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Aerospace Capstone Design: Interactive Initial Sizing Estimates for Increasing Designer Intuition and Mitigating Risk in the Early Stages of Aircraft Conceptual Design

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Abstract

In academia, aircraft design is a unique capstone course(s), measured in one or two semesters. In some cases, aircraft design courses introduce the student to both the design process as well as the complexities associated with designing an object that travels through the air.

In industry, aircraft design is a unique and complex process, measured in years. Success or failure of an aircraft development program is often the result of decisions made in the initial stages of the design process. At these early stages, design knowledge is low and technical risk is high. These factors increase the likelihood of requirements creep, and if not managed properly, can result in significant cost overruns, schedule slips, and cancellation of an aircraft program.

The first analysis step in aircraft design is the initial weight estimate. Initial sizing of an aircraft defines its rough size and weight based upon its intended requirements. At this very early stage of design, there is often no means of directly assessing the impact of creep-type changes in design parameters (e.g., range, payload, etc.) on the size of the aircraft, nor the effects of changing the input parameters themselves. This denies useful information to the students at the beginning stages of a course, educationally beneficial information to increasing student knowledge and intuition, as well as managing or reducing the risk inherent in design.

This paper presents an interactive sizing results using response surface techniques. It is intended to provide parametric information about the design space up-front, including the ability to perform several “what-if” scenarios early in the process. The interactive results presented in this paper provide value to the student and quantifiable information to reduce uncertainty in their design decisions. This method provides important student learning outcomes to the classroom environment.

Introduction

Design is not just the process of creating a system or product that meets certain performance metrics. It must include designing the processes that increase its likelihood of passing through the various stages of a system or product’s life cycle: research, development, test, evaluation, production, fielding, and support. In other words, with design comes risk and uncertainty. The design process must include the means to mitigate risk and offer the designer strategies for decision-making at all stages of the design.

In the context of engineering education, design coursework should encompass both broader topics of the design process that encompass all disciplines, and the specific nuances and challenges pertinent to the discipline of interest, to include risk. The coursework should also increase the student’s comfort and confidence with open-ended design problems, particularly in the student’s decision-making confidence [1].

In aircraft design, the primary variable through the design process is the aircraft weight. In the aircraft design process, risk arises primarily through requirements creep or technology availability. Risk physically manifests itself as either increases in weight (performance-related metrics) or technology requirements (new system development). Both can significantly increase the cost of the system. Evaluating risk requires some type of intuition, coupled with some qualitative or quantitative methods, that aids the designer in making appropriate decisions and increasing their confidence in the design.

This paper focuses on the introduction of an interactive aircraft sizing model to an aircraft design capstone course, which has been introduced over four iterations of an aircraft design capstone course at the authors' institution. It provides the basis of such a solution, gives a cursory overview of the methods used to obtain the results, and provides sample results from the design of two different aircraft. Benefits include

- Visual and, in some cases, interactive output depicting the impact of the variation of the initial input parameters on the resulting weight estimate (size) of the design.
- Visual results to increase student awareness regarding the sensitivities of the aircraft design to these parameters.
- Increased knowledge of the design space much earlier in the design process, leading to streamlined optimization and decision-making, and the ability to discard unacceptable areas of the design space.
- Increased ability to visualize and manage the effects of requirements creep.

These benefits are summarized in the following learning outcomes:

- *Students shall demonstrate an understanding of the risk and uncertainty inherent in the early stages of aircraft conceptual design.*
- *Students shall employ appropriate techniques for increasing knowledge of the design space, visualizing the results, and increasing confidence in their decision-making.*

Background

Aircraft design falls into the category of a large-scale engineering program. These types of programs include aircraft, spacecraft, skyscraper, ship, and power plants [2]. They are characterized by complex systems operating in extreme environments or conditions, where failure results in life-threatening or catastrophic results (e.g., airplane crash, capsized ferry, building collapse, Space Shuttle *Columbia* breakup during re-entry, Northeastern United States power blackout of 2003).

The first analytical step in aircraft design is the initial weight estimate. The initial weight estimate determines the first size estimate of the aircraft and the fuel requirements to achieve a specific mission profile. The required mission performance and payload requirements define the size and fuel consumption of the aircraft, and so it is important to define these requirements clearly.

In many cases, there is not enough information at the beginning of the design to develop a clear, concise set of requirements. Because those requirements can and often do change – an event called "creep" – this uncertainty increases the risk at the beginning of the design process. The inability to manage uncertainty during the initial stages of design can lead to cost overruns, scheduling slips, re-designs, or program cancellation [3]. The ability to add information in the early stages of conceptual design can decrease the risk during the design process and increase the likelihood of success [4].

Creep and uncertainty have affected the development times of major programs since the 1970s [3]. Recent large-scale programs have averaged 14.2 years for systems such as the F-35 Joint Strike Fighter, the F-22 Raptor, and the B-2 Stealth Bomber. This was a major shift from the 5-year average of high-profile programs such as the Saturn V rocket, the intercontinental ballistic missile, and the Manhattan Project (atom bomb). Furthermore, several recent high-profile development programs have been cancelled at extremely high cost, such as the Comanche helicopter ($5.9B), VH-71 Presidential helicopter ($3.3B), and the U.S. Army's Future Combat Systems ($20B). An understanding of risk and decision-making should play a significant role during capstone design so that students develop a solid understanding of their consequences.

Risk can be expressed as a function of uncertainty and knowledge and how they interact. As seen qualitatively in Figure 1, knowledge and risk have an inverse relationship. Uncertainty and risk, on the other hand, have a direct relationship. Risk can be written in the form of Equation 1.

$$Risk = f\left(uncertainty\right) + f\left(knowledge\right) + f\left(uncertainty * knowledge\right) \tag{1}$$

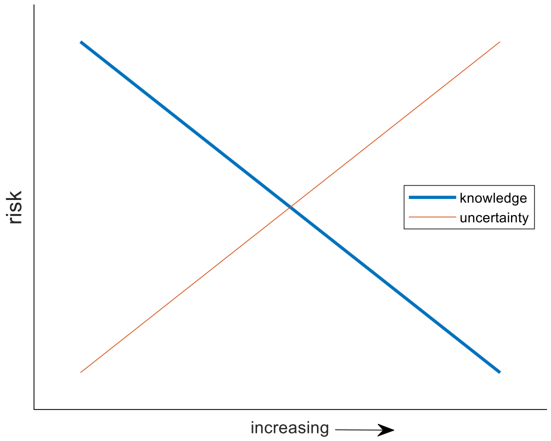

Figure 1: Risk versus knowledge and uncertainty in design

Uncertainty comes in many forms: technical, financial, industrial, legal, environmental, etc. While many steps in the design process can reduce technical uncertainty levels, many non-technical sources remain. We can never effectively eliminate design uncertainty.

Additionally, requirements creep describes the way that "requirements grow imperceptibly during the course of a project" [5]. Creep is not always a bad thing. Some changes must happen due to the evolution of a program, but processes must be in place to manage and minimize their effects [5]–[7]. If not managed effectively, these factors can form a relatively-inflexible open-loop system. Then, there is no adequate means of determining the feasibility of system requirements, which often creates a situation where no one system can meet the threshold of all requirements [3]. As with risk and uncertainty, an awareness of requirements creep should be a significant underpinning of the student design education, especially when the design course results in a tangible object.

An effective method of managing risk is to assess the effects of the variability of performance requirements on the initial sizing estimate of the aircraft, using techniques from optimization and trade-study analysis. In many design paradigms, such analysis does not occur in the conceptual design phase, but later in the preliminary design phase, once the aircraft conceptual layout is set. Aircraft design textbooks [8]–[11], which are fairly linear in their layouts, follow the same pattern, where optimization is discussed in the latter chapters of the text. However, incorporating these techniques in the initial sizing of the aircraft can streamline the process itself, produce clearer results, and at the same time increase the competence and confidence of the design student.

Design is fundamentally a decision-making process, and by its very nature produces uncertainty in the process [12], [13]. This encourages the use of a probabilistic or stochastic approach within the design process [14]. The application of stochastic models to aircraft design has proliferated over the past 20 or so years, becoming an integral technique in the integrated product and process development approach [14].

Aircraft First Weight Estimate Methodology

The gross weight (W_0) of an airplane is the sum of the crew weight (W_{crew}), payload weight ($W_{p/l}$), fuel weight (W_f), and the empty weight (W_e) of the aircraft.

$$W_0 = W_{crew} + W_{p/l} + W_f + W_e \tag{2}$$

Rearranging the equation and substituting yields the fundamental sizing equation in aircraft design.

$$W_0 = \frac{W_{crew} + W_{p/l}}{1 - {W_f}/{W_0} - {W_e}/{W_0}} \tag{3}$$

where

${W_f}/{W_0}$ = fuel weight ratio

${W_e}/{W_0}$ = empty weight ratio

The importance of Equation 3 cannot be overestimated. The initial weight estimate drives everything in the design from the initial sketch, to the sizing or choice of the engine(s); and sizing of the wing, fuel tanks, empennage (tail), landing gear, etc. [8].

The weights of the crew and payload are generally fixed by performance requirements. The empty-weight (W_e/W_0) ratio of the aircraft is determined by the type of aircraft, whether it is a sailplane, home-build, general aviation, twin turboprop, jet trainer, jet transport, cargo or bomber, or unmanned system, etc.

The fuel-weight ratio is a function of the mission profile of the aircraft and directly accounts for parameters such as range, endurance, specific fuel consumption, cruise speed, cruise altitude, and lift-drag ratio. The gross weight estimate is then determined using an iterative process. This general method is a staple of any aircraft design textbook [8]–[11].

Both the empty-weight ratio and fuel-weight ratio rely heavily on estimates of certain parameters. These estimates inject uncertainty into the design, which leads to further questions. What happens to the weight estimate if one or more of these parameters change? The weight estimate would change, but to what extent? Does one parameter influence another parameter? Perhaps it does, perhaps not. The answers are not intuitively obvious, nor can Equations 2 and 3 provide this level of insight. However, by using response surface methods and associated software tools, these questions are answered quite easily, and the parametric relationships become apparent.

Response Surface Methodology

In design, response surface equations are used primarily for optimization schemes. Furthermore, optimization courses are primarily at the graduate level. A response surface model takes the form of the equation

$$RSE = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} \sum_{j=1}^{k} a_{ij} x_i x_j \tag{4}$$

where
RSE = response (output)
a_i = regression coefficients
x_i = input factors (design variables)
$x_i x_j$ = interactions between factors

In Equation 4, the input factors are the design input variables such as range, payload, cruise speed, altitude, aspect ratio, and endurance. The response variable based upon these input parameters is the aircraft gross weight estimate.

The response surface model is a statistical regression of the design space. It is executed primarily using a software tool such as JMP® or Matlab's® Statistics and Machine Learning Toolbox (SMLT), both of which have been used by students. The steps in the methodology are outlined below. In-depth treatments are beyond the scope of this paper, but can be found in References [12]–[15].

1. Define the input variables and a corresponding range of acceptable values for each. Examples follows in Tables 2 and 6.
2. Generate a design of experiments (DOE) to populate a DOE table containing a specified number of iterations, or "runs." These runs contain different combinations of input parameter values, based upon the acceptable ranges in Step 1. These combinations help define the design space. The number of runs is determined by the type of design construction: composite, Box-Behnken, etc.
3. Using the aircraft sizing methodology described by Equations 2 and 3, calculate the weight estimate for each run in Step 2.
4. Determine the response surface equation (RSE) of the aircraft weight estimate as a function of the input parameters, using the results of Steps 2 and 3. The RSE will be in the form of Equation 4.
5. Analyze the model's goodness-of-fit.
6. Generate profile and interaction plots of the model.
7. Use these results to visualize and explore the design space.

Two different types of aircraft designs were considered in demonstrating this method to students. The first is a design textbook example from Raymer [11], which is an anti-submarine warfare (ASW) aircraft. The second design is for a light jet using a very small high-bypass ratio turbofan engine. This design has been used by students in the authors' aircraft design capstone course. This design is designated as light jet capstone (LJC).

Anti-Submarine Warfare Design

The essential design requirements the aircraft must meet are listed in Table 1. Other assumptions required to complete the initial design estimate are listed in Table 2. Table 3 lists the input variable boundaries for the ASW design of experiments in terms of a low value, the nominal value, and a high value. The initial weight estimate of the ASW design using the nominal values is approximately 56,500 lbf.

Table 1: ASW design requirements

Parameter	***Requirement***
Range	3000 nm (2 x 1500 nm)
Endurance	3 hrs
Payload	10,000 lbf
Crew	800 lbf (4 x 200 lbf)
Cruise speed	0.6 Mach

Table 2: ASW design assumptions

Parameter	***Assumption***
Altitude	30,000 ft
Aspect ratio	7.0
S-ratio	5.5

Specific fuel consumption (cruise)	0.5 hr^{-1}
Specific fuel consumption (loiter)	0.4 hr^{-1}
Maximum lift-drag ratio	16

Table 3: ASW input variable boundaries

Parameter	***Low value***	***Nominal value***	***High value***
Range (nm)	2 x 1,250	2 x 1,500	2 x 1,750
Altitude (ft)	28,000	30,000	32,000
Payload (lbf)	8,000	10,000	12,000
Endurance (hrs)	2	3	5
Aspect ratio	6.5	7.0	9
S-ratio	5	5.5	6

Light Jet Capstone Design

The essential design requirements for the second aircraft concept are listed in Table 5, with design assumptions presented in Table 6. Table 7 lists the input variable boundaries for the LJC design, similar to Table 3. The initial weight estimate of this design concept using the nominal values is approximately 10,000 lbf.

Table 4: LJC design requirements

Parameter	***Requirement***
Range	650 nm
Endurance	20 min
Payload	900 lbf
Crew	225 lbf

Table 5: LJC design assumptions

Parameter	***Assumption***
Altitude	18,000 ft
Aspect ratio	8.0
Cruise speed	0.33 Mach
S-ratio	5.0
Specific fuel consumption (cruise)	Function of altitude and thrust
Specific fuel consumption (loiter)	Function of altitude and thrust

Table 6: LJC input variable boundaries

Parameter	***Low value***	***Nominal value***	***High value***
Range (nm)	500	650	1100
Altitude (ft)	17,000	18,000	22,000
Payload (lbf)	450	900	1,125
Endurance (min)	15	20	25
Aspect ratio	7.0	8.0	10
S-ratio	4.0	5.0	6

Figure 2 presents the Matlab® output in the form of a profiler plot. When viewed in the Matlab® environment, this output is interactive. The values of the input parameters are located under each curve. The weight estimate with confidence interval is the number to the left of the curves. As the student types values for the input parameters at the bottom of each plot (e.g., R = 15), the dotted, vertical lines shift, and the weight estimate changes accordingly. The curves in Figure 2 represent the combined effects of the input variables on the weight estimate of the aircraft. Each plot has a solid line, representing the relationship between the input parameter and the weight. The slope of the curve indicates how sensitive the weight is to a change in the parameter. A positive slope indicates a direct relationship. A negative slope indicates an inverse relationship. A slope of zero indicates a neutral relationship. The steepness of the slope represents the degree of sensitivity between the input variable and the aircraft weight estimate. The dotted lines on either side of the main curve are 95% confidence intervals.

The input parameters have different effects depending upon the particular aircraft. For the ASW aircraft, the weight has a strong sensitivity to payload (PL), while for the LJC aircraft, the sensitivity to payload is much less. Observing these profile plots, students can instantaneously determine which parameters are going to have the most influence on the design estimate. These results provide credible, quantitative knowledge for making informed decisions, especially during a course or period in design marked by a lack of information or familiarity with the design process.

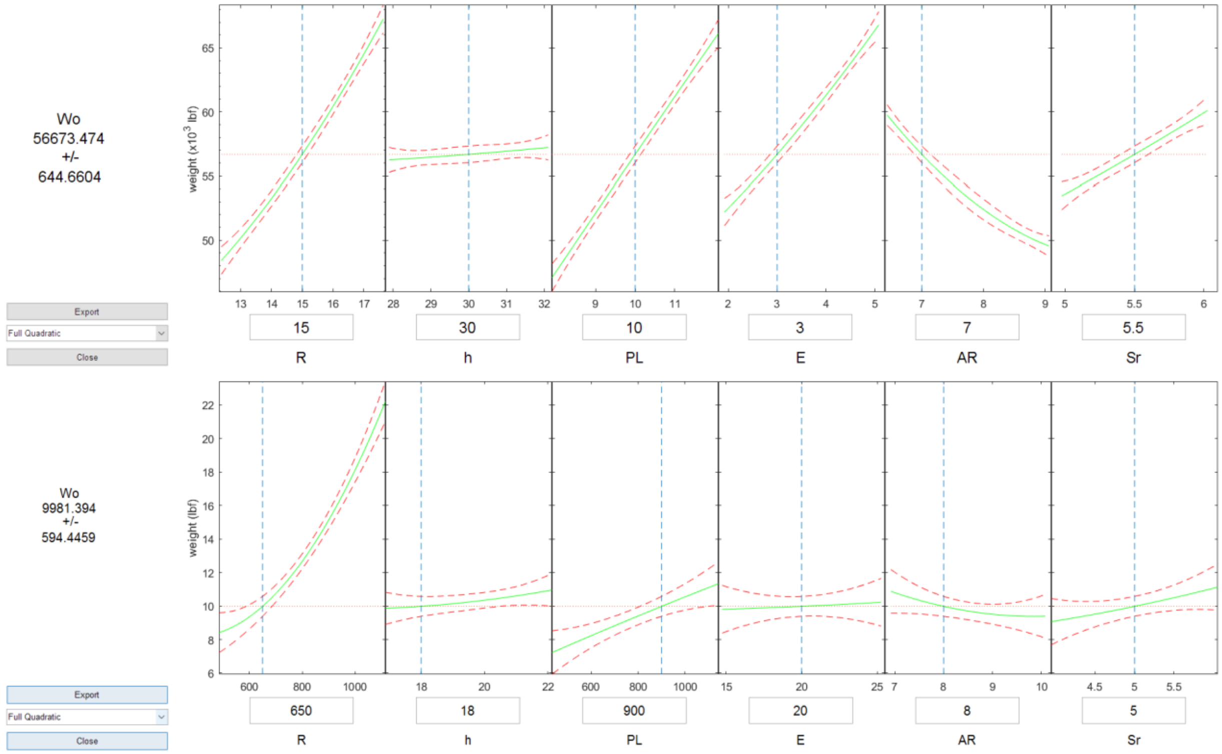

Figure 2: Profiler map for ASW weight estimate (top) and LJC weight estimate (bottom)

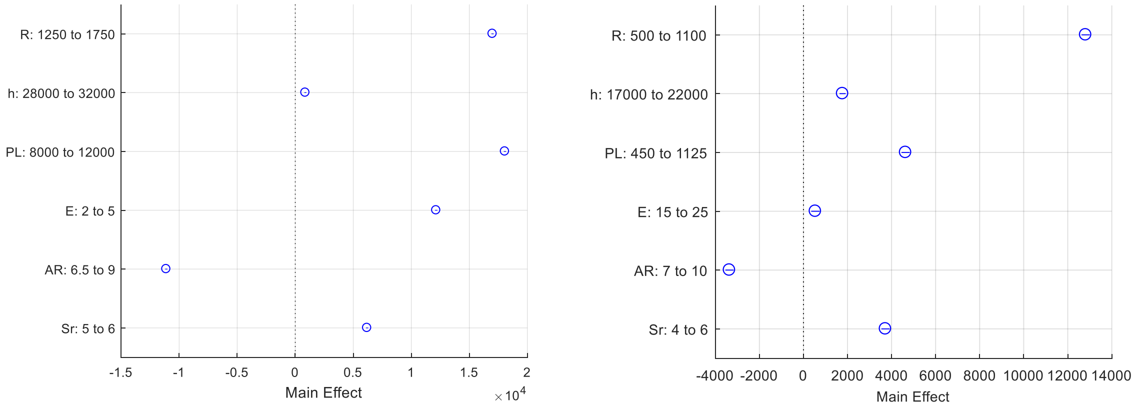

Figure 3: Main effect profiler – ASW weight estimate (left) and LJC weight estimate (right)

Figure 3 displays a main effect profiler, which in the software environment may or may not be interactive. Unlike the profiler plots, these predict the weight estimate change based upon a change in each individual parameter. The effects are different based upon the type of aircraft.

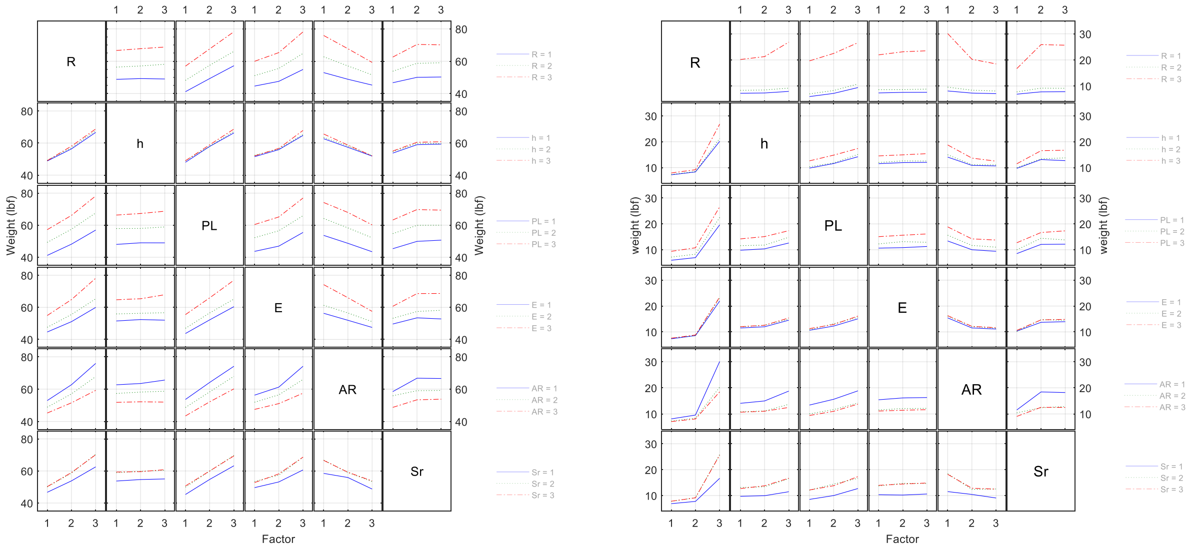

Figure 4: Variable interactions for ASW weight estimate (left) and LJC weight estimate (right)

Figure 4 displays the interactions between two input variables and their combined effects on the aircraft weight estimate. For example, one can compare the effects of range (R) and altitude (h) on the resulting estimate. Each mini-plot contains three curves, representing the three values of an input parameter (e.g., R): low, nominal, high. Each of those three curves is constructed by cycling through the three values of the other input parameter. One can immediately observe that the interactions differ based upon differing parameters settings. For example, a higher value of endurance (E) may have a more pronounced interaction with payload (PL) than a lower value would.

The output provided in Figures 2 through 4 is powerful. Through a very simple methodology, the student has quantitative information to support decision-making at an early stage, and to support early design trade studies. For example, the following might represent the student conclusions:

> "The design requirements call for a range of 1,500 nm. After our initial analysis, we discovered that if we increased the aspect ratio of the aircraft from 7 to 8, we could achieve a maximum range of 1,600 nm with only an approximate 500 lbf weight penalty. This seems like a minimum penalty for achieving 100 additional nautical miles. Therefore, we chose to look at both data points going forward."

Furthermore, these results easily address the natural tendency of a design to creep. Students can ask the questions, "What happens if we want to increase the maximum range by 100 nm? What happens if we double the amount of payload?" Lastly, we can also expand the input parameters to include several others such as specific fuel consumption and maximum cruise airspeed.

Revisiting the student learning outcomes presented earlier:

- *Students shall demonstrate an understanding of the risk and uncertainty inherent in the early stages of aircraft conceptual design.*

  > This method forces students to set initial boundaries for the input parameters. These parameters yield sensitivities. Students use those results to determine which parameters have the highest consequences in weight estimate, and whether the boundary values themselves are feasible.

- *Students shall employ appropriate techniques for increasing knowledge of the design space, visualizing the results, and increasing confidence in their decision-making.*

  > This method provides students with stochastic, quantitative results to populate the design space. These results provide information to validate early decisions. The method is easily correctable when assumed parameter values change. The method is iterative and becomes more precise as the design matures and as more information becomes known.

Conclusions

Applications of response surface methodologies to the analysis of aircraft initial weight estimates have been presented. Two sample design scenarios, a mid-size anti-submarine warfare aircraft and light jet capstone aircraft, were analyzed.

From this work, the authors reach the following conclusions:

- The methodology for visualizing aircraft initial sizing provided important information beyond deterministic results.

- The results showed the influence of each variable to the overall weight estimate. The influence of the variables changed depending upon the type of aircraft.
- The results depicted the interactions of the input variables with each other and how changing one input variable changed another variable's influence on the overall weight estimate.
- The interactive profiler tools provided a decision-making aid when input parameters must change.
- The interactive profiler tools provided a means to address and mitigate risk in capstone work.
- The stochastic method provided information and insight, not available using conventional deterministic methods in aircraft design.
- The method is easily achievable within the times constraints of an academic course.

Through this type of exposure in an academic environment, students gain the "enduring understanding" [16] of the dangers and importance of identifying and managing risk, uncertainty, and requirements creep to the design of large-scale programs.

As mentioned previously, this method has been an introductory topic in recent iterations of the authors' design course. To date, it has been a selective assignment for students who have requested extra-curricular research. These students have provided positive feedback, but no formal assessment has been conducted. Nevertheless, it is a planned lesson block in an upcoming two-course capstone sequence with first offering in 2019.

Symbology

AR	aspect ratio
E	endurance
PL	payload weight
R	range
RSE	response surface equation
Sr	S-ratio; ratio of wetted area to planform area
W_{crew}	crew weight
W_e	aircraft empty weight
W_f	aircraft fuel weight
W_o	aircraft gross weight
W_{pl}	payload weight
a	response surface equation coefficient
h	altitude
x	input variable

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