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Interactive Analysis and Visualization of Parametric Design Spaces for Conceptual Aircraft Design

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Abstract

The aerospace industry is increasingly reliant on conceptual design spaces to evaluate and explore early-stage aircraft designs, including both new concepts and improvements on existing models. However, the high dimensionality and complexity of these design spaces present significant challenges in fully exploring potential design alternatives. Traditional methods often fail to fully leverage combinatorial design spaces and lack sufficient visualization tools, making it difficult to understand how design decisions impact performance and limiting the effectiveness of the conceptual design process. This research aims to address these challenges by developing an interactive analysis and visualization tool for aircraft conceptual design. Key objectives include (1) employing combinatorial methods, such as Latin Hypercube sampling, to create a design space that captures interactions between design variables, (2) developing efficient algorithms for design space exploration, (3) incorporating uncertainty quantification and reliability simulations for design effectiveness assessment, and (4) facilitating design decision-making through enhanced visualization tools. The research utilizes the SUAVE aircraft design tool to analyze each design generated within the Latin Hypercube-based design space. Initial progress includes the creation of an interactive application that integrates SUAVE for design evaluation and comparison through robust analysis.

The purpose of this research is to develop an interactive tool that enhances the exploration, analysis, and visualization of complex aircraft conceptual design spaces, enabling more effective design decision-making in early-stage aerospace concepts.

Methods

Objective (1) was completed through the exploration of MDO (Multidisciplinary Design and Optimization) tools, ultimately settling on the method of Latin Hypercube sampling for design space creation. Latin Hypercube is able to evenly and efficiently explore every corner of the design space without bias, and works most effectively for conceptual designs where the desired outputs are often undefined and require a broad, balanced exploration of possibilities.

Objective (2) was completed through the incorporation of the SUAVE aircraft design tool developed at Stanford University, which is a powerful analysis tool for exploring the specific design of aircraft attributes. Through SUAVE, we can perform detailed analyses on the various design configurations.

Objectives (3) and (4) are continuously being explored as the application is developed, with some functionality already being created. Each aircraft design is run through the SUAVE analysis and compared for robustness against each other design, for which comparison plots such as CDFs (Cumulative Distribution Functions) can be created to analyze the overall design performance.

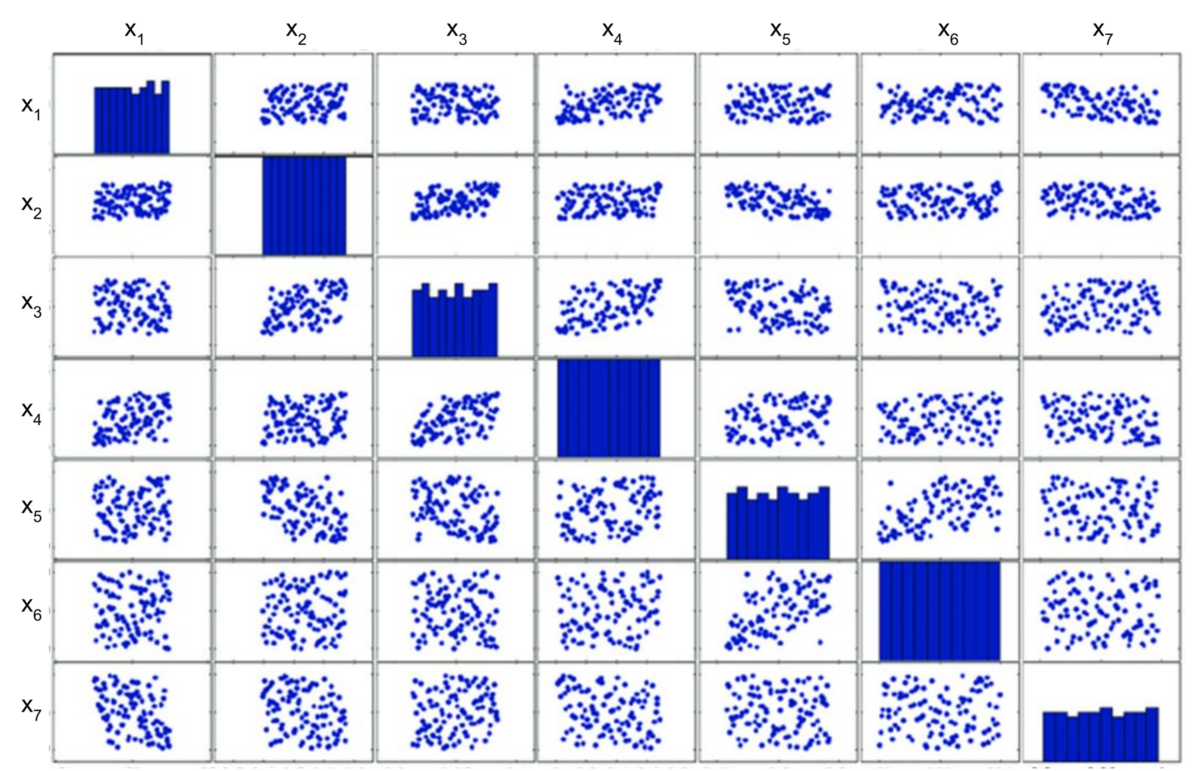


Figure 1. Visualization of the Latin Hypercube method. Each column and row represents a separate variable range to be sampled, defining a full design space without overlap.

Image Credit: Mohanty, Sankhya & Hattel, Jesper. (2014). Numerical Model based Reliability Estimation of Selective Laser Melting Process. Physics Procedia. 56. 379–389. 10.1016/j.phpro.2014.08.135.

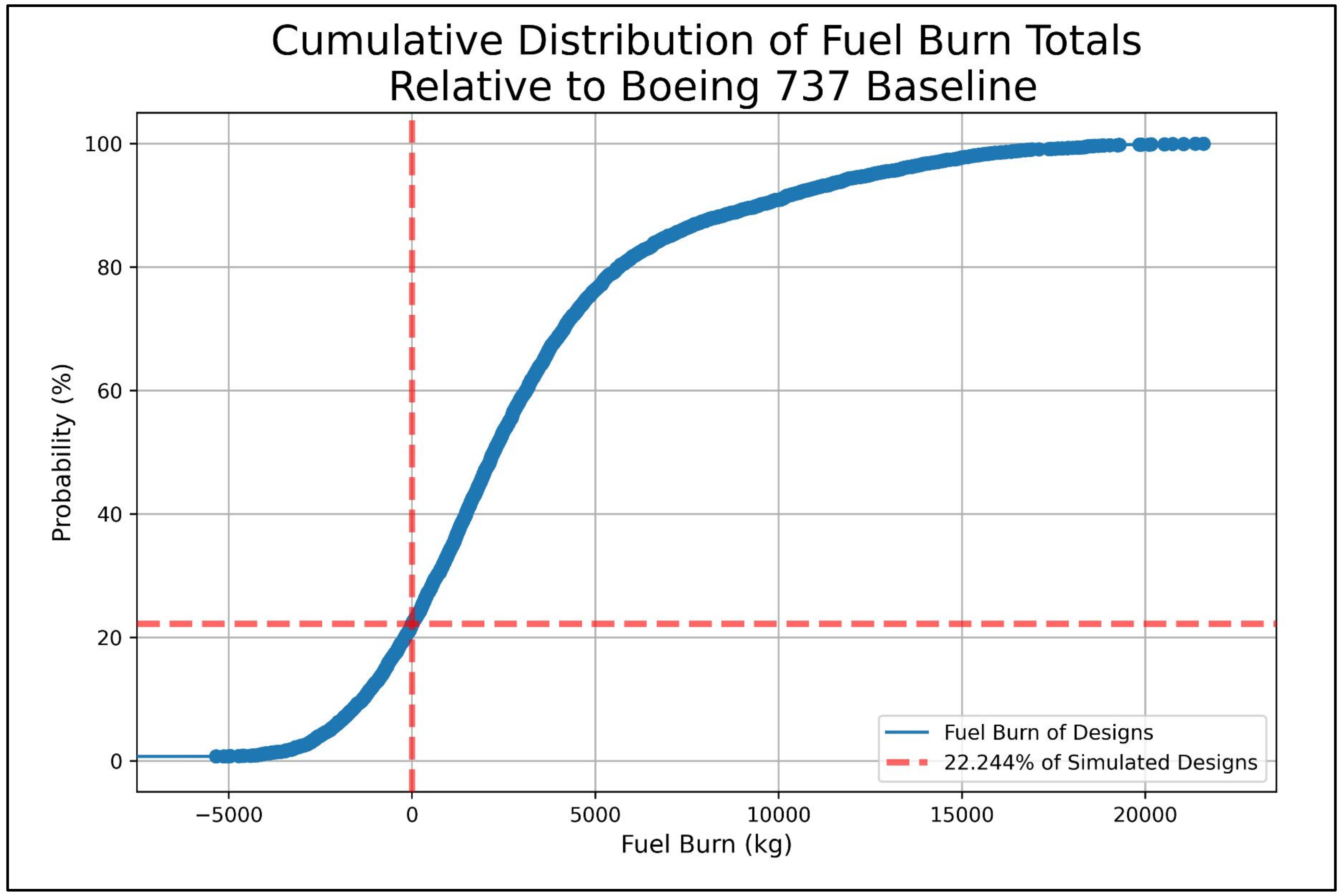


Figure 2. This analysis shows the final results of a Fuel Burn analysis using SUAVE. Just over 22% of the 5,000 designs generated within the design space demonstrate more efficient fuel consumption than the current Boeing 737. This dataset can be used to analyze design conditions that may inform modifications to the current design.

Results

An interactive conceptual design tool has been developed to create a design space which works in conjunction with SUAVE for in-depth analysis. Aircraft concepts are generated in a design space governed by Latin Hypercube sampling to ensure diverse configurations, and run through SUAVE to produce accurate results for a variety of output conditions. Each generated aircraft concept undergoes rigorous analysis, yielding a range of performance metrics.

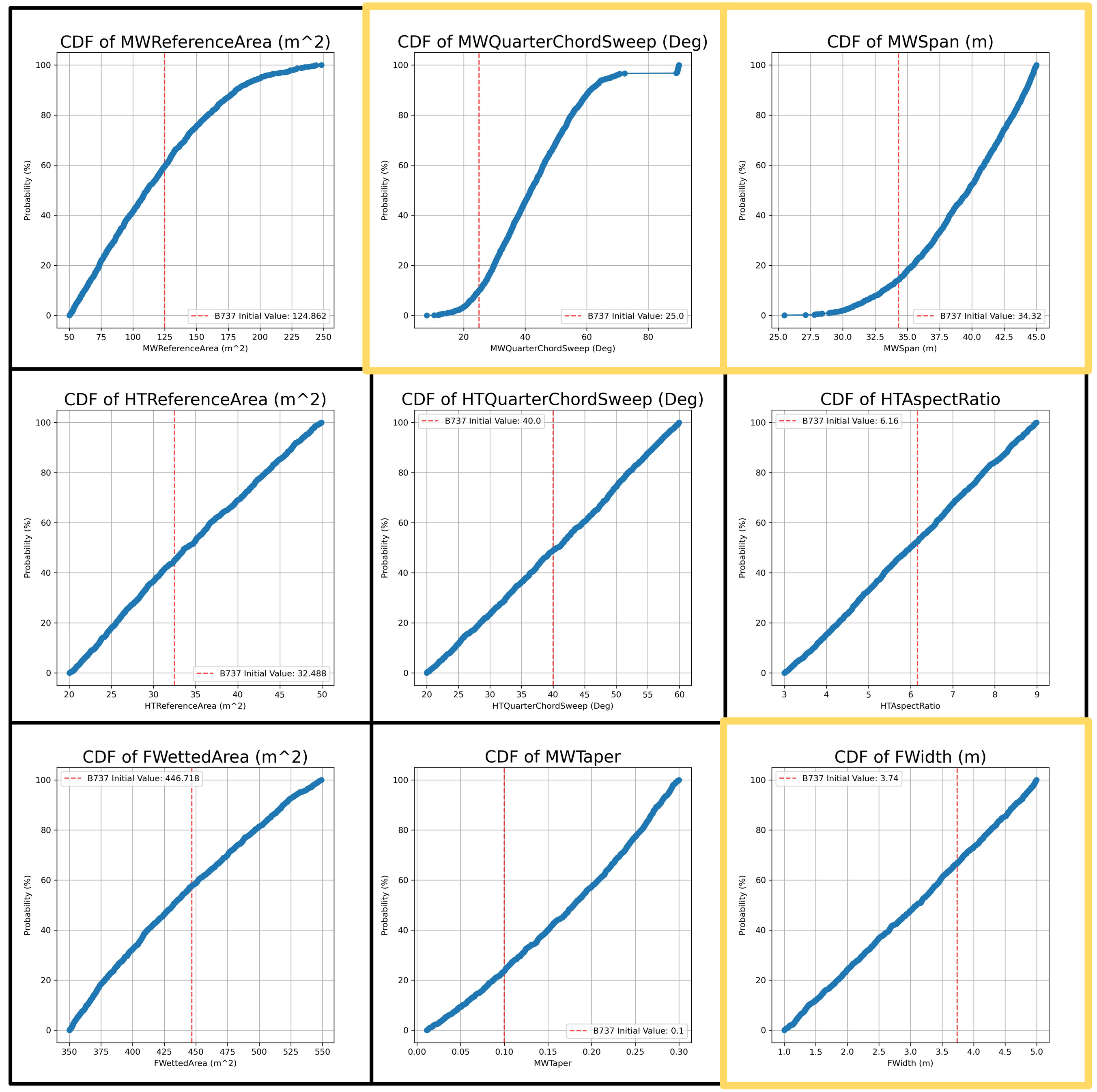
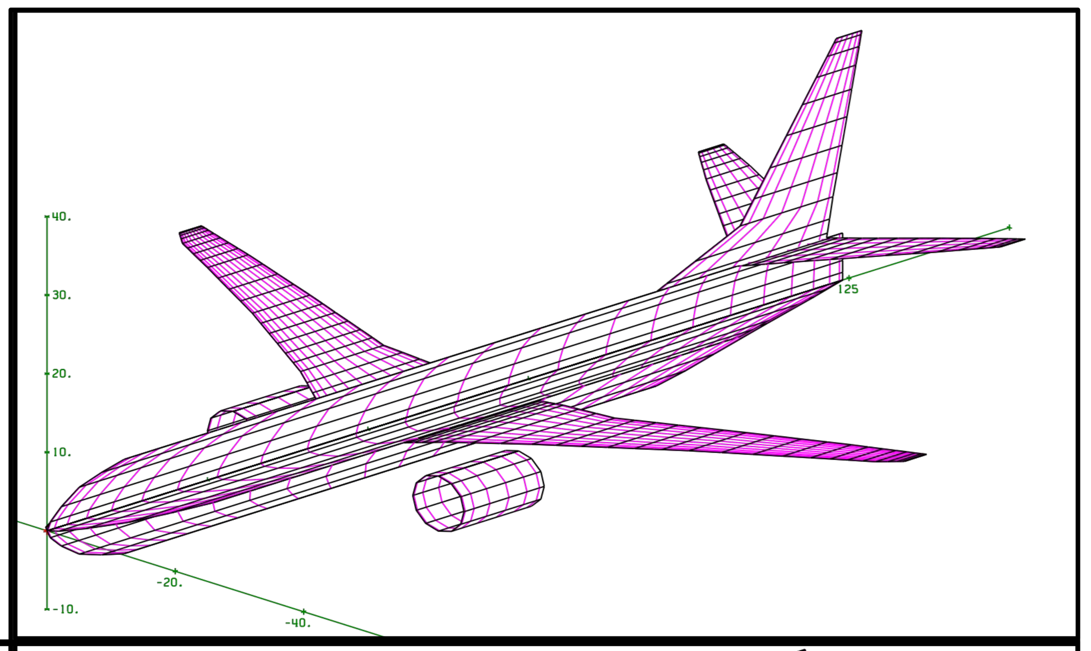


Figure 3. These nine plots display a set of variables from the fuel analysis in Figure 2, with three highlighted as promising for future design improvements. Each point represents a design condition that reduced Boeing 737 fuel consumption. This approach can be applied to optimize many more aircraft components.

The current Main Wing Quarter Chord Sweep and Span are at the lower end of efficient designs, suggesting that increasing their angle or length could improve fuel efficiency.

In contrast, the Fuselage Width is at the higher end, indicating a reduction in width may also enhance fuel efficiency. However, changes to fuselage width may be limited by other factors, like passenger capacit



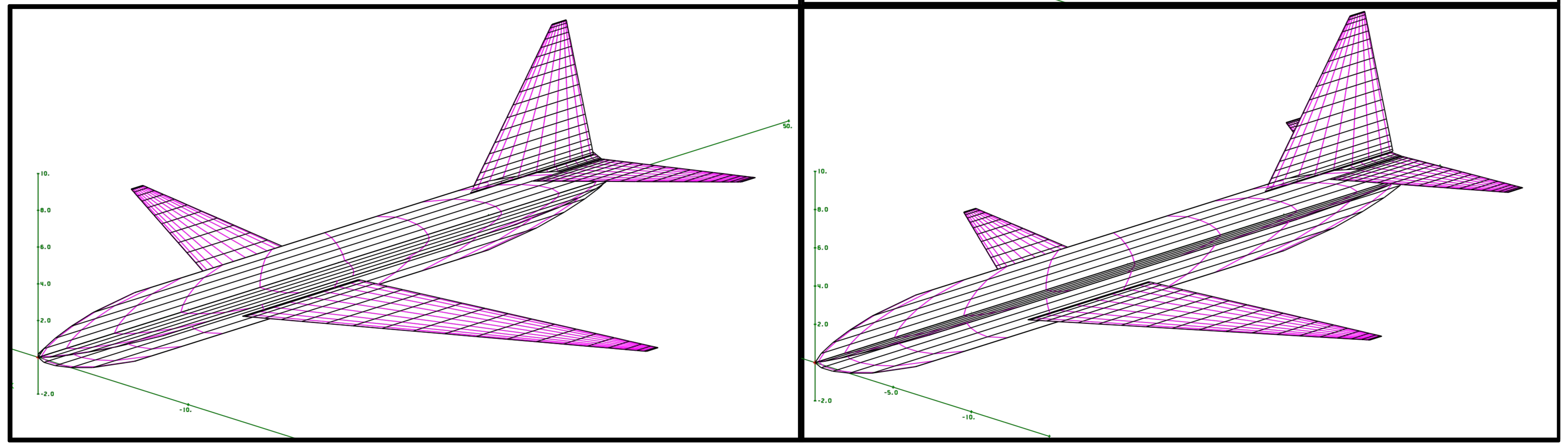


Figure 4. This figure presents three designs generated from the interactive interface: the baseline SUAVE Boeing 737 (left), a fuel-efficient 'good' design (right), and the standard AVL Boeing 737 (top). The AVL plots demonstrate how future visualization tools could be integrated within the application. As additional visualization capabilities are developed, complete plots for each design will facilitate clearer comparisons of performance and key design features.

Future Work

- Add Visualization functionality through AVL (Athena Vortex Lattice) which is a powerful tool for both visualization of the aircraft and aerodynamic analysis.
- Add more analysis variables, as the only current output calculates a design's fuel consumption.
- Add more design variables.
- Improve decision making tools, including the ability to highlight the most impactful variables or rerun a new design space to produce more optimal designs.

SUAVE
An Aerospace Vehicle Environment for Designing Future Aircraft

This research was conducted in conjunction with SUAVE, an open source platform for aircraft conceptual design