinkel He 112 was a relatively portly aircraft, featuring the Günther brothers' signature elliptical wing planform as first seen on the He 70.

Figure 5. Arado Ar 68 (top) and Heinkel He 51 (bottom).

The biplanes were well out performed by the design of Willy Messerschmitt in 1933 when the Luftwaffe desired to make the substitution. This out-performance was seen from the prototype of the new monoplane itself.

The requirements imposed by the Luftwaffe included for a capability of 400 km/h at 6000 meters, climbing to the 6000 meters in 17 minutes and an operational service of 10,000 meters.

Some of the features that brought about innovating differences were the incorporation of the enclosed cockpit, which was something that many pilots found strange at the time but demonstrated to have great benefits for the design. Retractable landing gear was another major improvement compared to the Arado's and the Hinkel's fixed landing gear.

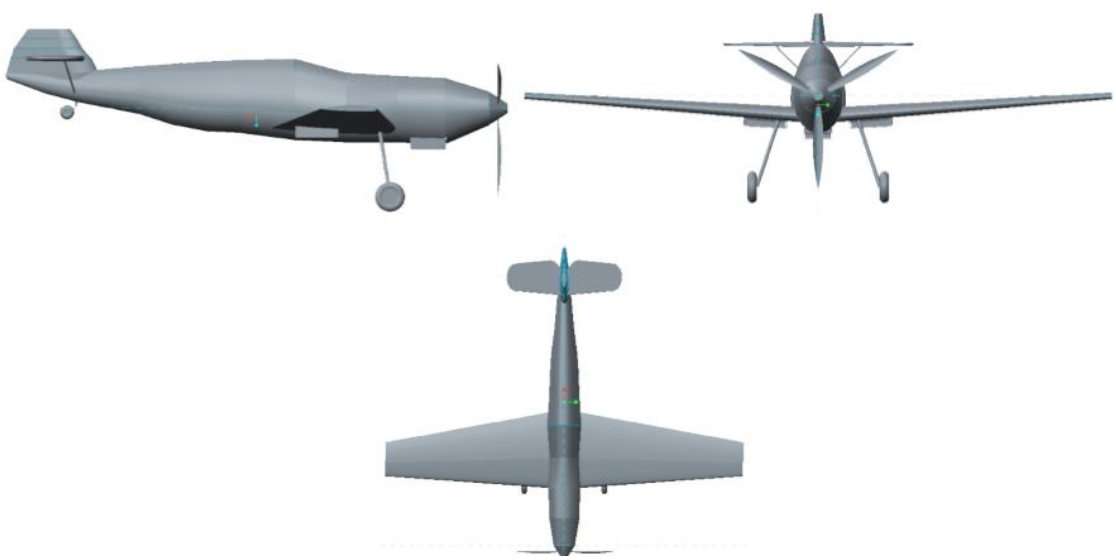


Figure 6. Messerschmitt Bf 109 Variant E model renderings from CREO 2.0

Educational Applications and Experience

The Aerospace Engineering Capstone program at the University of Texas at Arlington exposes the senior student to a more realistic level of application based on the knowledge and methodologies acquired as an undergraduate. It is not until this point in the final year that the student applies higher levels of thinking to arrive at designing success. Methodology, which is not expressed traditionally in any required course within the curriculum of engineering, is now a key developmental process for the success of the project.

The explanation of learning capabilities and process has been for years modeled in Bloom's Taxonomy (Forehand 2010). General courses will for the most part cover the two lower parts of the pyramid diagram, in Figure 7. Remembering and Understanding. Remembering is the capability of recalling the information without much high order process. Comprehension is the understanding of the information. Educators who are familiar with Bloom's Taxonomy, or any other effective learning techniques, will request the students to employ their understanding to valid conceptual applications.

As for Applying, it implements solving problems preceding the recalling and understanding levels. Higher order of thinking proceeds, as Analyzing and Evaluating.

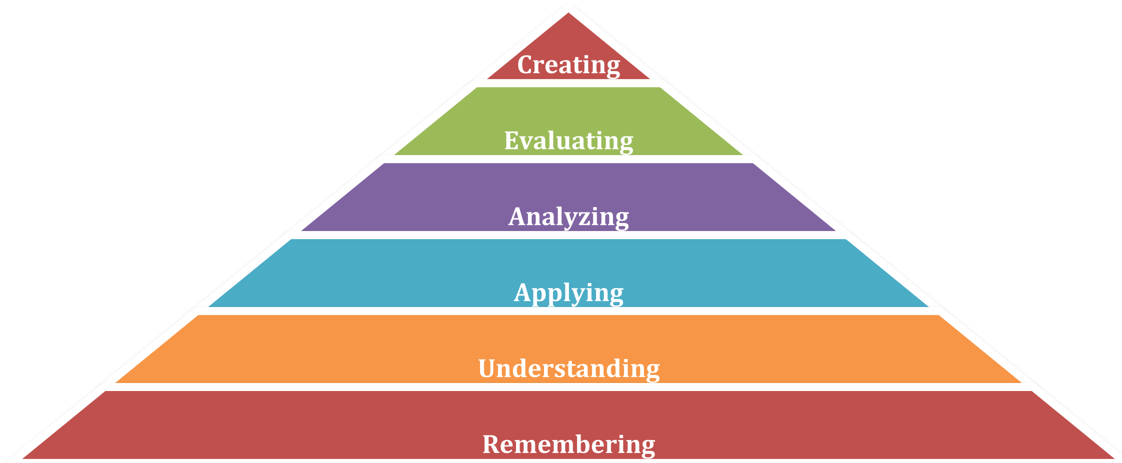


Figure 7. Bloom's Taxonomy overviewing thinking levels of information beginning basic remembering to elaborate composition.

The ability to create is considered the highest level of thinking. It is defined simply as the ability to put elements together to form a coherent or functional whole, organized into elements of a new pattern or structure. It is the Creative level in Bloom's Taxonomy which the student is exposed to by the senior capstone project. With the exception of the extracurricular lab assistant or intern student in the field of engineering, this level of execution may be unfamiliar to the scholar. It is not until the exiting capstone course that the composing of these conceptual designs are created.

In aircraft design, there is a general procedure that heavily utilizes the concepts of Creating in Bloom's Taxonomy. The method consists of seven clear steps required to effectively produce an aircraft. It provides the ability to assess the possible configurations, that would meet the mission and the design constraints, and the risk involved with the selection of an intended flight operation. The steps, as shown in Figure 8, are in the following order: 1) Analysis, 2) Integration, 3) Iteration, 4) Convergence, 5) Solution Space Screening, 6) Solution Space Visualization, and 7) Risk Assessment.

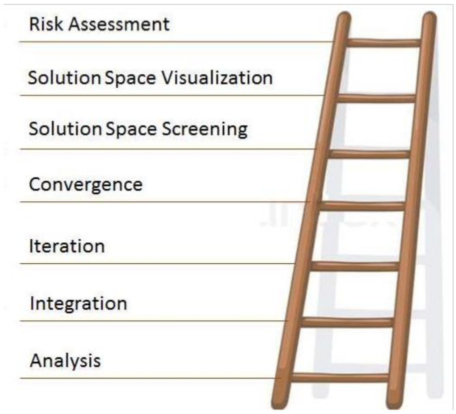


Figure 8. The seven step conceptual design procedure.

Analysis is the step in the design method that involves the general studies of aerospace engineering: aerodynamics, propulsion, controls and stability, structures, and aircraft performance. This is mainly the focus of general undergraduate courses. Thus for the beginning capstone student, Analysis is the only step with certain familiarity.

Integration is the step which takes all the separate disciplines of the design and builds them into a parametric calculation code. For example, calculating the values of aerodynamic drag at certain velocities contribute to an assessment of power required by the propulsion system for operation at the desired speed. This interchangeability of calculations between the disciplines may alter the design configurations indefinitely if continued. Thus, it is necessary to implement a Convergence step that will, as the name indicates, converge on specific values that dictate the configuration of the design based on an iterative process of calculation.

After a convergence is reached satisfying the constraints of the design configuration, solution space assessment is implemented to visually demonstrate the possible configurations of the aircraft, ideally based on parametric sizing values. The parametric sizing values for the project are considered to be Wing Loading (lbf/ft^2) and Power Loading (lbf/hp). This was applied following Loftin's procedure of fixing the calculations in terms of Wing Loading, and output values of Power Loading for each required design configuration or constraint. The purpose of Solution Space Screening and Visualization is to view the optimal point of performance for the design. In the Solution Space generated from the project, in Figure 9, the Match Point is the optimal configuration of the design in which the Wing Loading of the aircraft will provide the most Power Loading values based on the input parameters.

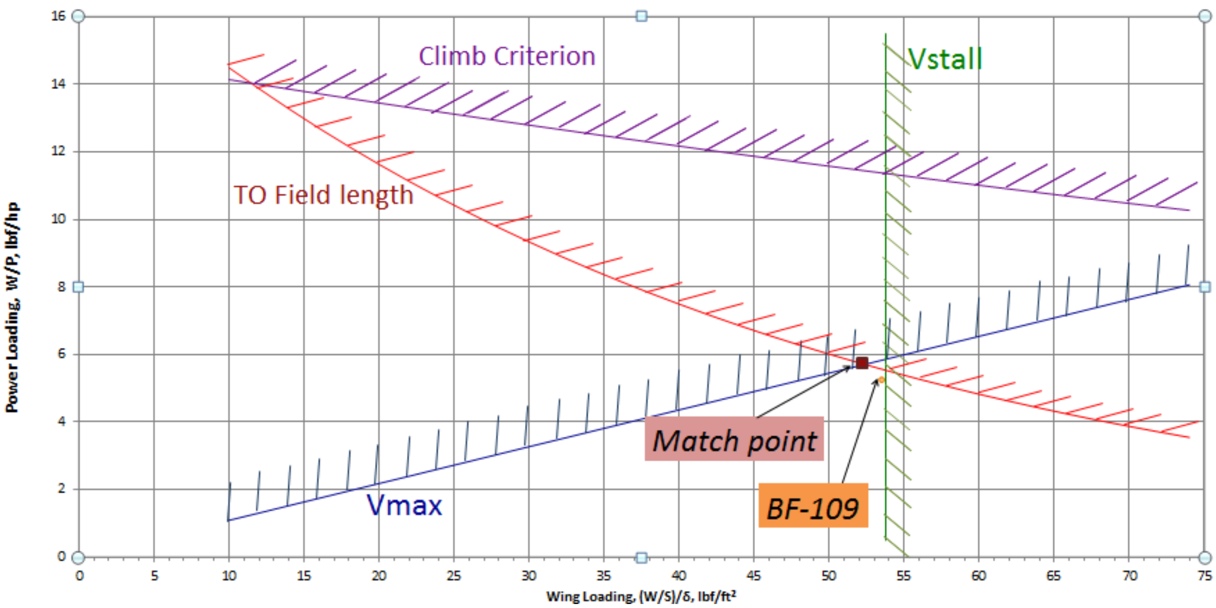


Figure 6. Solution Space Visualizing-The Matching Chart obtained from the AVD project for the Messerschmitt Bf 109 aircraft.

This point is seen at the corner of the Take-off Field Length and the Max Velocity constraints within the solution space. The solution space is recognized in the bottom portion of the graph where no hash markings are present. The point marked as BF-109 corresponds to the actual Wing Loading based on historical values. This is seen to be very near the Match Point approximation. This is considered appropriate for the German World War II fighter since performance is prioritized over the cost, compared to general aviation at the time. Although the design methodology utilized originally for the aircraft at the time is unknown, this parametric analysis concurs the decision to ultimately perform at great high magnitude.

Some of the risks that would be addressed in viewing the Solution Space are costs and safety considerations. Although performance is desired at optimal settings, designing the aircraft to such extent may consequently create safety complications. Such would be an example of risk that is taken by choosing the specific design point in the Solution Space. Although in this project the aircraft was not itself designed from scratch, but rather compared to the original parameters and assessed for the accuracy of the Loftin's sizing techniques, it served as an impressive example and valuable experience of the aircraft design process.

Concluding Remarks

Arriving at a Solution Space becomes the Creation-Level of thinking in Bloom's Taxonomy. It is not until that point in the design process is reached that the aircraft begins to take shape physically and tangibly. The design point is selected from the Solution Space by cautiously evaluating the risk. This has been demonstrated in previous years in all the Capstone Aerospace Vehicle Design courses. It is only with this level of critical thinking that engineering solutions to the relevant problems in the world can be addressed.

In encouraging these levels of thinking at earlier stages in the academic careers of students, the rate of processing information will be more and more effective with the development of these abilities. In the age of information where there is not enough time to fully grasp all available quantities, much less retain it, the individual becomes suppressed by the Remembering and Understanding stages. With correct influence from the educators, the mental capacities will increase in cognitive thinking and follow the stride the international community.

In intense academic competition, a framework is set to define right and wrong. To lose the fear and to think simply without the concern of being right or wrong is something that is lacked in many educational systems today. As demonstrated in the Solution Space with an infinite amount of valid configurations, the Match Point is not necessarily the only possibility or the selected configuration for that matter. The point in the Solution Space is obtained after analysis and evaluation of the selected configuration designs.

The exposure thus far in the Vehicle Design Course has, from personal experience, allowed the teams to become proficient with the process of designing. Even though the chief engineer in the project selects the final point of design, this process requires a full collaborative effort of every individual in the team. With such an effort, arduous feats can be accomplished through the contribution of critical thinkers organized to achieve specific objectives.

References

1. Anderson, Lorin W., and David R. Krathwohl. *A taxonomy for learning, teaching and assessing: A revision of Bloom's Taxonomy of educational objectives: Complete edition* . New York: Longman, 2001.
2. Forehand, Mary. *Bloom's Taxonomy-From emerging prespectives on Learning, Teaching, and Technology.* Atlanta, Georgia: Ther University of Georgia, 2010.
3. Fredriksen, John C. *International Warbirds: An Illustrated Guide to World Military Aircraft, 1914-2000.* Santa Barabara, California: Abc-Clio Inc, 2001.
4. Loftin, Laurence K. *Subsonic Aircraft: Evolution and the Matching of size to Performance.* Hampton, VA: NASA Reference Publication Ed. 1060, 1980.
5. Nicolai, Leland M. *Fundamentesl of Aircraft and Airship Design.* Vol. 1. 2 vols. Reston, VA: American Institute of Aeronautics and Astronautics, 2010.
6. Rickard, J. *Messerschmitt Bf 109E "Emil".* March 26, 2007. http://www.historyofwar.org/articles/weapons_bf_109E.html.

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