Environmentally Focused Aircraft:
Regional Aircraft Study

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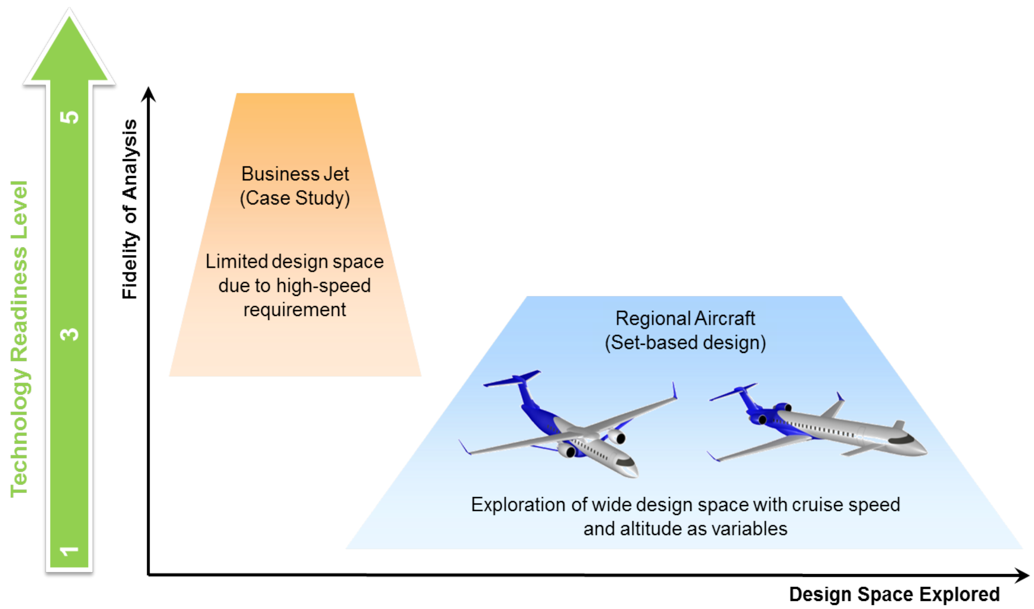
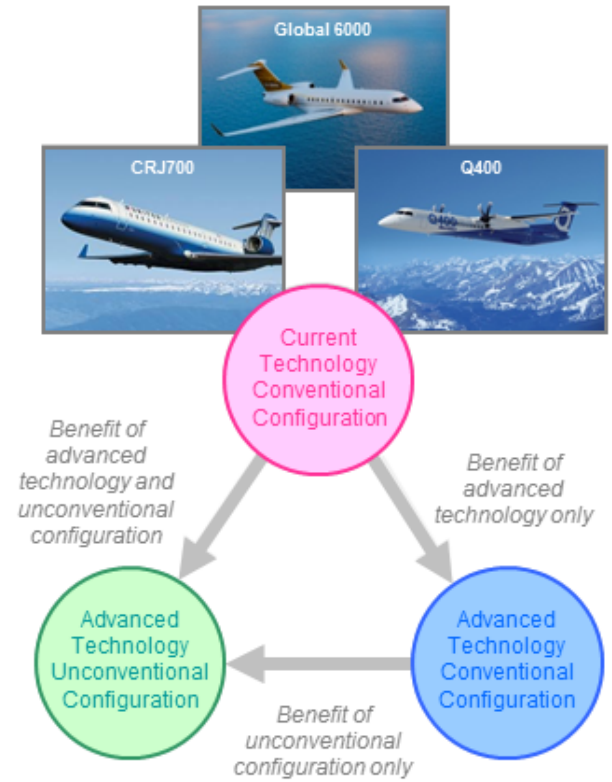
Environmentally Focused Aircraft Study

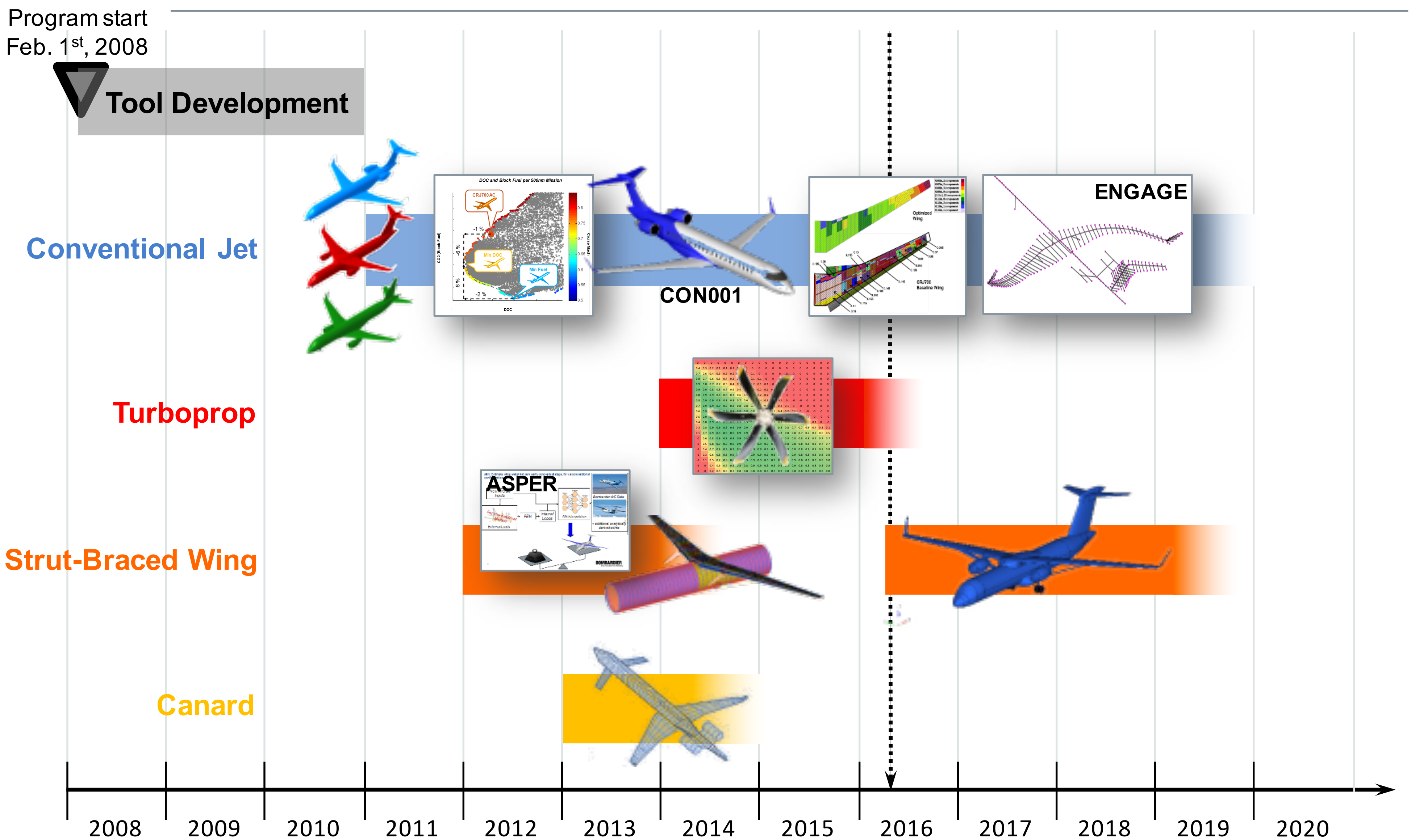
- **Environmentally Focused Aircraft (EFA) study objective:**
  - Significantly reduce environmental impact (emissions, local air quality and community noise) by evaluating alternative long-range business jet and regional aircraft configurations
- **Technology assumption:**
  - Consistent with EIS 2025-2030
- **Aircraft requirements:**
  - Based on existing Bombardier products





EIS Entry-Into-Service

Regional Aircraft – Configuration Evolution



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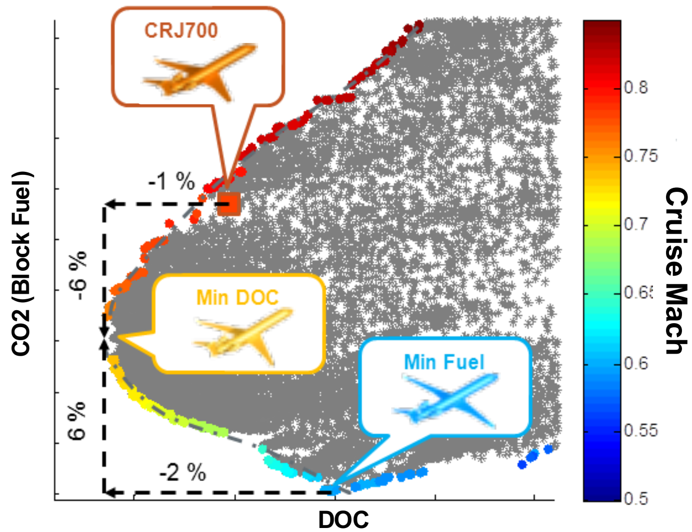
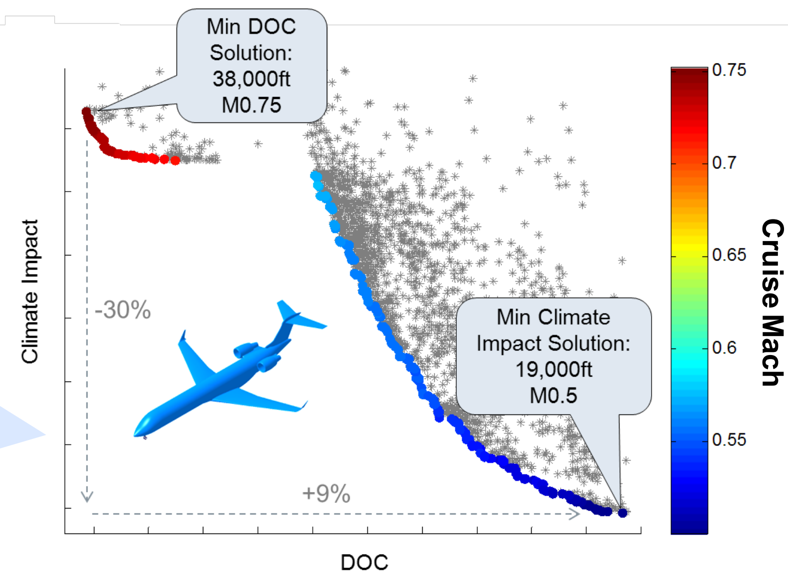
Design-Space Exploration



- Combined aircraft and mission profile optimization, cruise Mach and altitude are design variables
- Fuel burn can be reduced by lowering cruise Mach
- Optimum Mach for minimum DOC is dependent on fuel price and other economic assumptions
- Can identify robust cruise Mach for future scenarios

- Climate impact represents temperature change from all emissions, not just CO_2
- Minimizing climate impact is achieved by reducing cruise altitude to prevent contrail generation and limit NOx effects
- DOC increases due to higher fuel burn and increased block time



DOC Direct Operating Cost

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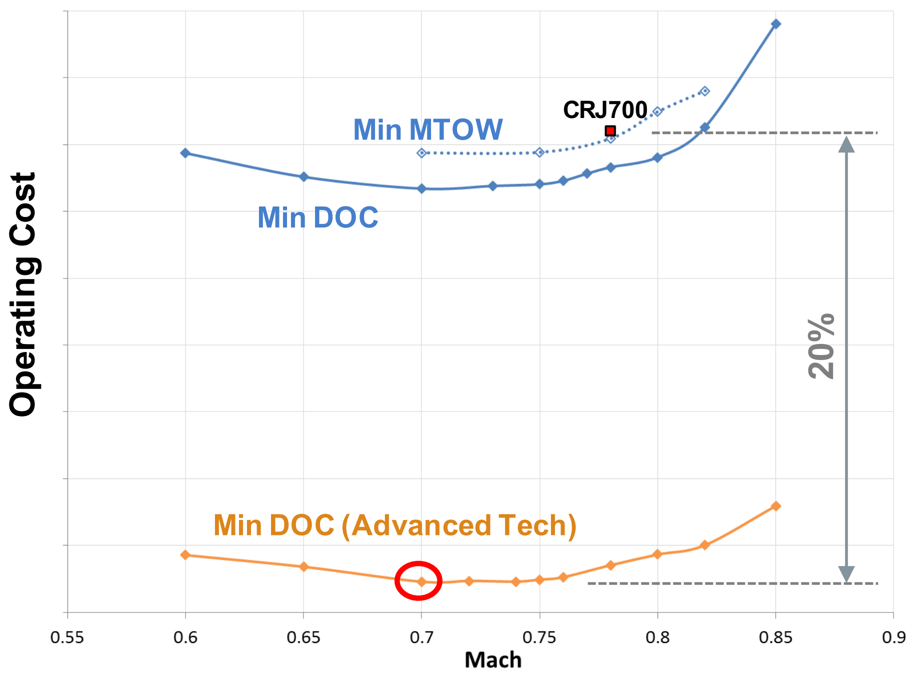
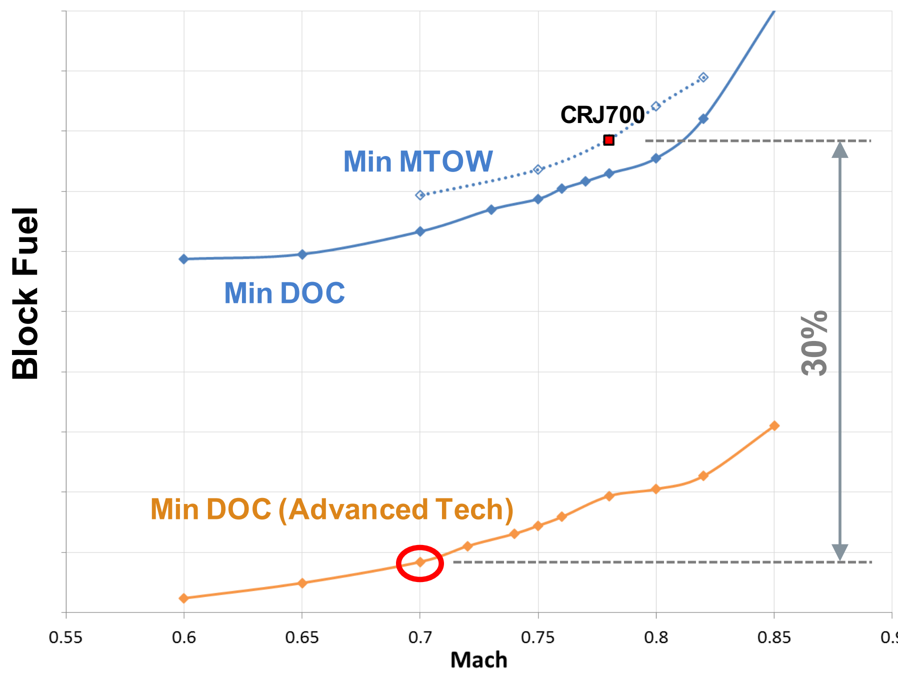
Application of Advanced Technologies

- Design-space exploration repeated with advanced technologies applied
- Mach 0.7 offers minimum operating cost (assuming $3 per gallon fuel price)
- Operating cost is 20% lower than today's aircraft
- Fuel burn (and CO_2) is 30% lower than today's aircraft





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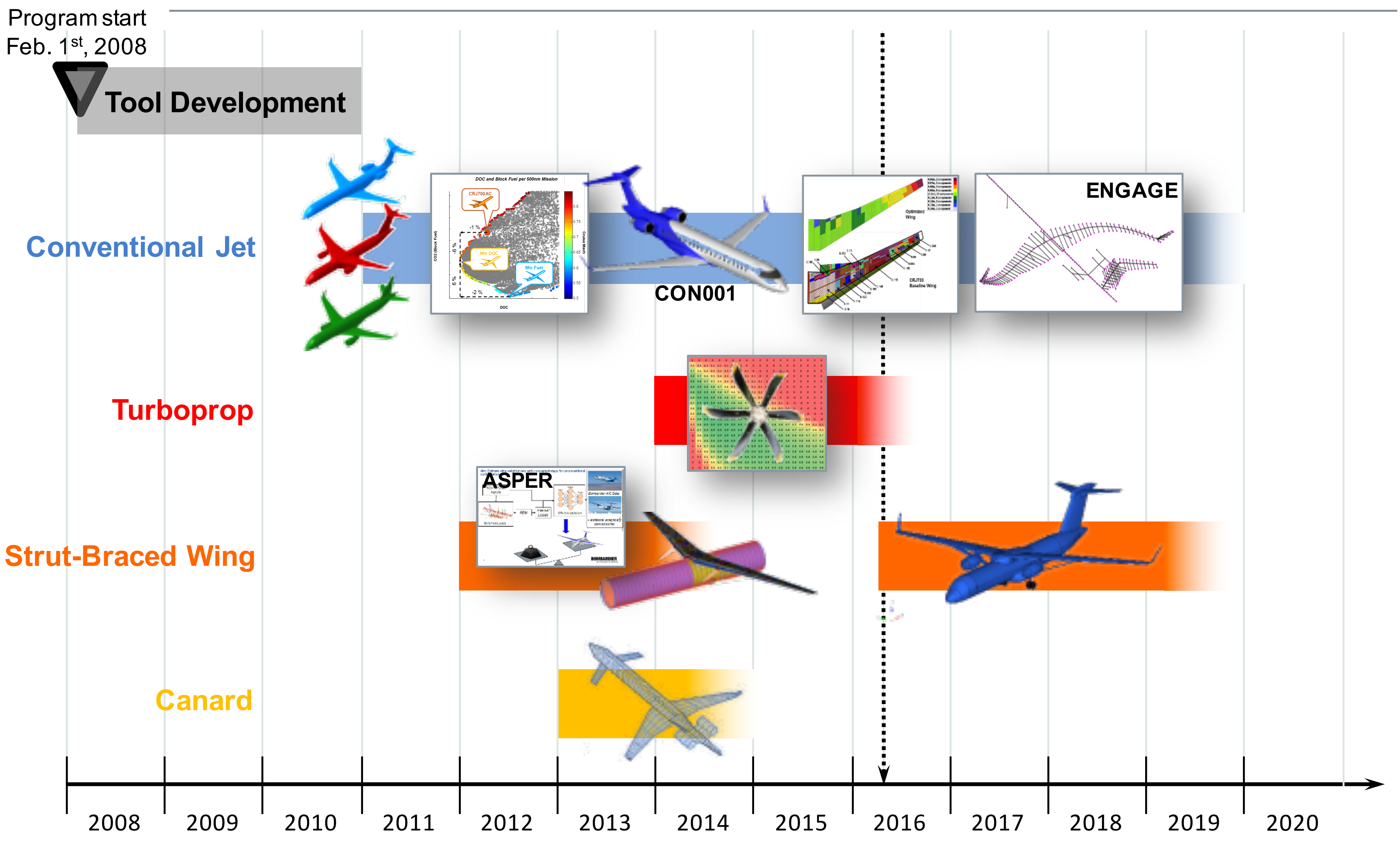
Regional Aircraft – Configuration Evolution



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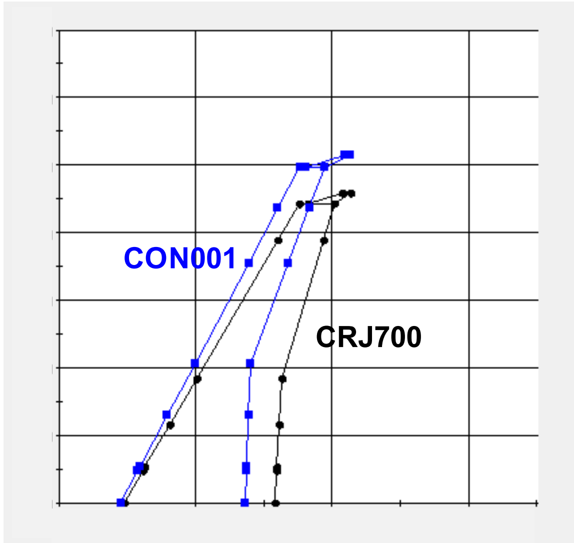
Advanced Conventional Configuration (CON001)

- Intended to act as benchmark for comparison with unconventional configurations
- Based on CRJ700 (but clean-sheet design, not derivative)
- Optimized using CMDO workflow for minimum operating cost assuming M0.7 cruise
- Assumed advanced technology level (EIS 2025)
  - High bypass ratio advanced turbofan
  - Structural mass savings
  - Systems mass savings



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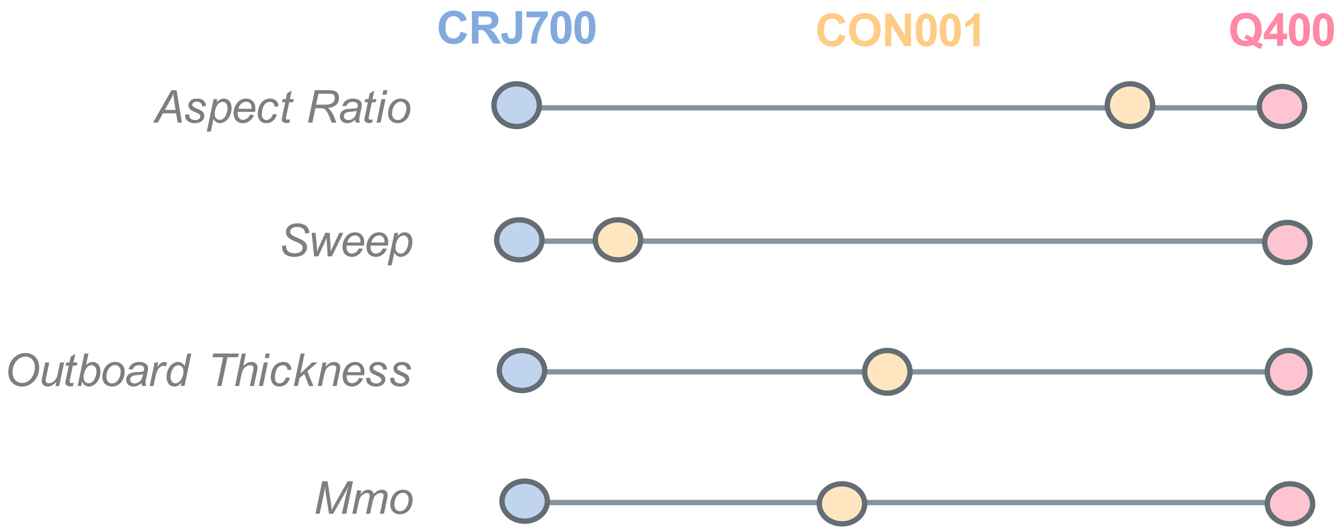
Comparison to Existing Aircraft

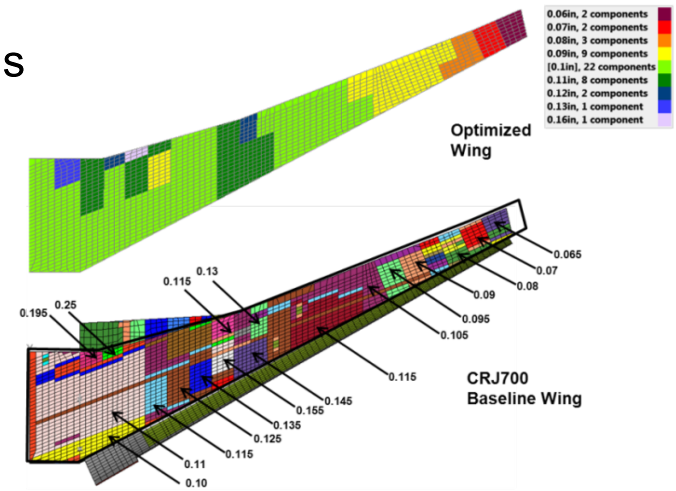


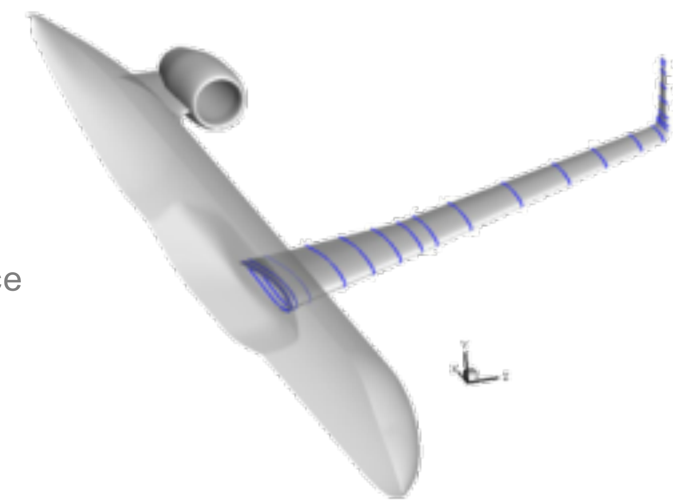
- CON001 wing parameters lie between existing Bombardier aircraft
- The combination of wing parameters is outside of our design experience
- Can we trust our empirical estimates for mass and drag?
- How big is the risk of aero-elastic issues?

Mmo Maximum Operating Mach

CON001: Key Uncertainties

- High fidelity analysis applied early in the design process
- Wing structural mass
  - High-fidelity methods used to validate estimates
  - GFEM developed to size wing structure
  - Results compare well to empirical estimate
- Cruise drag
  - High-fidelity methods used to validate estimates
  - CFD profile optimization performed and polars generated
  - Results compare well to empirical estimate
- Aero-elastic characteristics
  - No analysis performed within CMDO
  - Minimum wing thickness constraint applied in order to represent stiffness requirements, based on existing aircraft
  - Need to assess CON001 characteristics in terms of flutter, divergence and control reversal

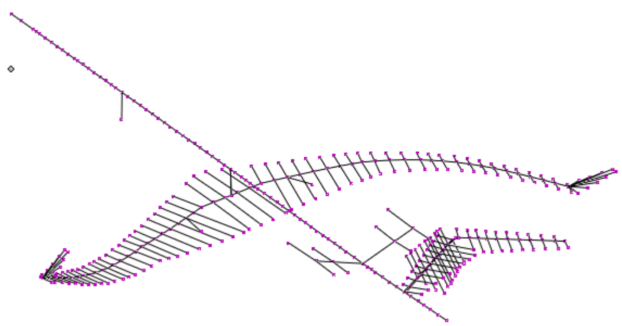


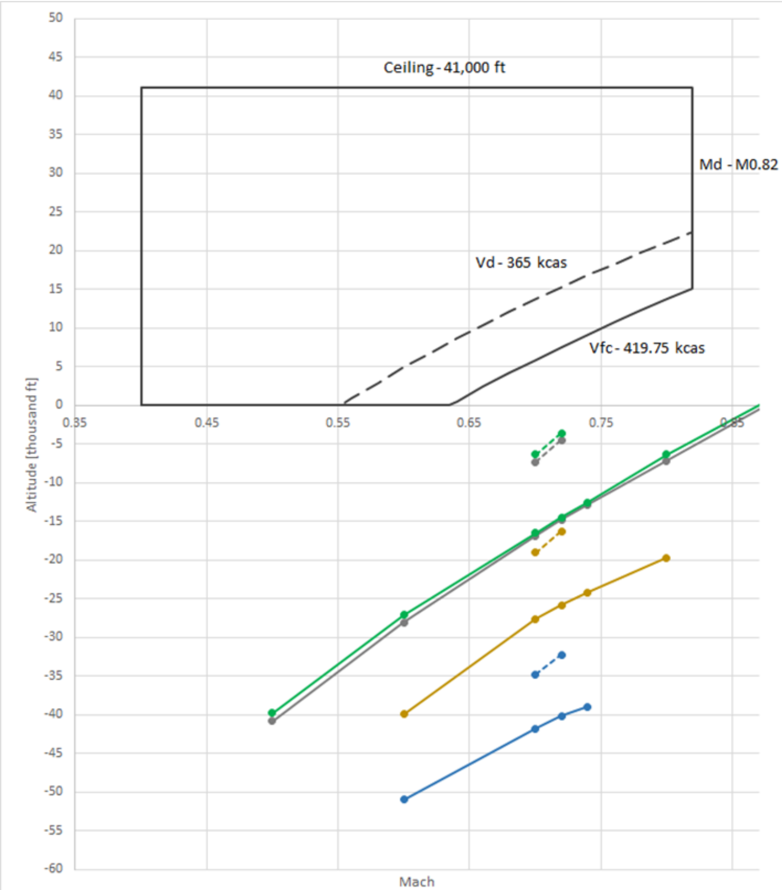


GFEM Global Finite Element Model
CFD Computational Fluid Dynamics
CMDO Conceptual Multi-Disciplinary Optimization

Aero-Elastic Analysis

- ENGAGE collaboration performed with University of Victoria
- Assessed aero-elastic characteristics of CON001 configuration
- Analysis suggested CON001 flutter boundary is outside the required clearance envelope
- Control effectiveness has not yet been assessed





University of Victoria

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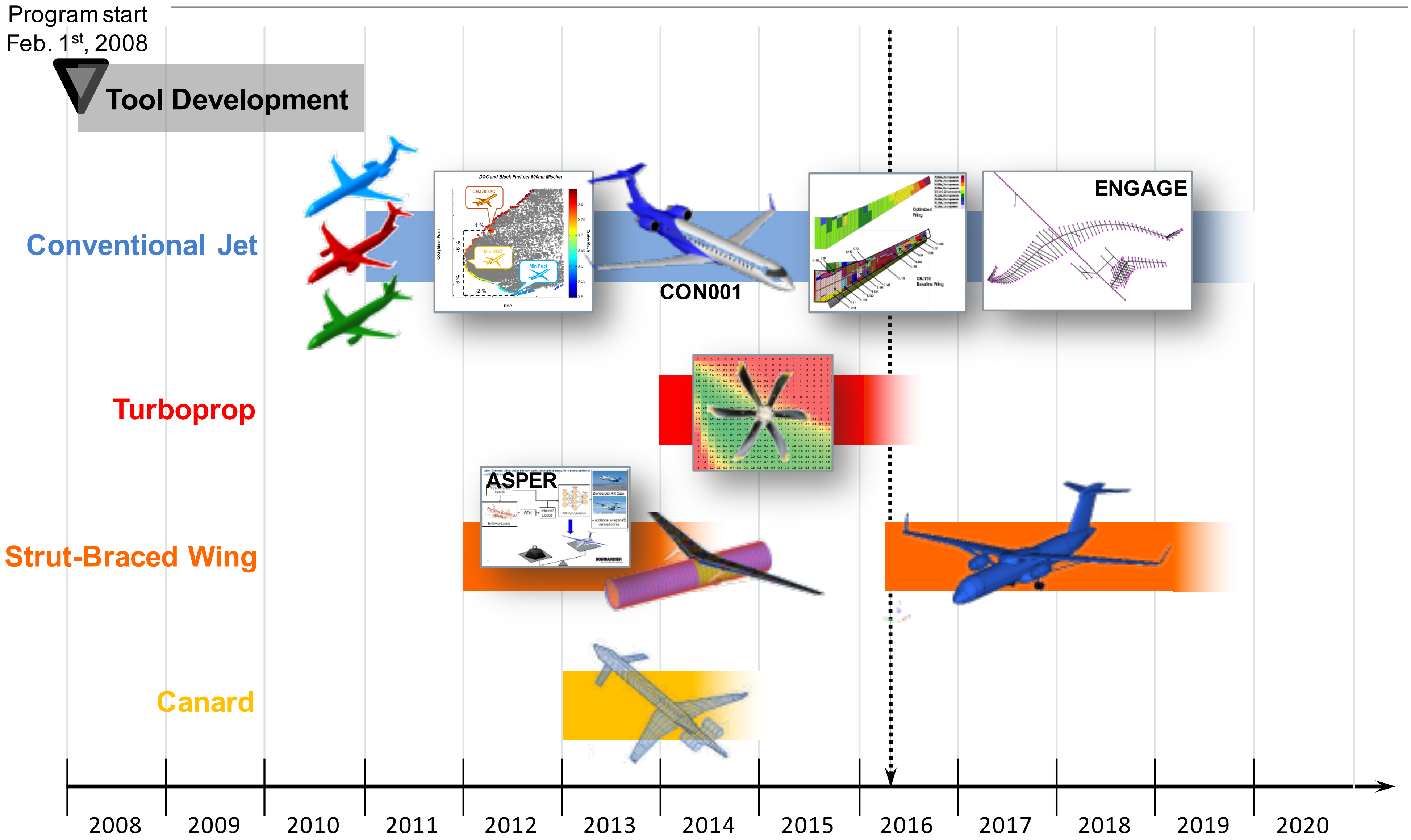
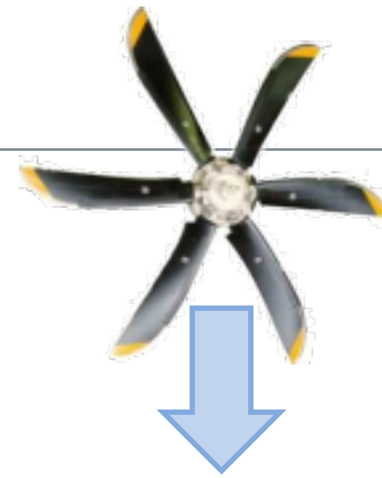
Regional Aircraft – Configuration Evolution



Turboprop Capability

- Implemented conceptual propeller performance method
- Generates propeller map as a function of high-level parameters
  - Diameter
  - Number of blades
  - Blade activity factor
  - Blade integrated design CL
  - Blade tip sweep
- Predicted efficiency used to calculate thrust for given power
- Produces ‘regular’ engine performance tables featuring thrust, fuel-flow as function of Mach, altitude, throttle setting
- Propeller parameters added as design variables for aircraft optimization



Power Coefficient (Cp)

Advance Ratio (J)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
0.01	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.48	0.42	0.35	0.29	0.23	0.19	0.16	0.13	0.11	0.09	0.08	0.07	0.06	0.05	0.00	0.00	0.00	0.00	0.00	0.00
0.50	0.64	0.67	0.60	0.53	0.46	0.38	0.31	0.26	0.22	0.18	0.16	0.13	0.11	0.10	0.08	0.00	0.00	0.00	0.00	0.00
0.75	0.59	0.78	0.73	0.68	0.62	0.56	0.48	0.40	0.33	0.28	0.23	0.20	0.16	0.14	0.12	0.09	0.07	0.00	0.00	0.00
1.00	0.44	0.79	0.78	0.75	0.71	0.67	0.62	0.55	0.47	0.39	0.33	0.27	0.23	0.19	0.15	0.12	0.10	0.07	0.00	0.00
1.25	0.26	0.78	0.82	0.81	0.78	0.75	0.72	0.68	0.64	0.56	0.48	0.41	0.34	0.28	0.23	0.18	0.14	0.11	0.07	0.04
1.50	0.04	0.71	0.83	0.84	0.82	0.81	0.78	0.75	0.73	0.70	0.65	0.58	0.49	0.41	0.34	0.28	0.22	0.17	0.12	0.08
1.75	-0.23	0.60	0.79	0.84	0.85	0.84	0.82	0.80	0.78	0.76	0.73	0.71	0.67	0.60	0.52	0.43	0.36	0.28	0.22	0.16
2.00	-0.56	0.45	0.73	0.82	0.85	0.85	0.84	0.83	0.82	0.80	0.78	0.76	0.74	0.72	0.69	0.64	0.56	0.47	0.38	0.30
2.25	-0.94	0.28	0.65	0.78	0.84	0.86	0.86	0.85	0.84	0.83	0.82	0.80	0.78	0.76	0.75	0.72	0.70	0.67	0.61	0.53
2.50	-1.37	0.08	0.53	0.72	0.81	0.85	0.86	0.86	0.86	0.85	0.84	0.83	0.81	0.80	0.78	0.77	0.75	0.73	0.71	0.69
2.75	-1.85	-0.16	0.39	0.64	0.76	0.82	0.85	0.86	0.86	0.86	0.85	0.84	0.83	0.82	0.81	0.80	0.78	0.77	0.75	0.74
3.00	-2.43	-0.41	0.23	0.53	0.69	0.78	0.83	0.85	0.86	0.86	0.85	0.85	0.84	0.83	0.83	0.82	0.81	0.80	0.78	0.77
3.25	-2.98	-0.70	0.05	0.41	0.60	0.72	0.78	0.82	0.84	0.85	0.85	0.85	0.85	0.84	0.84	0.83	0.82	0.81	0.80	0.79
3.50	-3.65	-1.03	-0.17	0.25	0.49	0.63	0.72	0.78	0.81	0.83	0.84	0.85	0.85	0.84	0.84	0.83	0.83	0.82	0.81	0.81
3.75	-4.40	-1.38	-0.42	0.06	0.35	0.53	0.64	0.72	0.77	0.80	0.82	0.83	0.84	0.84	0.84	0.83	0.83	0.82	0.82	0.81
4.00	-5.16	-1.85	-0.71	-0.15	0.18	0.39	0.54	0.63	0.70	0.75	0.78	0.80	0.81	0.82	0.83	0.83	0.83	0.82	0.82	0.81
4.25	-5.98	-2.32	-1.03	-0.39	-0.01	0.24	0.41	0.53	0.61	0.68	0.72	0.76	0.78	0.79	0.81	0.81	0.81	0.81	0.81	0.81
4.50	-7.27	-2.86	-1.39	-0.66	-0.23	0.06	0.26	0.41	0.51	0.59	0.65	0.69	0.73	0.75	0.77	0.78	0.79	0.80	0.80	0.80
4.75	-8.41	-3.46	-1.79	-0.94	-0.47	-0.14	0.10	0.26	0.39	0.48	0.56	0.61	0.66	0.69	0.72	0.74	0.76	0.77	0.78	0.78
5.00	-9.41	-4.02	-2.20	-1.28	-0.73	-0.36	-0.10	0.10	0.25	0.36	0.45	0.52	0.57	0.62	0.66	0.69	0.71	0.73	0.74	0.75

$$J = \frac{V}{ND}$$

$$C_P = \frac{P}{N^3 D^5 \sigma}$$

V	=	*Flight Speed (ft/s)*
N	=	*Propeller Rotational Speed (rev/s)*
D	=	*Propeller Diameter (ft)*
P	=	*Available Engine Power (ftlb/s)*
σ	=	*Air Density (slug/ft^3)*

CL Lift Coefficient

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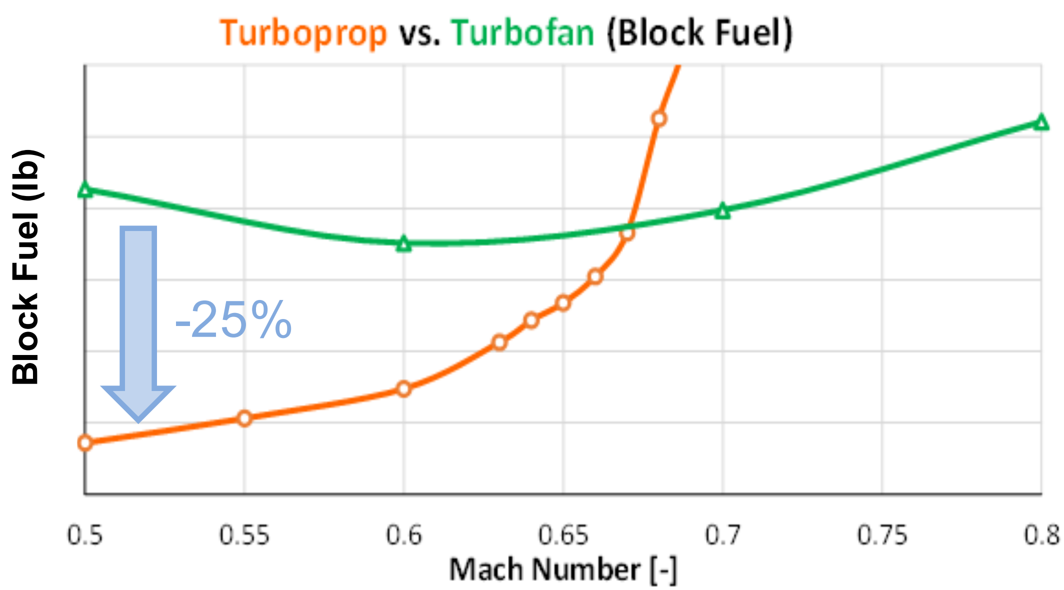
Turboprop Sizing Results

- Performed aircraft optimizations assuming both turbofan and turboprop engines
- Applied same requirements to both (range, field performance, etc.)
- Both engine options assume technology level consistent with 2025 EIS
- Design cruise Mach varied from M0.5 to M0.8
- Turboprop offers significant fuel burn saving at lower cruise Machs
- Turbofan offers lower fuel burn at higher cruise Machs
- Note: Results may be highly sensitive to design range



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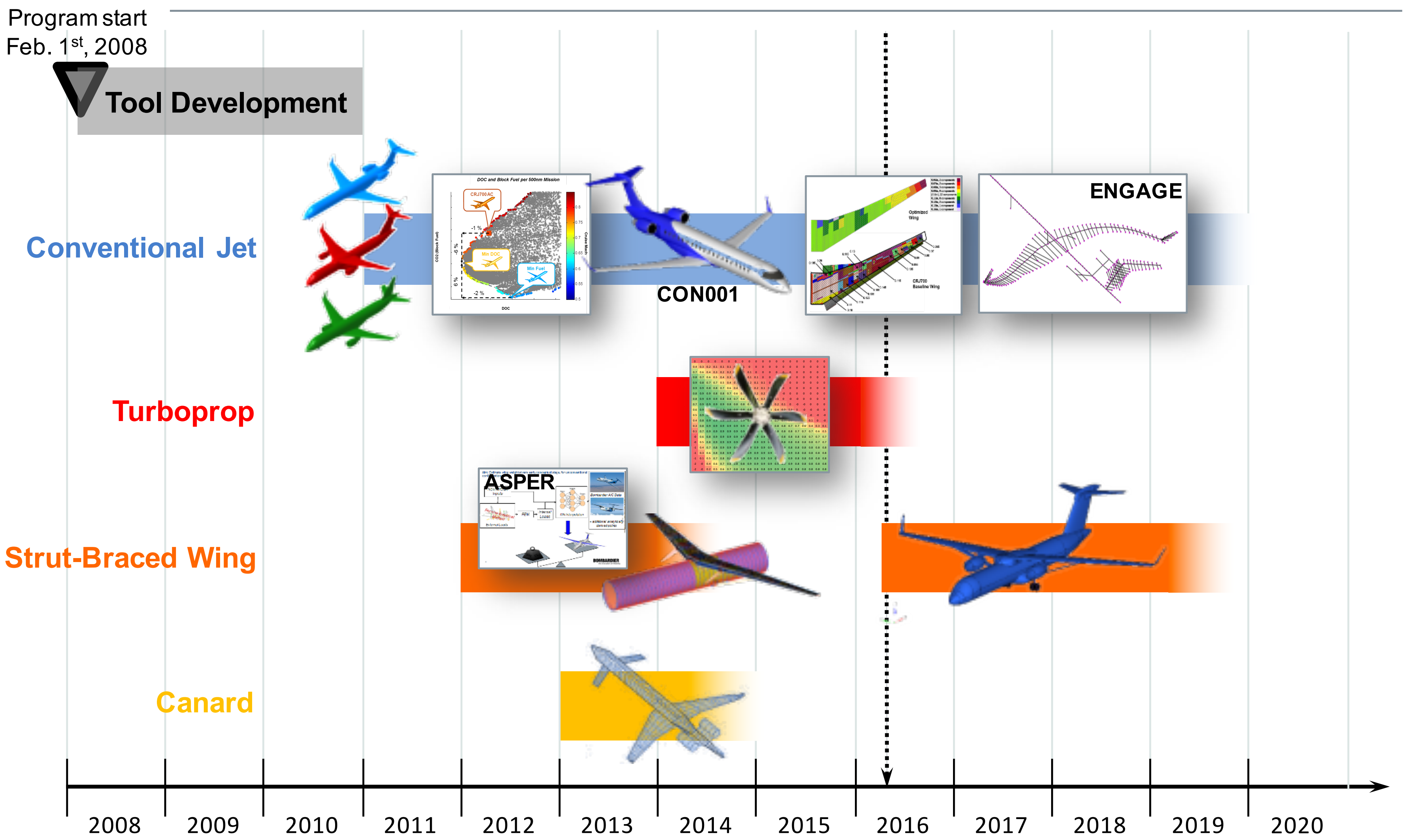
Regional Aircraft – Configuration Evolution



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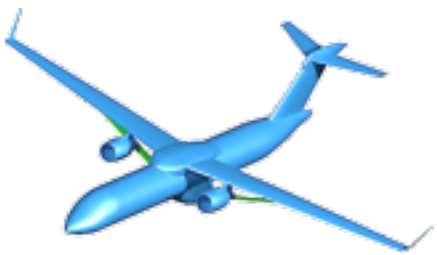
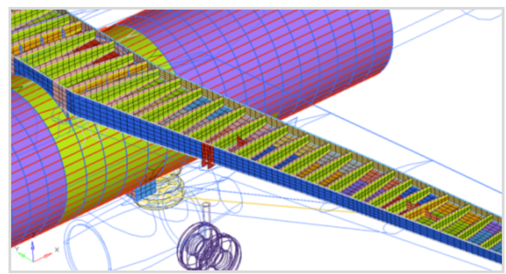
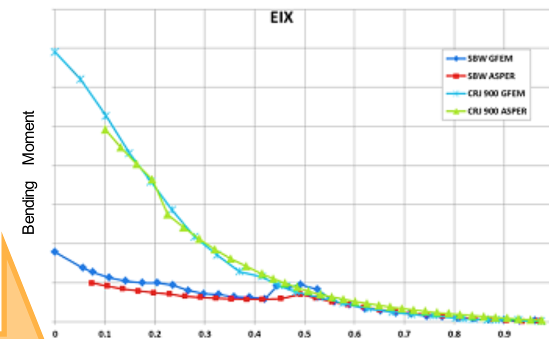
Unconventional Configurations

- What level of climate impact reduction can be achieved by utilizing unconventional aircraft configurations?
- Dependant on physics-based analysis methods, but need short run-time to allow wide design-space exploration

SBW





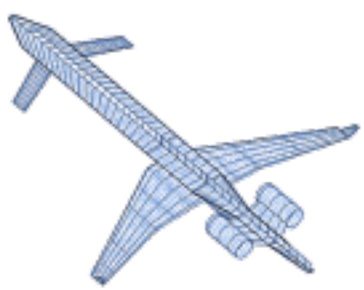


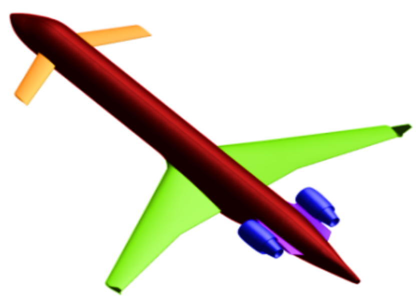
Design with low fidelity tools

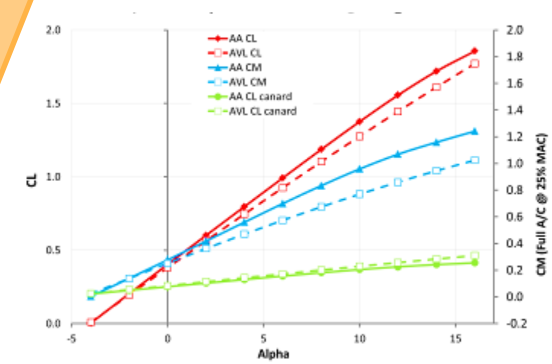
Analysis with high fidelity tools by Expert Departments

Comparison between low and high fidelity results

Canard







SBW Strut-Braced Wing

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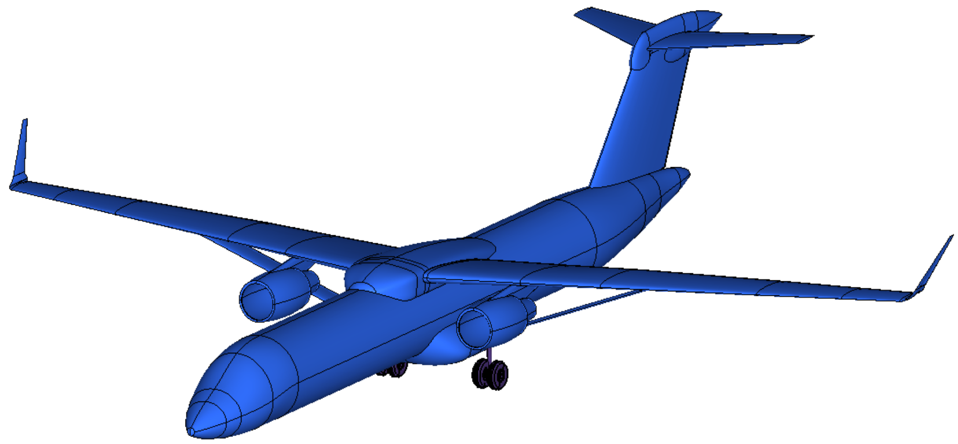
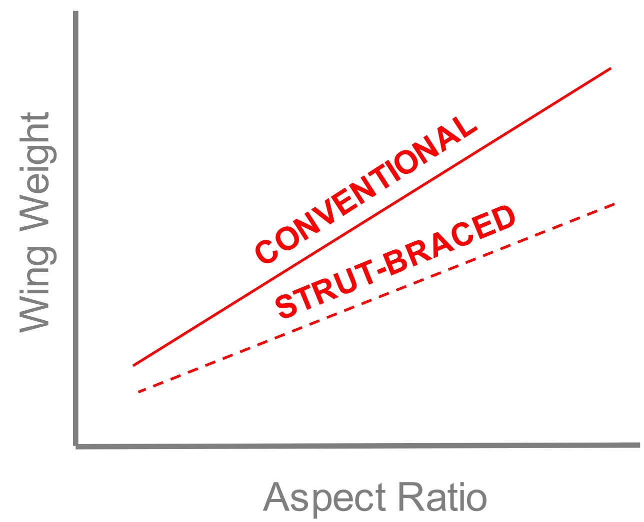
Strut-Braced Wing

- Optimum wing aspect-ratio is a compromise between wing weight and drag
- Strut-braced wing configuration allows reduced wing weight at a given aspect ratio
- Allows optimization to higher aspect ratios with large reductions in induced drag
- Initial studies suggest approx. 10% fuel burn savings compared to equivalent conventional configuration





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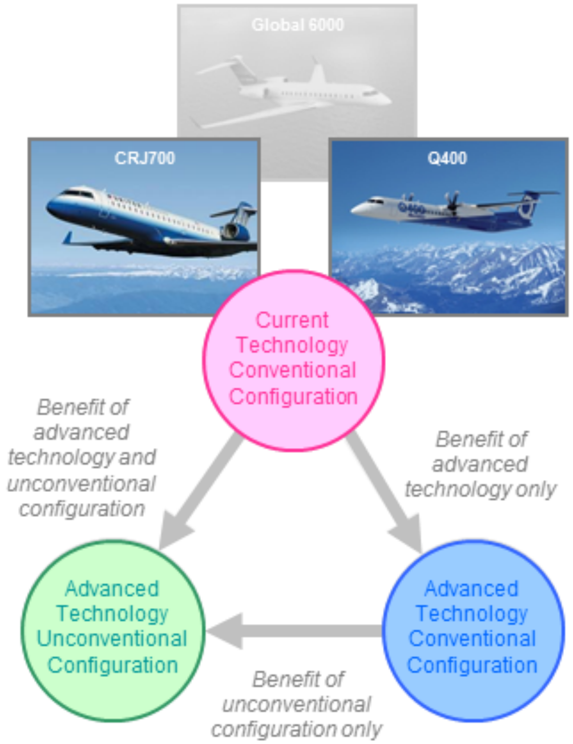
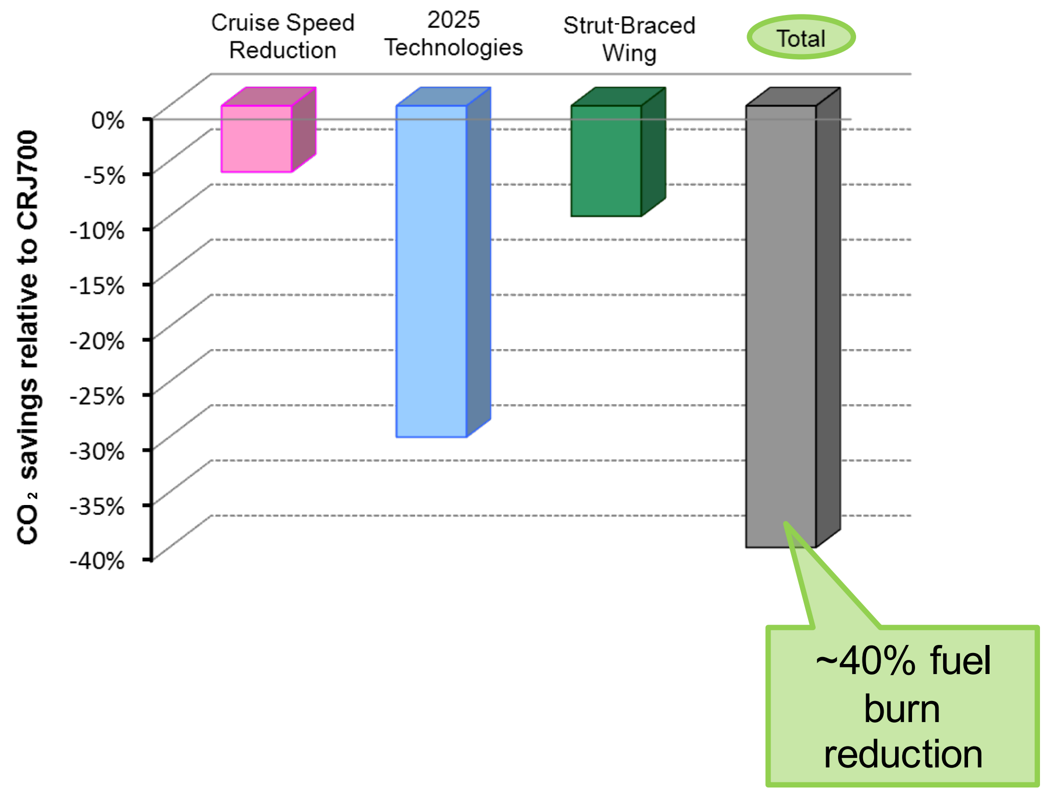
Total Fuel Burn / CO2 Reductions

- Combining reduced cruise speed and advanced technologies with the Strut-Braced Wing configuration offers approximately 40% CO_2 reduction over the baseline





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Conclusions

- Efficiency Improvements
  - Reduced cruise speed offers significant fuel burn and CO_2 reduction
  - Higher fuel prices encourage lower cruise speeds for economic reasons
  - Advanced technologies provide large fuel-burn and CO_2 savings
- Risk Reduction
  - High-fidelity analysis has been performed early in the design process to reduce risk associated with less familiar configurations
  - Simplified analysis methodologies allow high-fidelity approach with limited resources – suitable for research studies
- Unconventional Configurations
  - Various airframe configurations being investigated
  - At least 10% fuel burn advantage possible

Advanced Technology Conventional Configuration

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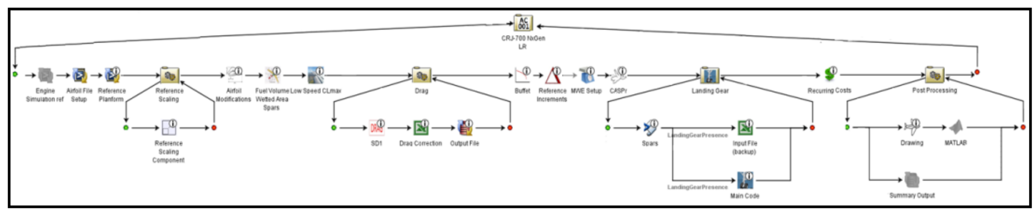
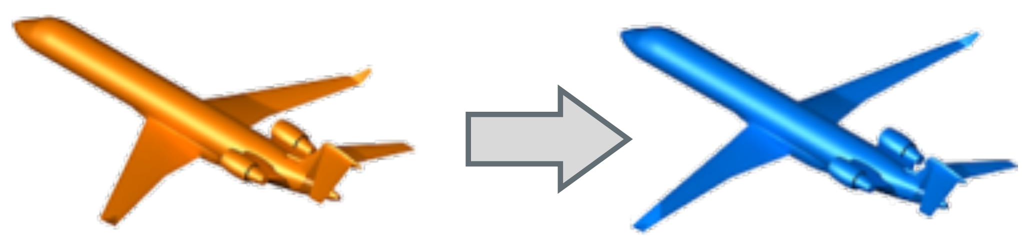
Application of Conceptual Multi-Disciplinary Optimization (CMDO)

- EFA study makes use of Bombardier's CMDO capability
- Analysis components are modular – empirical to physics based
- CRJ700 used as reference aircraft and optimization start point
- Design Variables
  - Wing geometry (area, aspect-ratio, sweep, thickness to chord)
  - Engine scale factor
  - Cruise Mach
  - Initial Cruise Altitude
- Constraints
  - Design range
  - Take-off field length
  - Single engine climb gradient
  - Approach speed
  - Fuel volume
- Objectives
  - Minimum MTOW
  - Minimum fuel burn
  - Minimum climate impact
  - Minimum operating cost



CMDO Workflow



Initial Geometry (CRJ700) **Optimized Geometry**

MTOW Maximum Take-Off Weight

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