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AIRCADIA – AN INTERACTIVE TOOL FOR THE COMPOSITION AND EXPLORATION OF AIRCRAFT COMPUTATIONAL STUDIES AT EARLY DESIGN STAGE

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Abstract

Presented in this paper is a novel framework and associated prototype tool (AirCADia) for interactive composition and exploration of innovative aircraft design studies. The tool incorporates a number of novel methods (enablers) that facilitate the Set Based Design (SBD) paradigm. In contrast to a point based design which is practiced currently, SBD advocates for the composition and exploration of wider design spaces which are gradually reduced by options down selection, aiming to converge on a final design solution. The effectiveness of the AirCADia enablers with regard to SBD is demonstrated with a representative example of aircraft concept design where a tradeoff between environmental impact (Noise and Nitrogen Oxide Emissions) and performance efficiency (Block Fuel, Maximum Takeoff Weight, and Takeoff Field Length) is investigated.

1 Introduction

The world is undergoing unprecedented economic, geo-political, and (apparently) man-made climatic changes, which require a substantial improvement not only in the cost effectiveness but also in the environmental impact of most transport modes, including aircraft. Addressing this formidable challenge necessitates significant advancements in the research and development of new, possibly radically different aircraft configurations allowing the integration of further novel technologies such as novel means for propulsion. These in turn require novel design methods and tools enabling the synthesis and exploration of wide and evolving design spaces, rather than focusing on the design and optimisation of fixed design points.

One approach which advocates the exploration of wider design spaces is the Set Based Design (SBD) paradigm. In SBD, the initial wider design space is progressively narrowed down through the gradual elimination of infeasible/inferior solutions. This is intended to help the designers make better informed decisions and be more innovative in their solutions.

Although the SBD paradigm is seen as a promising approach to complex product design, currently there is a lack of supporting tools. Within this context the objective of this paper is to present a number of novel methods (enablers) for design space exploration integrated in a prototype tool named AirCADia.

The rest of the paper is structured as follows. Section 2 briefly describes the novel methods (enablers) for design space exploration. The effectiveness of these enablers is illustrated in Section 3 with the help of a relatively simple, but still a representative example of aircraft concept design where the tradeoff between environmental impact (Noise and Nitrogen Oxide Emissions) and performance efficiency (Block Fuel, Maximum Takeoff Weight, and Takeoff Field Length) is investigated. Finally conclusions are drawn and future work is outlined in Section 4.

2 Brief Descriptions of Enablers for SBD

This section briefly describes key enablers implemented in AirCADia which can assist designers to utilize the SBD principles effectively. These include:

- Dynamic (automatic) Reconfiguration of Computational Workflows. This method allows the interactive and where appropriate, automatic (re)formulation of computational design studies. For example, as part of the design exploration one or more design variables may need to be converted into constraints (or objectives), which in turn requires the "behind the scenes" reconfiguration of the computational workflow. In realistic design studies these workflows can include hundreds of (low order) computational models and thousands of variables.
- Design of Experiment, Filtering and Design Optimisation. At early design stage these enablers are focused predominantly on the identification and exploration of multiple promising concepts that satisfy a precise set of functional requirements and often conflicting objectives. AirCADia provides various sampling methods (e.g. Monte Carlo, Full Factorial, Latin Hypercube) which can quickly generate large data sets by executing the above mentioned dynamically-configured workflows composed of low-fidelity models. The tool allows solutions to be filtered according to feasibility and (Pareto) optimality criteria.
- Design Robustness. This feature of the tool allows robust multi-objective optimisation with probabilistic satisfaction of constraints.
- Feasibility Analysis. This enabler is an implementation of a generalized iso-contour method which allows the decision maker to gaining insight into the topology of the feasible region(s) within the design space. For example, the designer is able to visualize the active constraints of a study and identify the ones that prevent him/her from obtaining the largest feasible space possible, and consequently, from gaining the full benefits of the design concept.
- Rapid Aircraft Geometry Synthesis. This enabler was developed specifically for aircraft design. It is based on the Class-Shape function Transformation (CST) method developed by Kulfan [1] and allows the rapid synthesis of component-based parametric aircraft geometries. These allow the investigation and analysis of novel aircraft configurations at early conceptual design stage.
- Interactive Visualisation. AirCADia provides an interactive visualization environment (AirCADia Vision) for rapid exploration of the hundreds and thousands of potential design solutions, while giving the freedom to modify on the fly both the design points and the constraints. AirCADia Vision comprises a number of interactive plots (e.g. scatter plots, parallel coordinates plot, surface plots, etc.) which can be synchronised together so that a change in a design point in one plot will be reflected simultaneously across all the other plots of the AirCADia Vision window.

A more extensive description of these enablers can be found in [2].

3 Application Test Case

Demonstrated in this section are the AirCADia SBD enablers via an illustrative example of aircraft conceptual design (feasibility study) where a tradeoff between environmental impact (e.g. Noise and Nitrogen Oxide Emissions) and performance efficiency (e.g. Block Fuel, Maximum Takeoff Weight, and Takeoff Field Length) is investigated. The subject of the study is a conventional narrow-body (single-aisle), low-wing aircraft with twin turbofan engines. The mission considered for the test case is the 3000 nautical miles (nmi) range with 150 passengers in a two-class (138 economy class + 12 business class) seating arrangement.

The Flight Optimization System (FLOPS) developed by McCullers at NASA [3] has been used in the current research. In its original state FLOPS is a complex monolithic multidisciplinary aircraft sizing and optimization tool (applicable mainly to conceptual and preliminary design stage). The original monolithic code has been converted from FORTRAN into a library of 176 models in a C# environment. This library consists of 7 parts (disciplines), including: structure and weights, aerodynamics, mission analysis, detailed take-off and landing, and performance. Fig. 1 shows the complexity of the default FLOPS workflow created automatically by AirCADIA upon selection of the constituent models.

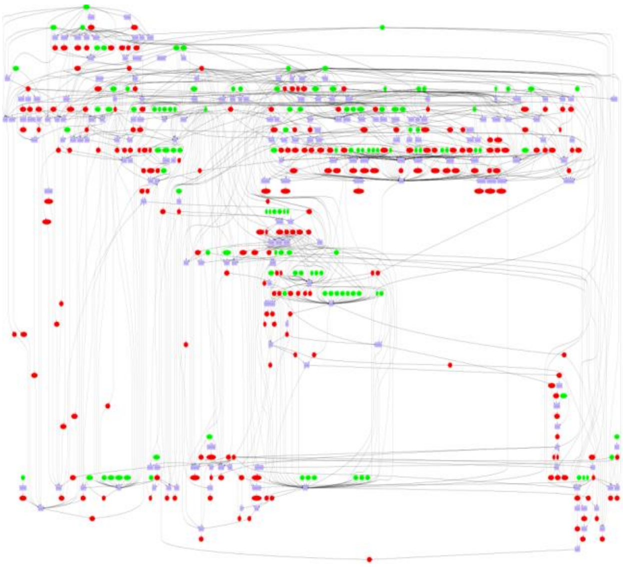

Fig. 1 Default workflow for FLOPS comprising 176 models (represented by rectangles) and 325 variables (represented by ovals)

For the sake of simplicity, the design parameters, wing reference area, wing span, and wing sweep angle are chosen to create the set of wings. Similarly, engine sea-level static thrust and engine bypass ratio are the design parameters considered for creating set of engines.

A full factorial deign of experiment method is employed for the creation of sets of wings and engines. Table 1 and Table 2 show the initial ranges of the design parameters along with discrete levels of full factorial design of experiment. The discrete levels result in a set of 125 (5x5x5) wings and a set of 20 (4x5) engines. The combination of wings and engines results in a set of total 2500 aircraft design solutions, which will be reduced gradually by eliminating the infeasible/inferior design solutions.

It ought to be mentioned at this stage that the initial ranges of the design (decision) variables are usually specified from previous experience and wealth of domain knowledge. However, in the case of lack of knowledge, the boundaries of the design space are often set arbitrarily and therefore other exploration means need to be applied for a more precise definition [4].

Table 3 and Table 4 show the list of assumed Figures of Merits (FOM) that are considered for narrowing-down/reducing the sets. In the first iteration of set reduction these constraints will be imposed to eliminate infeasible design solutions.

Table 1 Initial ranges and discrete levels of wing design parameters

Parameter Name	Unit	Range	Discrete Levels
Wing Area	sq. ft.	[1400.0 – 1800.0]	{1400, 1500, 1600, 1700, 1800}
Wing Span	ft.	[105.0 – 125.0]	{105.0, 110.0, 115.0, 120.0, 125.0}
Wing Sweep Angle	deg.	[23.0 – 27.0]	{23.0, 24.0, 25.0, 26.0, 27.0}

Table 2 Initial ranges and discrete levels of engine design parameters

Parameter Name	Unit	Range	Discrete Levels
Sea-Level Static Thrust	lb.	[28000 - 31000]	{28000.0, 29000.0, 30000.0, 31000.0}
Bypass Ratio		[5.0 – 7.0]	{5.0, 5.5, 6.0, 6.5, 7.0}

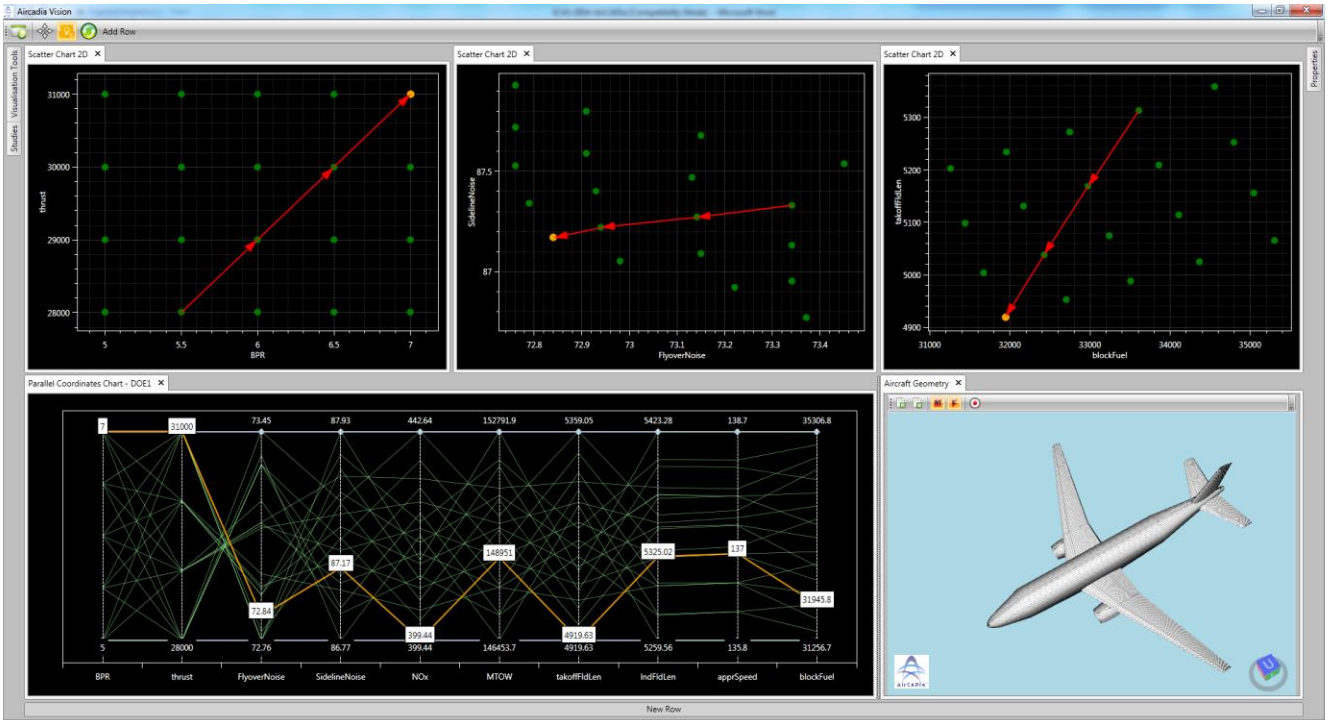

Fig. 2 AirCADia Vision - Interactive design space exploration environment (engines design space and the figures of merit space)

Table 3 Environmental impact figures of merit

Figures of Merit (FOM)	Units	Initial Values
Max. Flyover Noise	dB	73
Max. Sideline Noise	dB	87.5
Max. Nitrogen Oxide Emissions	lb	425

Table 4 Performance efficiency figures of merit

Figures of Merit (FOM)	Units	Initial Values
Max. Takeoff Weight	lb	150000
Max. Takeoff Field Length	ft	5200
Max. Block Fuel	lb	34000

The following two sections illustrate the reduction process of the engine design space (set of bypass ratio and sea-level static thrust) and wings design space (wing area, wing span, and wing sweep angle) through feasibility analysis.

3.1 Engine Design Space

As mentioned before, two parameters, bypass ratio and sea-level static thrust, are considered for creation of the engines. Fig. 2 shows a number of different plots in the AirCADia Vision. These plots enable the designers to map the design space to the Figures of Merit (FOM) space. The left plot in the top row shows the design space (bypass ratio and sea-level static thrust). The other two plots in the top part of the figure show the FOM spaces (flyover noise vs. sideline noise in the middle plot and block fuel vs. takeoff field length in the right plot). The left plot in the bottom row shows the multidimensional view of the design space and the figures of merit space together in a parallel coordinates plot. The 3D view in the bottom row shows the parametric geometry of the point selected in any of the other plots. [As mentioned above the parametric geometry can serve as a link to a higher fidelity analysis]

By clicking on different points in the sampled design space (the sequence of which is displayed by arrows in the direction of movement) the designer is able to see the same sequence but in the Figures of Merit (FOM) space.

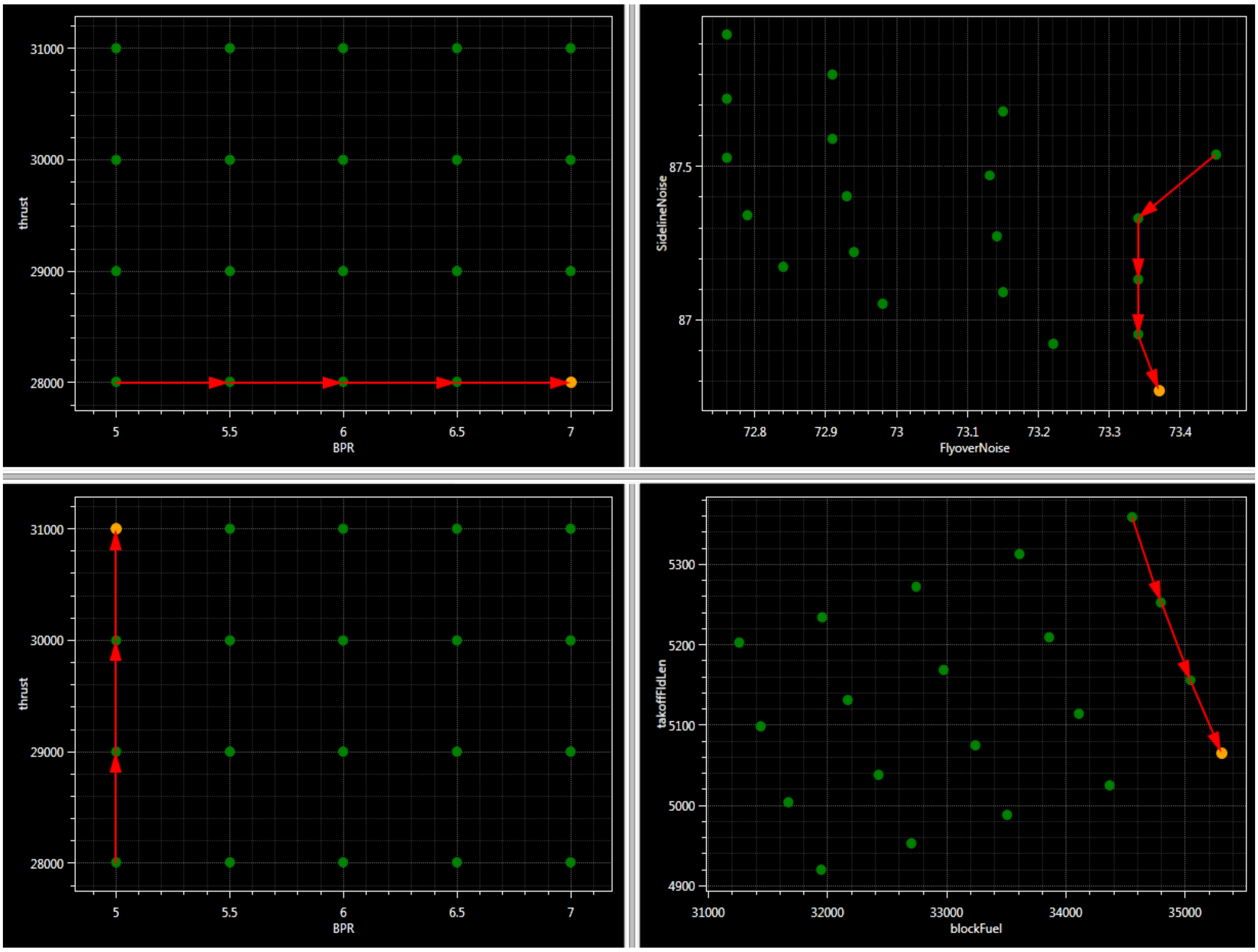

Fig. 3 Variation of nitrogen oxides emissions and specific fuel consumption with respect to sea-level static thrust

Fig. 3 exhibits an enlarged version of Fig. 2, where the left plots show the design space and the right plots show the figures of merit space. The top row shows the effect of increasing bypass ratio on flyover noise and sideline noise; in this case increasing bypass ratio (while keeping the sea-level static thrust constant) reduces sideline noise. Whereas, the bottom row shows the effect of increasing sea-level static thrust on block fuel and takeoff field length; in this case increasing sea-level static thrust (while keeping the bypass ratio constant) increases block fuel but reduces takeoff field length. The availability of these interactive features enables the designer to understand the design space and subsequently to make better decisions.

The next stage of the exploration requires a closer inspection of the design space through the constriction and exploration of 2D projections of the engines design space, in this case, bypass ratio and sea-level static thrust, and by imposing the constraints shown in Table 3 and Table 4.

The entire design space of many dimensions is impossible to visualize graphically, therefore 2D projections (slices) of the multidimensional design space can be used to gain insight into the topology of the feasible design space. Two of the possible slices with design parameters wing span and wing area are shown in Fig. 4 for the values of sea-level static thrust equal to 26000 lb and 28000 lb, where the contour values for maximum take-off weight and nitrogen oxides emissions are 166000 lb and 650 lb respectively. AirCADia Vision enables the designers to visualise different slices by changing the values of the design parameters through sliders, as shown in Fig. 5 where the value of sea-level static thrust is changed to get the different contours and feasible regions.

By using the concept of 2D projections (slices), Fig. 6 and Fig. 7 show the reduction process of the engines design space (bypass ratio and sea-level static thrust) with respect to environmental impact constraints (flyover noise, sideline noise and nitrogen oxides emissions) and performance efficiency constraints (maximum takeoff weight, takeoff field length and block fuel) listed in Table 3 and Table 4. The red bars in Fig. 6 and Fig. 7 show the new (reduced) sets/ranges of the bypass ratio and sea-level static thrust by imposing constraints. It should be noted that Fig. 6 and Fig. 7 show a particular 2D projection (slices) of the engines design space. These projections are the most constrictive with respect to the constraints shown by contours. AirCADia Vision allows the designers to "move from slice to slice" the by changing the values of the other design parameters through sliders. This will result in different contours and hence different feasible regions.

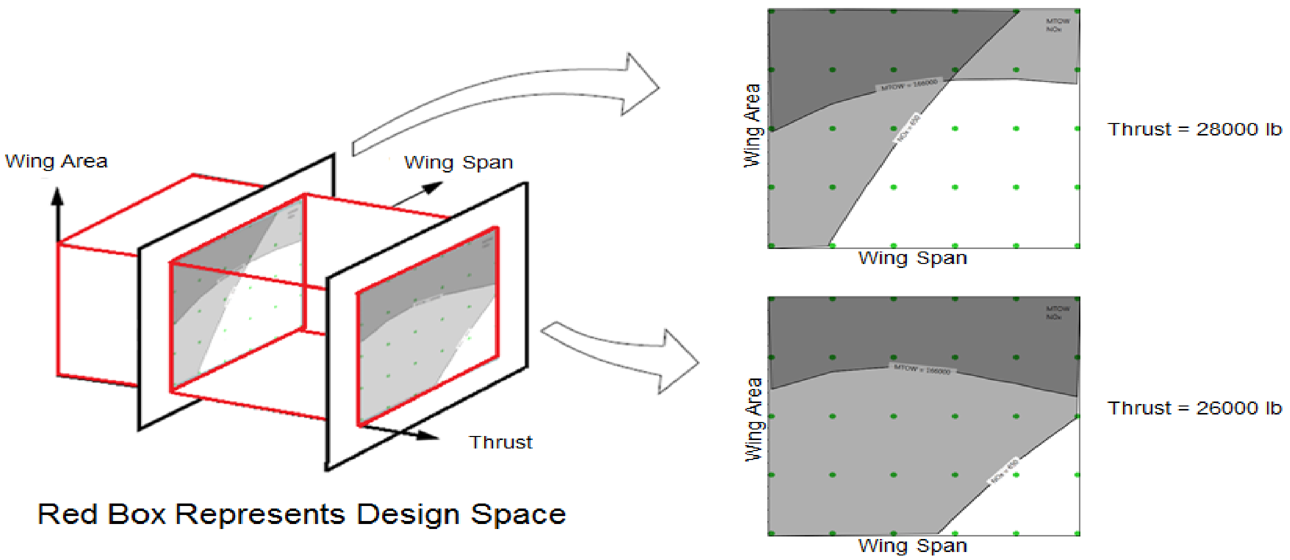

Fig. 4 2D projections (slices) of a multidimensional design space

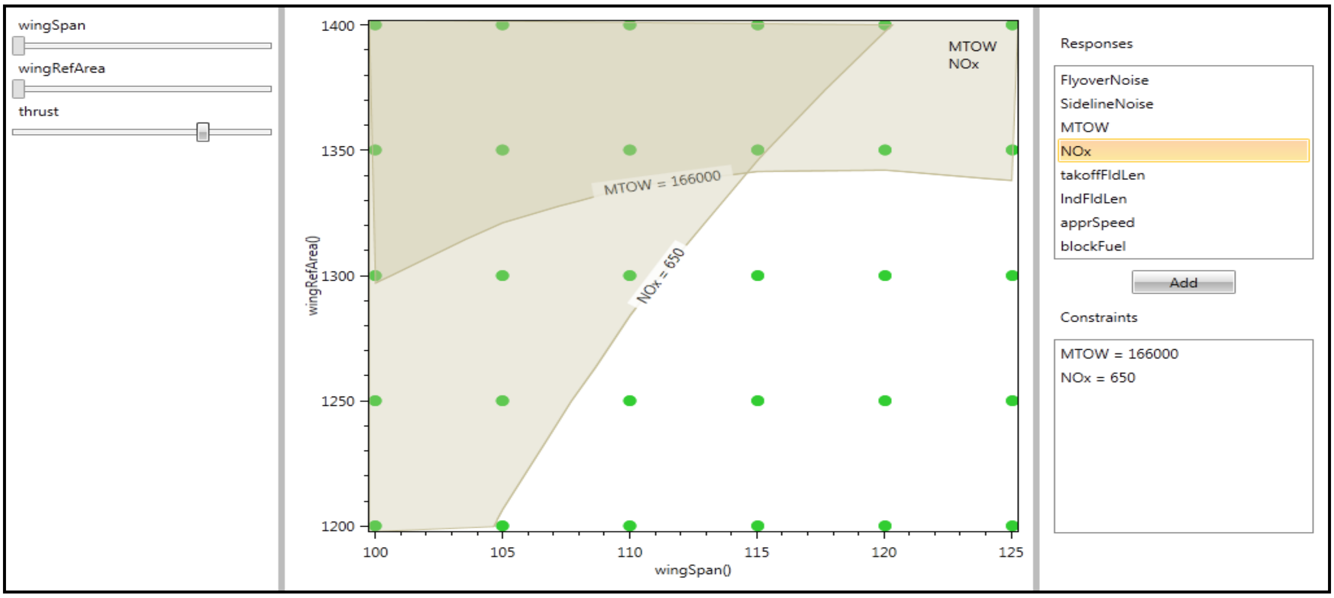

Fig. 5 Interactive exploration of different slices by changing design parameter values (Thrust) through sliders

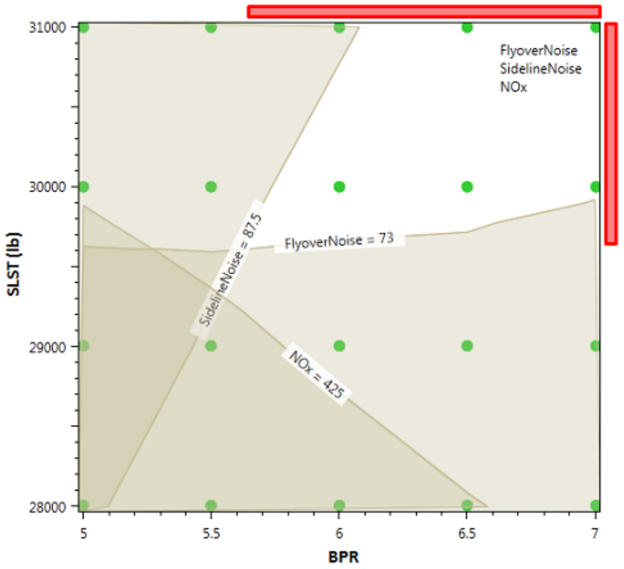

Fig. 6 Set (design space) reduction for bypass ratio and sea-level static thrust with respect to environmental impact constraints

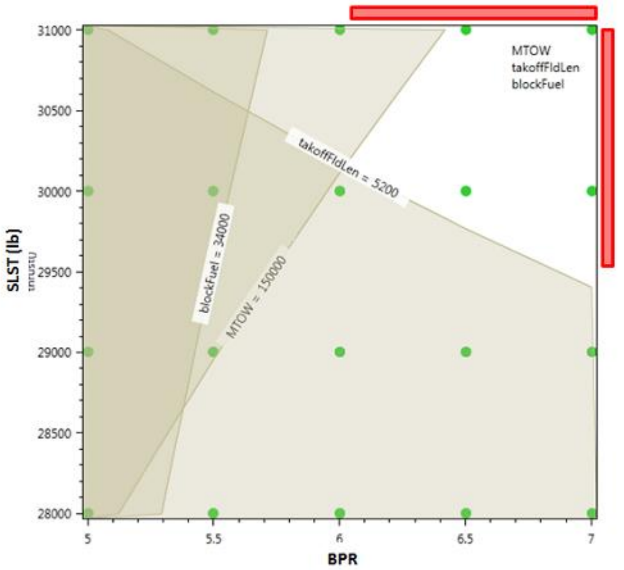

Fig. 7 Set (design space) reduction for bypass ratio and sea-level static thrust with respect to performance efficiency constraints

Fig. 8 shows the set intersection process of the engines design space with respect to environmental impact constraints and performance efficiency constraints. The red bars show the reduced sets of bypass ratio and sea-level static thrust obtained from Fig. 6 and Fig. 7, whereas blue bars show the reduced sets for bypass ratio and sea-level static thrust after intersecting the respective sets between environmental impact and performance efficiency. The set for bypass ratio is now reduced to [6.15 – 7.0], whereas the set for sea-level static thrust is now reduced to [29600 – 31000].

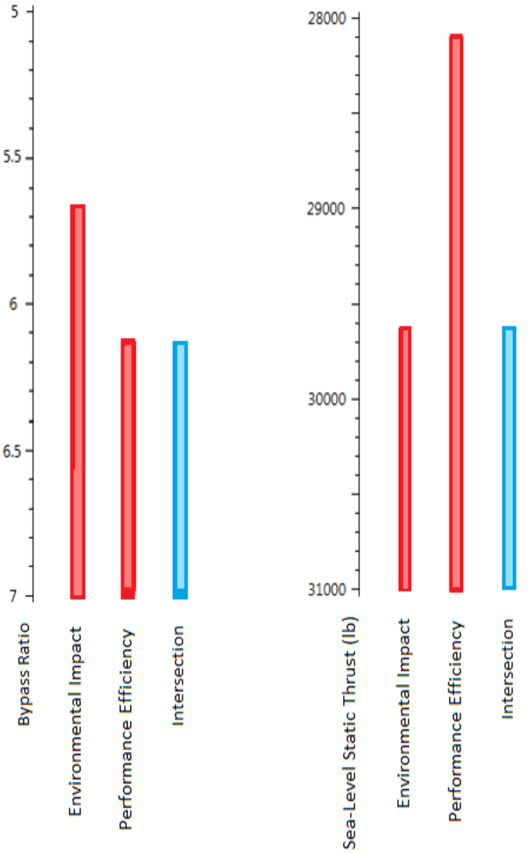

Fig. 8 Set (design space) intersection for bypass ratio and sea-level static thrust between environment impact and performance efficiency

After the intersection process for engines design space, the original set of 20 engines is now reduced to 4 (corresponding to higher values for both bypass ratio and sea-level static thrust). Table 5 lists the specifications of the reduced set of four engines.

Table 5 Reduced set of four engines

	BPR	SLST (lb)
Engine 1	6.5	30000
Engine 2	7.0	30000
Engine 3	6.5	31000
Engine 4	7.0	31000

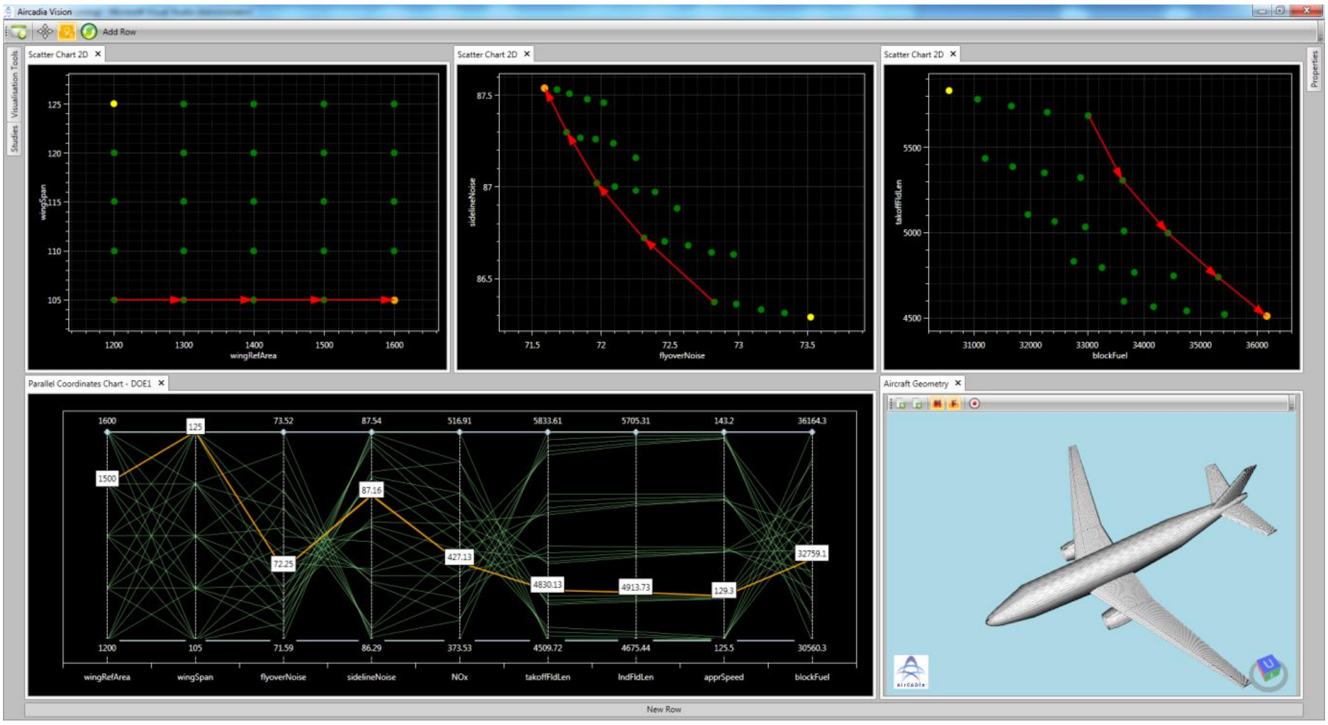

Fig. 9 AirCADia Vision - Interactive design space exploration environment (design space and the figures of merit space for wings)

3.2 Wing Design Space

Three parameters, wing area, wing span, and wing sweep angle, are considered for the creation of wings. Fig. 9 shows the wings design space and figures of merit spaces in a number of different plots in AirCADia Vision. As discussed above, these are synchronised together so that a change in a design point in one plot will be reflected simultaneously across all the other plots of the AirCADia Vision.

The initial design exploration in this particular example revealed that the figures of merit were almost insensitive to the sweep angle variation in that range, as illustrated in Fig. 10 and Fig. 11. Fig. 10 shows the 2D projection of wing design space (wing area and wing span) with contours for noise and block fuel at minimum value of wing sweep angle, i.e. 23.0 degrees. Fig. 11 shows the 2D projection of same design space but at maximum value of wing sweep angle, i.e. 27.0 degrees. The variation to figures of merit contours is almost negligible. AirCADia Vision allows the designers to change the slices through the sliders, as shown on the left of Fig. 10 and Fig. 11. This results in screening out of the wing sweep angle, i.e. reducing the dimensionality of the wings design space.

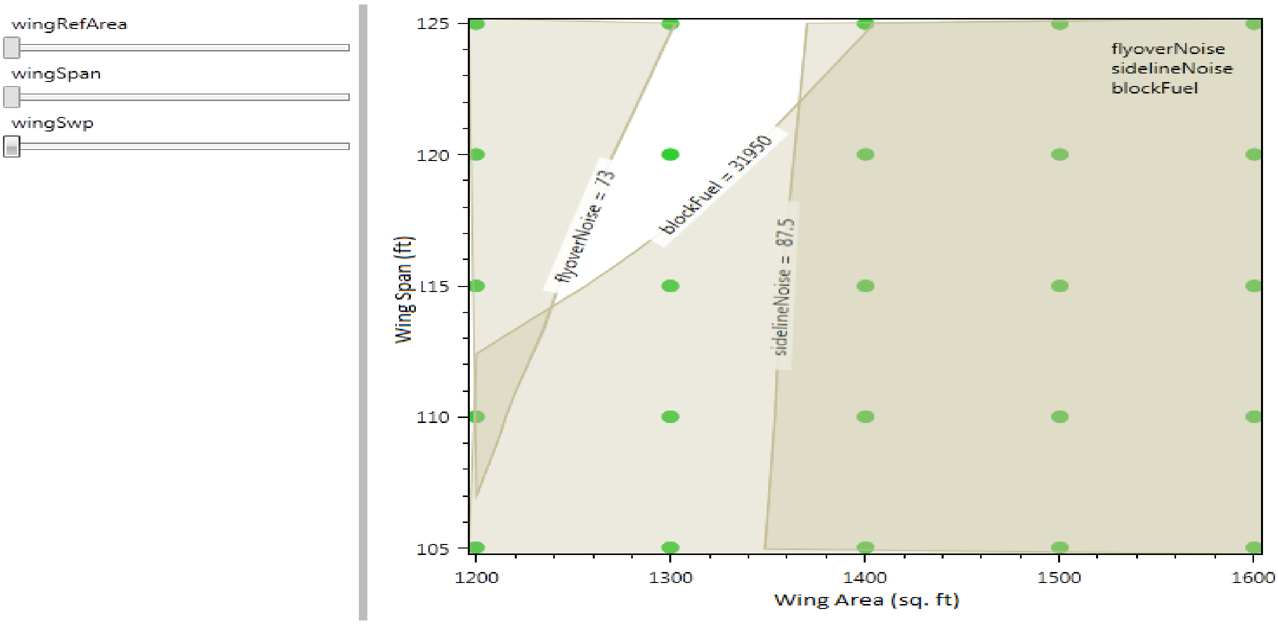

Fig. 10 Figures of merit (noise and block fuel) for slice where wing sweep = 23.0 deg

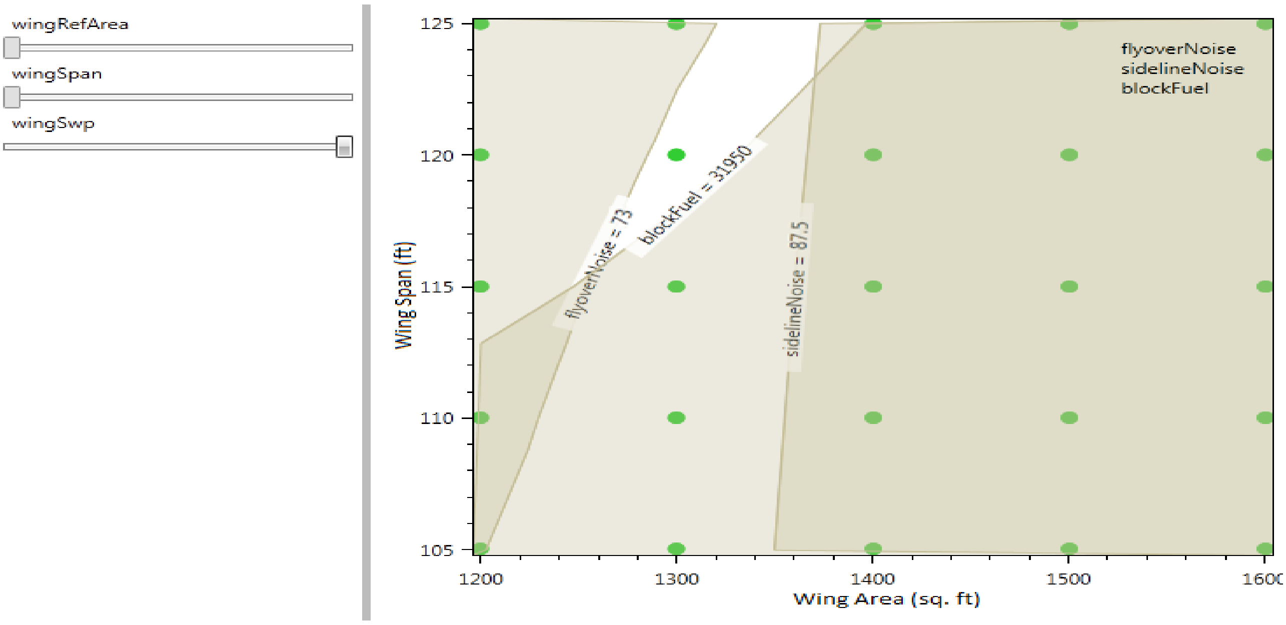

Fig. 11 Figures of merit (noise and block fuel) for slice where wing sweep = 27.0 deg

Similar to the engines design space reduction process described above, a closer inspection requires the constriction and exploration of the 2D projections of the wings design space (wing area and wing span) by imposing the constraints shown in Table 3 and Table 4 which enables the designers to narrow-down the initial set of wings.

Fig. 12 and Fig. 13 illustrate the reduction process of the wings design space (wing area and wing span) with respect to environmental impact constraints (Flyover Noise, Sideline Noise and Nitrogen Oxides Emissions) and performance efficiency constraints (Maximum Takeoff Weight, Takeoff Field Length and Block Fuel) listed in Table 3 and Table 4. The red bars show the new (reduced) sets/ranges (interval) of the wing area and wing span by imposing constraints.

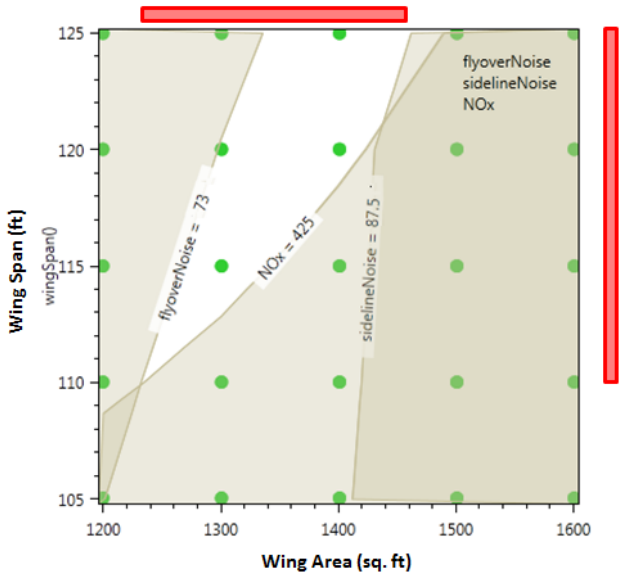

Fig. 12 Set reduction for wing area and wing span with respect to environmental impact constraints

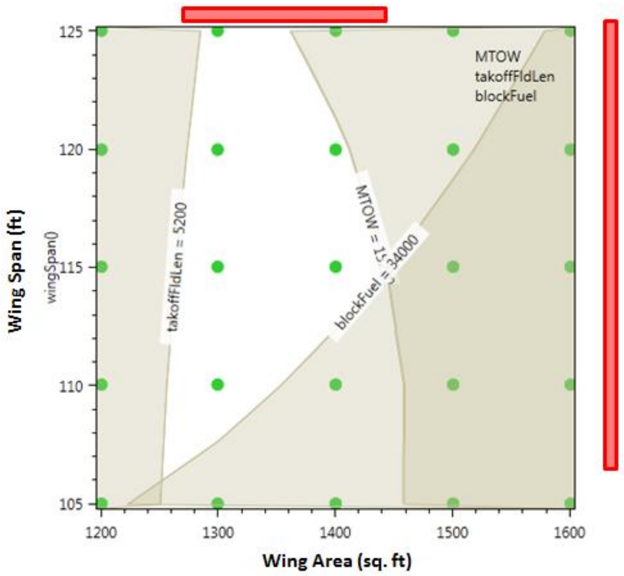

Fig. 13 Set reduction for wing area and wing span with respect to performance efficiency constraints

Fig. 14 shows the set intersection process of wings design space with respect to environmental impact constraints (Flyover Noise, Sideline Noise and Nitrogen Oxides Emissions) and performance efficiency constraints (Maximum Takeoff Weight, Takeoff Field Length and Block Fuel). The red bars show the reduced sets of wing area and wing span obtained from Fig. 12 and Fig. 13, whereas blue bars show the reduced set for wing area and wing span after intersecting the respective sets between environmental impact and performance efficiency. The set for wing area is now reduced to [1300 - 1400] sq. ft., whereas the set for wing span is now reduced to [110 - 120] ft.

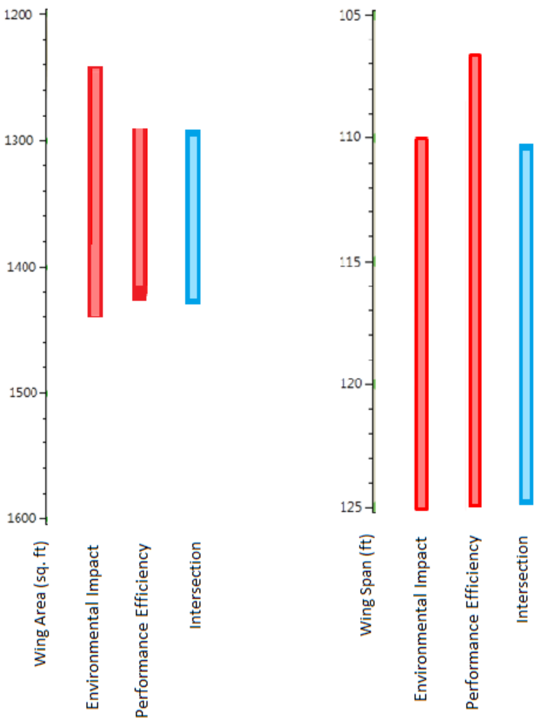

Fig. 14 Set intersection for wing area and wing span between environment impact and performance efficiency

After the intersection process concerning the wings design space, the original set of 25 wings is now reduced to 8 wings. Table 6 lists the specifications of the reduced set of eight wings.

Table 6 Reduced set of eight wings after intersection

	Wing Area (sq.ft)	Wing Span (ft)
Wing 1	1300	110
Wing 2	1400	110
Wing 3	1300	115
Wing 4	1400	115
Wing 5	1300	120
Wing 6	1400	120
Wing 7	1300	125
Wing 8	1400	125

3.3 Subsequent Iterations

The first iteration reduced the set of wings from 25 wings to 8 wings and the set of engines from 20 engines to 4 engines, resulting in 32 (8x4) aircraft designs. After the first iteration of removing infeasible region of the design space, the next step would be to further reduce the design space, either by progressively introducing more design constraints, progressively tightening the existing constraints or by filtering out non-dominated design solutions.

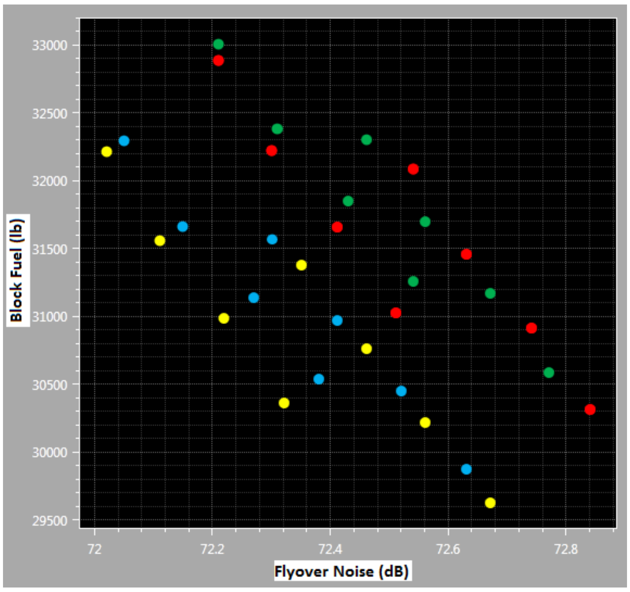

Fig. 15 Set of wings with different engines

Fig. 15 shows the reduced set of 32 aircraft (eight wings combined with four engines) on a FOM space (Flyover Noise vs. Block Fuel). The red design points show the reduced set of eight wings combined with Engine 1 in Table 5 (bypass ratio = 6.5 and sea-level static thrust = 30000 lb). Similarly, the yellow design points correspond to Engine 2, the green design points correspond to Engine 3, and the blue design points correspond to Engine 4 (see Table 5 for respective engine specifications). Fig. 15 illustrates that the yellow and blue design points (with engines of highest bypass ratio value, i.e. 7.0) outperform the red and green design points, which results in further reduction of aircraft set to 16 solutions (set of eight wings combined with Engine 2 and Engine 4).

Another important fact revealed by Fig. 15 is that Engine 2 and Engine 4 (yellow and blue design points) result in almost similar values for flyover noise and block fuel for the set of eight wings, enabling designers to choose one or the other. However, this may not be the case in other FOM spaces, as illustrated in Fig. 16 where the FOM space is constructed from maximum takeoff weight versus takeoff field length.

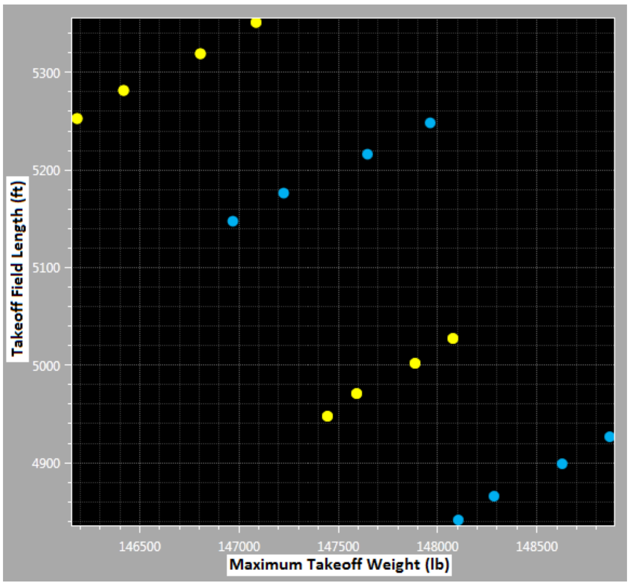

Fig. 16 Set of eight Wings (with Engine 2 and Engine 4)

Furthermore, factors such as the "-ilities" (e.g. manufacturability, maintainability, etc.) which are hard to model quantitatively at early design stage require the designers' experience in order to assess and further reduce the remaining options. Thus after the second iteration, the designers may use their domain knowledge to further reduce the set of 16 remaining design solutions.

4 Summary and Conclusion

Presented in this paper is a novel framework and associated prototype tool (AirCADia) for interactive composition and exploration of innovative aircraft design studies.

The novelty of this work arises from the integration and implementation of advanced enablers for Set-Based Design in a single design framework allowing the designers to

interactively explore and refine a multidimensional design space without the need for knowledge of computer science methods and/or lower level computer programing. In a wider context this work contributes to the composition and numerical solving of complex networks of low-fidelity models and the introduction of higher fidelity analysis earlier in the design lifecycle, thus allowing the investigation of novel configurations.
Current efforts are concentrated on extending the capabilities of AirCADia to enable the synthesis/sizing of aircraft systems earlier in the architectural design process, including integration with physics-based models developed with the Modelica [5] programming language.

Acknowledgements

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