SUPERSONIC BUSINESS JET

Design Space Exploration and Optimization

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Overview

- Problem Formulation
  - Motivation and Challenges
  - Objectives and Constraints
- Model and Simulation
  - Model Overview and Description
  - Benchmarking and Validation
- Optimization
  - Algorithms and tuning
  - Post Optimality Analysis
  - Multi-Objective and Tradeoff Analysis
- Conclusions and Recommendations

Problem Formulation

Motivation and Challenges

- Motivation
  - Large potential market for a Supersonic Business Jet[1,2]
    - Fast transportation for executives who travel frequently and are able to afford more expensive transportation (20-50% reduction in travel time)[3]
  - Business aircraft less sensitive to economic fluctuations
  - Application outside of solely business executives
    - MEDEVAC
    - Airfreight
    - Military
- Challenges
  - High speed flight aerodynamics
  - Very expensive aircraft to own and operate[1]
  - "Because of increasing environmental awareness, the focus for the design of this aircraft must include environmental concerns in addition to traditional performance and economic metrics."[4]
    - Overland flight with minimal sonic boom
    - Engine must meet noise and emissions standards

Problem Formulation

Objectives and Constraints

- **Objective Statement:** Design a highly profitable supersonic business jet that complies with noise and performance regulations required to operate out of commercial airports
- Outputs from system model divided into constraints or objectives based on their potential impact on profits (objectives) or compliance with regulations (constraints)

Type	Variable	Name	Min	Max
Performance Constraints	Take-off Field Length (ft)	`TOFL`		11,000
	Landing Field Length (ft)	`LANDFL`		11,000
	Approach Speed (kts)	`APPSPD`		155
	Approach Angle of Attack (deg)	`AANGLA`		12
	Fuel Volume Ratio (available/required)	`FRATIO`	1.0	
Environmental Constraints	Delta Sideline Noise	`SNOISE`		10
	Delta Flyover Noise	`FNOISE`		10
	Delta Approach Noise	`ANOISE`		10

Objective	Name
Take-off Gross Weight (lbs)	`TOGW`
Fuel Weight (lbs)	`FUELWT`
Average Yeild per Revenue Passenger Mile ($/mi)	`DPRPM`
Acquisition Cost (Million $)	`ACQCST`

Model and Simulation

Overview

- Inputs
  - Wing and tail geometry
  - Engine Parameters
- Outputs
  - Objective and Constraints
- Each output is modeled using a Response Surface Equation (RSE)
  - Linear and interaction terms only

$$RSE = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \beta_{ij} x_i x_j$$

Model and Simulation

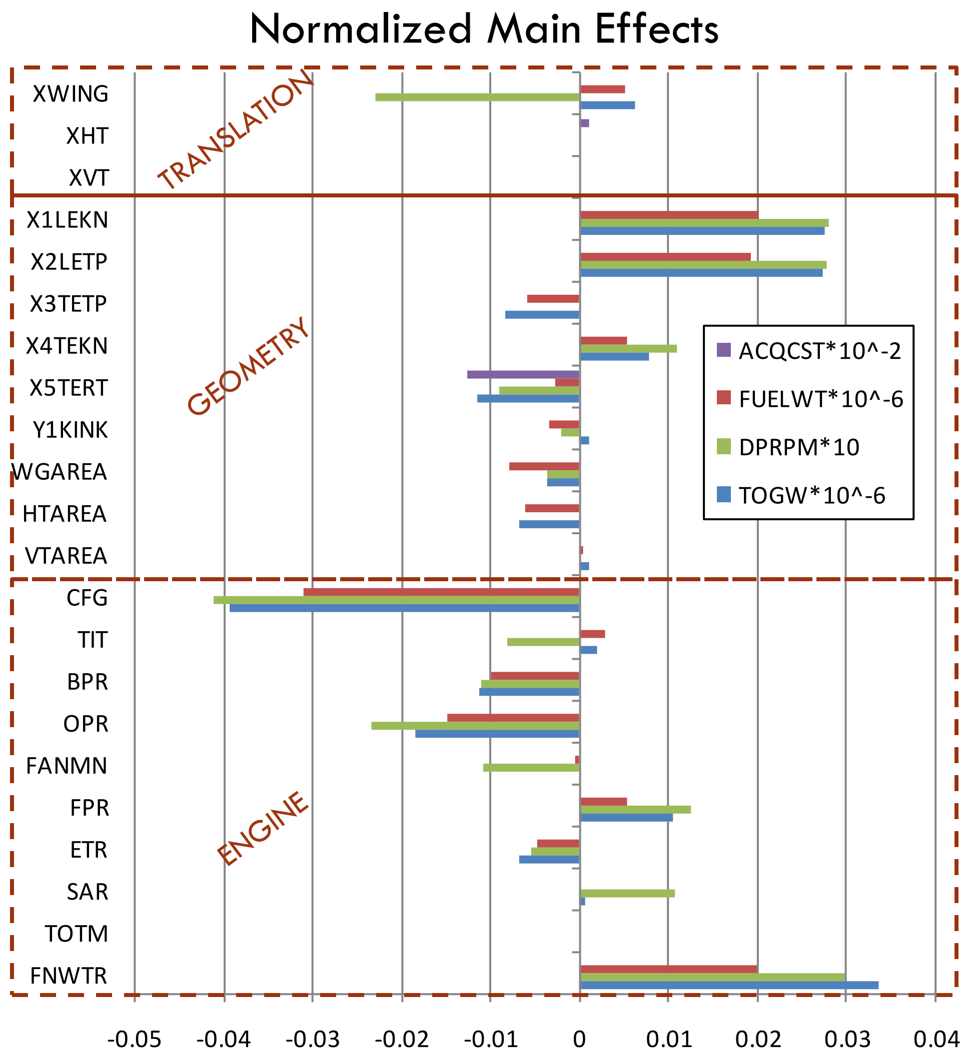
Overview

- Limitations/Features of RSE[6]
  - Accuracy only guaranteed in a small trust region around sample points
  - Unable to predict multiple extrema
  - Assumes randomly distributed error (not usually the case in computer experiments)

Model and Simulation

Variables and Parameters

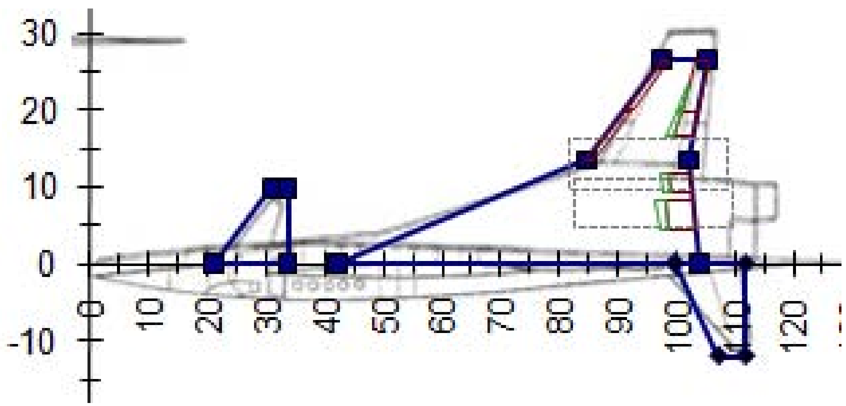
Type	Variable	Name	Min	Max
Translation Variables	Wing Apex (ft)	XWING	25	28
	Horizontal Tail Apex (ft)	XHT	82	87.4
	Vertical Tail Apex (ft)	XVT	82	86.4
Planform Geometry Variables	Leading Edge Kink X-Location	X1LEK	1.54	1.69
	Leading Edge Tip X-Location	X2LET	2.1	2.36
	Trailing Edge Tip X-Location	X3TET	2.4	2.58
	Trailing Edge Kink X-Location	X4TEK	2.19	2.36
	Trailing Edge X-Location	X5TER	2.19	2.5
	Kink Y-Location	Y1KIN	0.44	0.58
	Wing Area (ft^2)	WGARE	8500	9500
	Horizontal Tail Area (ft^2)	HTARE	400	700
	Veritical Tail Area (ft^2)	VTARE	350	550
Engine Variables	Nozzle Thrust Coefficient	CFG	0.97	0.99
	Turbine Inlet Temperature (^oR)	TIT	3050	3140
	Bypass Ratio	BPR	0.36	0.55
	Overall Pressure Ratio	OPR	18	22
	Fan Inlet Mach Number	FANMN	0.5	0.7
	Fan Pressure Ratio	FPR	3.2	4.2
	Engine Throttle Ratio	ETR	1.05	1.15
	Suppressor Area Ratio	SAR	1.9	4.7
	Take-off Thrust Multiplier	TOTM	0.85	1.0
	Thrust-to-Weight Ratio	FNWTR	0.28	0.32



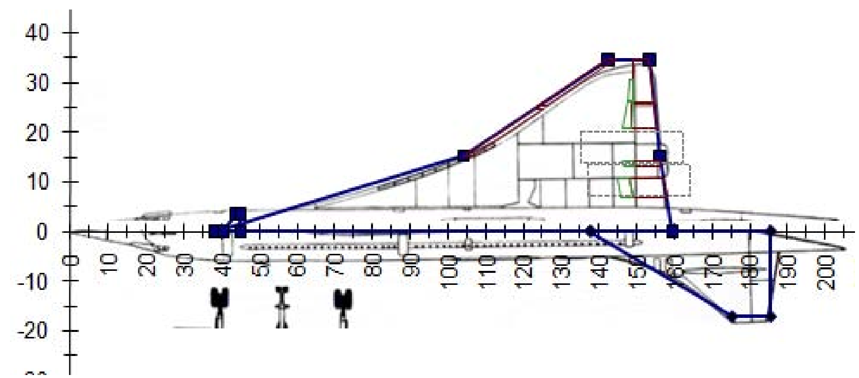
Model and Simulation

Benchmarking and Validation

- Very fast
  - Run time on the order of 7e-6 sec
- Modeled geometry of several supersonic business jet designs
  - Model design space is unique, even for SSBJ
  - Much larger than most supersonic aircraft



Sukhoi-Gulfstream S-21



Aérospatiale-BAC Concorde

Model and Simulation

Benchmarking and Validation

Type	Variable	Min	Max	Sukhoi-Gulfstream S-21	Aérospatiale-BAC Concorde
Translation Variables	Wing Apex (ft)	25	28	40	19
	Horizontal Tail Apex (ft)	82	87.4	20	82
	Vertical Tail Apex (ft)	82	86.4	95	68
Planform Geometry Variables	Leading Edge Kink X-Location	1.54	1.69	1.615	1.9
	Leading Edge Tip X-Location	2.1	2.36	2.1	3
	Trailing Edge Tip X-Location	2.4	2.58	2.4	3.32
	Trailing Edge Kink X-Location	2.19	2.36	2.275	3.4
	Trailing Edge X-Location	2.19	2.5	2.345	3.5
	Kink Y-Location	0.44	0.58	0.51	0.44
	Wing Area (ft^2)	8500	9500	1399	3856
	Horizontal Tail Area (ft^2)	400	700	75	20
	Veritical Tail Area (ft^2)	350	550	100	500
Engine Variables	Nozzle Thrust Coefficient	0.97	0.99	0.98	0.98
	Turbine Inlet Temperature (^oR)	3050	3140	3095	3095
	Bypass Ratio	0.36	0.55	0.83	0.1
	Overall Pressure Ratio	18	22	20.2	15.5
	Fan Inlet Mach Number	0.5	0.7	0.6	0.6
	Fan Pressure Ratio	3.2	4.2	2.99	3.7
	Engine Throttle Ratio	1.05	1.15	1.1	1.1
	Suppressor Area Ratio	1.9	4.7	3.3	3.3
	Take-off Thrust Multiplier	0.85	1.0	0.925	0.925
	Thrust-to-Weight Ratio	0.28	0.32	0.333	0.373

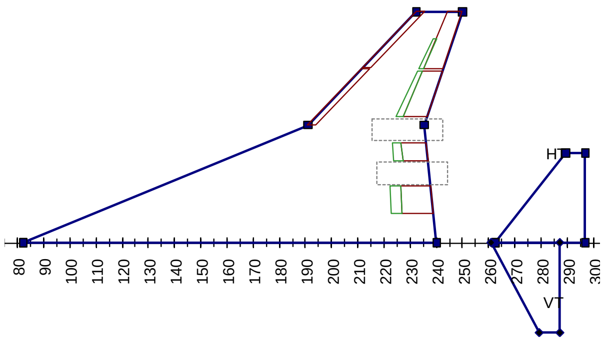
Objective	S21 Model	S1 Actual	Concorde Model	Concorde Actual
Take-off Gross Weight (lbs)	512,090	106,924	807,610	412,000
Fuel Weight (lbs)	289,560	67,409	2,502,000	210,940
Average Yeild per Revenue Passenger Mile ($/mi)	0.1314		0.105	
Acquisition Cost (Million $)	260.2814		303.8597	350

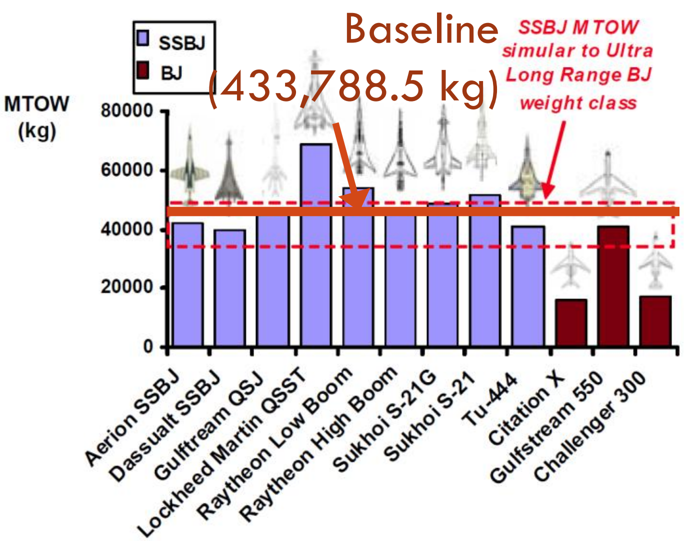
Type	Variable	Min	Max	S21 Model	S1 Actual	Concorde Model	Concorde Actual
Performance Constraints	Take-off Field Length (ft)		10,500	19,358	6,496	103,360	11,778
	Landing Field Length (ft)		11,000	12,503	6,496	14,024	
	Approach Speed (kts)		155	185	146	242	
	Approach Angle of Attack (deg)		12	11.19		12.10	
	Fuel Volume Ratio (available/required)	1.0		0.58		0.01	
Environmental	Delta Sideline Noise		10	-2.6		23.6	
	Delta Flyover Noise		10	34.9		-207.0	
	Delta Approach Noise		10	22.1		-195.8	

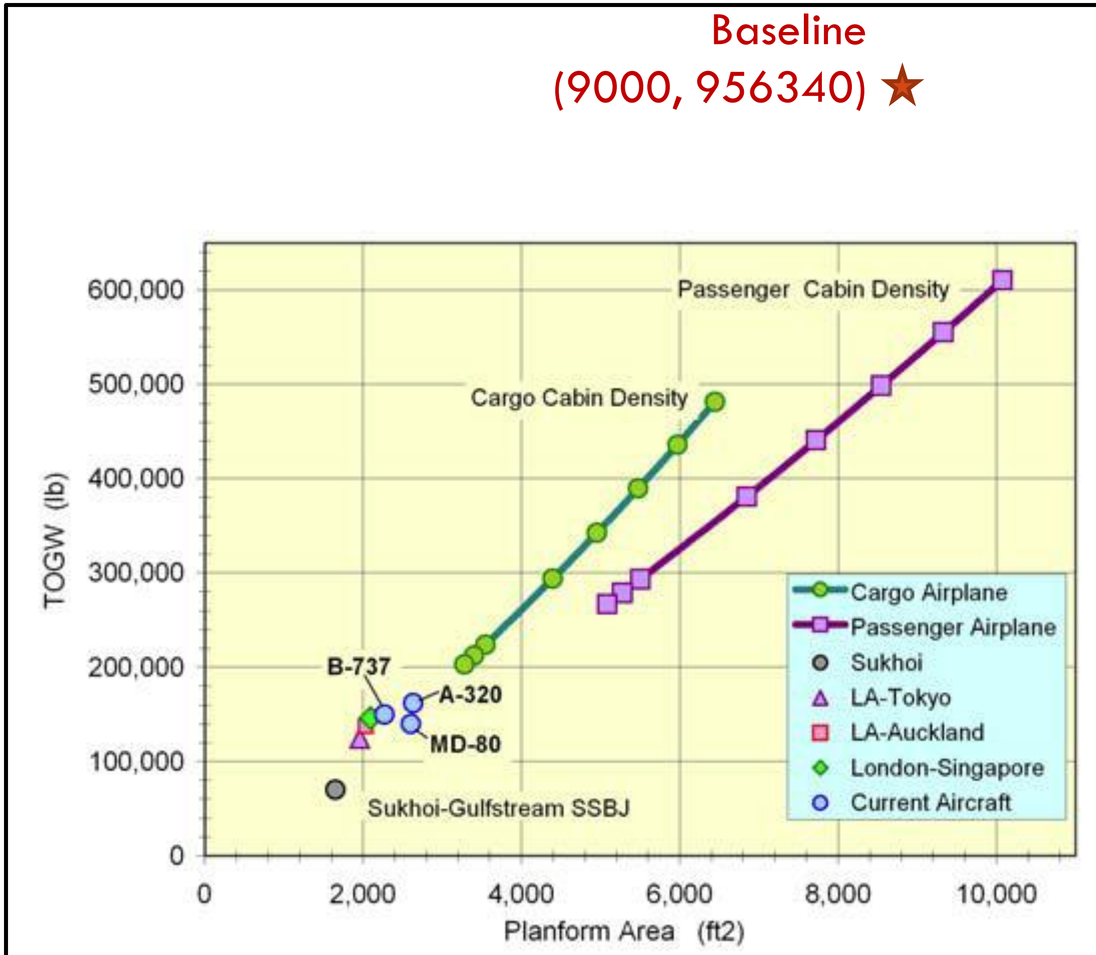
Model and Simulation

Benchmarking and Validation

- Baseline design at center of regression



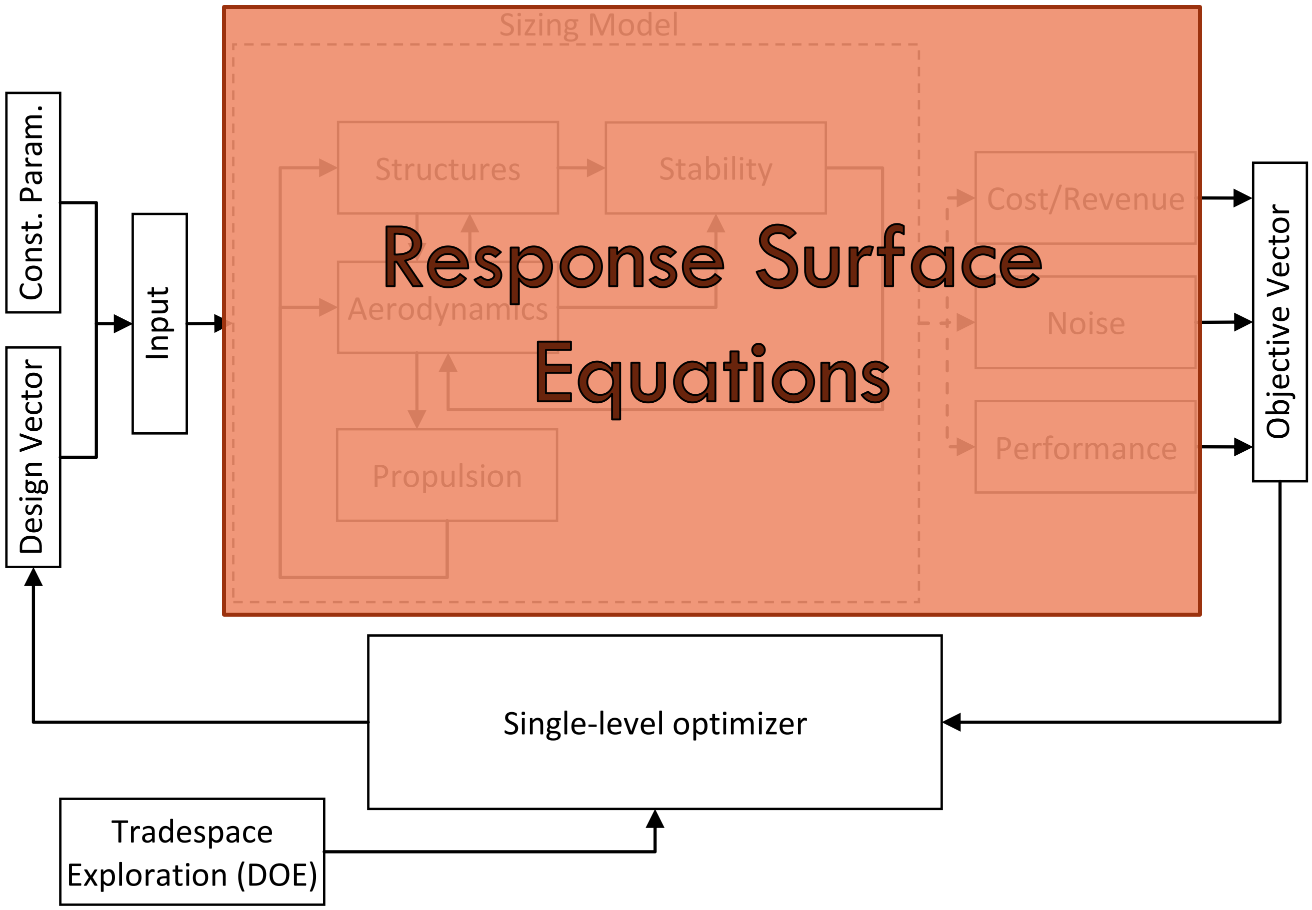




Optimization

Overview

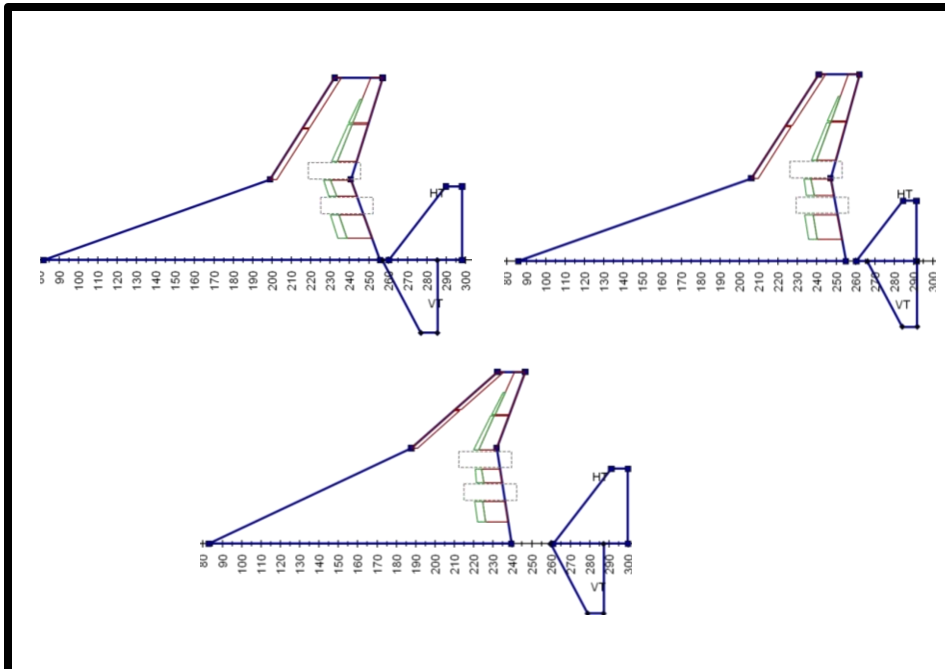
- Multidisciplinary aspects of the model are masked by the RSE's
  - Necessitates Single level optimization



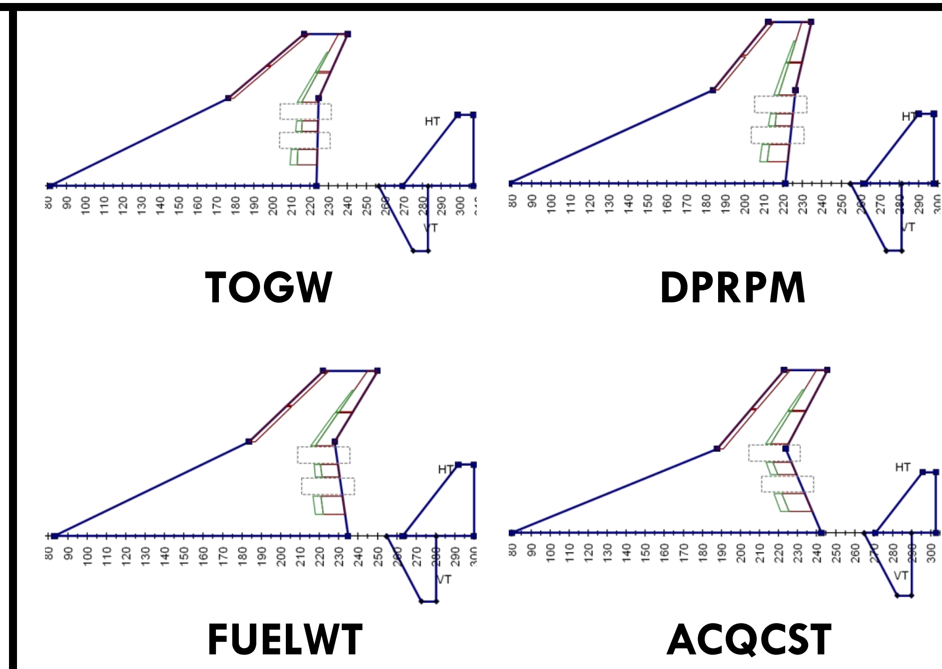
Optimization

DOE and Design Space Exploration

- DOE
  - Latin Hypercubes
  - 10,000 levels
  - Only 3 feasible designs found
    - Most designs excluded based on TOFL and ANOISE constraints



Feasible Designs



"Best" Designs from all Samples

Optimization

Gradient Based

- Used DOE designs to come up with "ballpark" objective scaling to form a multi-objective objective function

$$J = 0.20\frac{TOGW}{750000} + 0.25\frac{FUELWT}{400000} - 0.30\frac{DPRPM}{0.12} + 0.25\frac{ACQCST}{230}$$

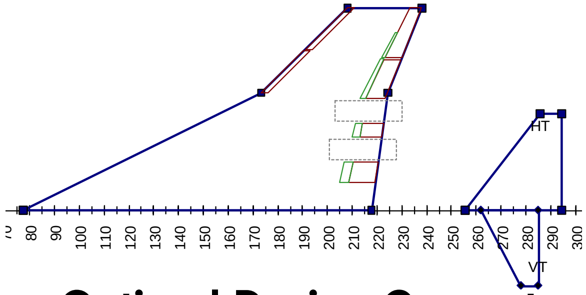
- SQP implemented in MATLAB
  - Very efficient on smooth response surfaces
  - Fast convergence
  - Convergence tolerance set to 1e-6 on constraints and objective function
- Started from feasible designs as well as "Best" designs found in DOE
  - Very fast convergence
  - Each starting point converged to a different optimal solution
    - Islands of feasibility in design space
    - Gradient solver not a very good solution

Optimization

Heuristic - SA

- SA implemented in MATLAB
  - Much more costly than gradient based optimization
  - Better, more stable solutions
  - Run from multiple starting locations

Tuning Parameter	Value
T0	100
Cooling Schedule	exponential
dT	0.95
neq	5.00E+03
nfrozen	10



Optimal Design Geometry

TOGW: 849,647 FUELWT: 447,648

DPRPM: 0.1555 ACQCST: 262.5

J: 0.3827

- Design perturbation
  - 4 variables at a time
  - Normal distribution (standard deviation equal to 1/3 the allowable range
  - Reset to upper and lower bounds if exceeded

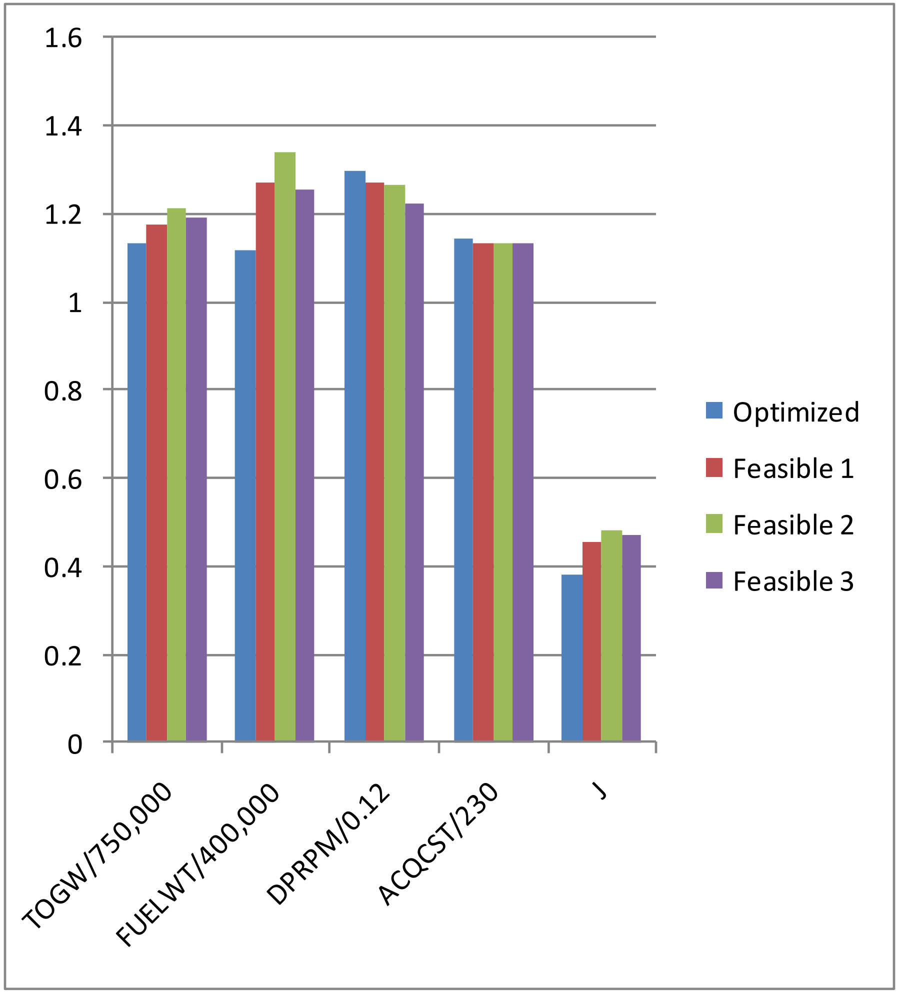
Type	Variable	Value	Min	Max
Translation	Wing Apex (ft)	25	25	28
	Horizontal Tail Apex (ft)	82.5	82	87.4
	Vertical Tail Apex (ft)	84.5	82	86.4
Planform Geometry Variables	Leading Edge Kink X-Location	1.54	1.54	1.69
	Leading Edge Tip X-Location	2.1	2.1	2.36
	Trailing Edge Tip X-Location	2.58	2.4	2.58
	Trailing Edge Kink X-Location	2.36	2.19	2.36
	Trailing Edge X-Location	2.26	2.19	2.5
	Kink Y-Location	0.58	0.44	0.58
	Wing Area (ft^2)	9011	8500	9500
	Horizontal Tail Area (ft^2)	700	400	700
	Veritical Tail Area (ft^2)	350	350	550

Optimal Design Geometry

Active Constraints Shown in Red

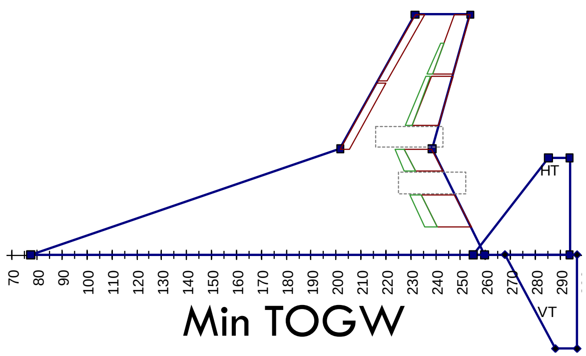
Optimization

Heuristic - SA



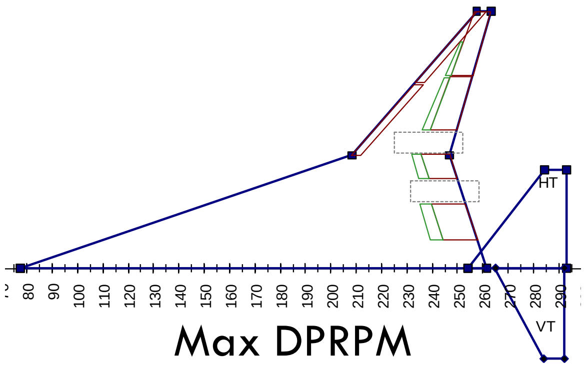
Optimization
MOO

- Individual objective optimizations



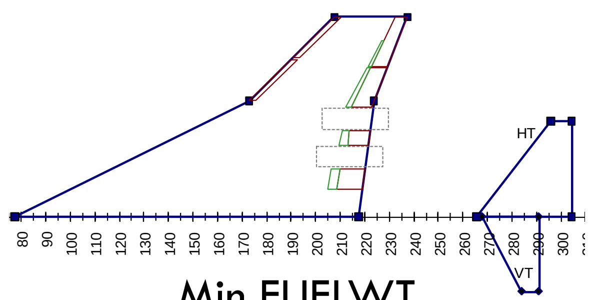
Min TOGW

TOGW: 825,974 FUELWT: 484,575
DPRPM: 0.1519 ACQCST: 267.0



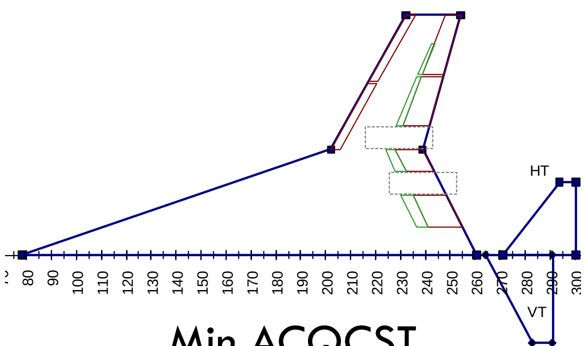
Max DPRPM

TOGW: 932,407 FUELWT: 517,315
DPRPM: 0.1645 ACQCST: 264.1



Min FUELWT

TOGW: 832,765 FUELWT: 438,856
DPRPM: 0.1583 ACQCST: 265.0

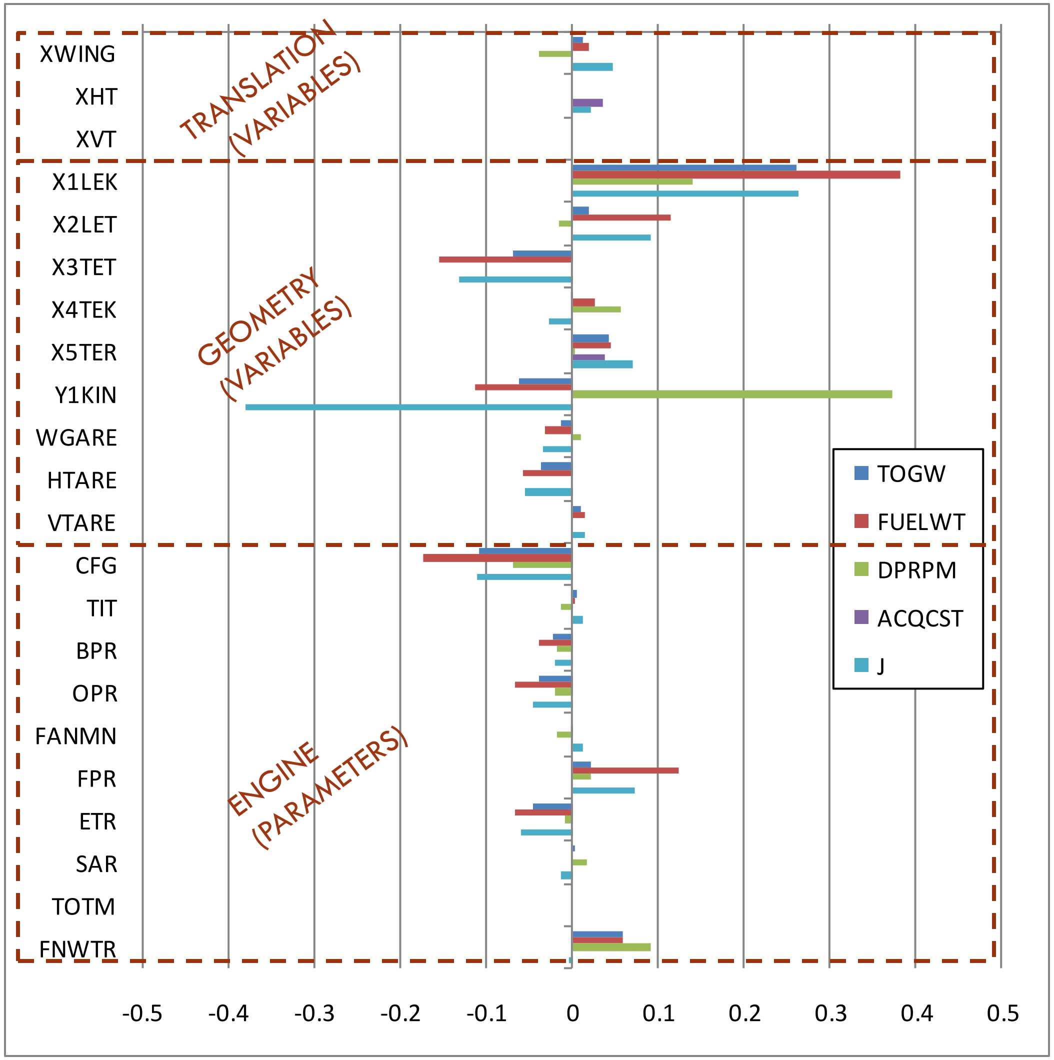


Min ACQCST

TOGW: 826,734 FUELWT: 487,553
DPRPM: 0.1515 ACQCST: 255.7

Post Optimality

Sensitivity



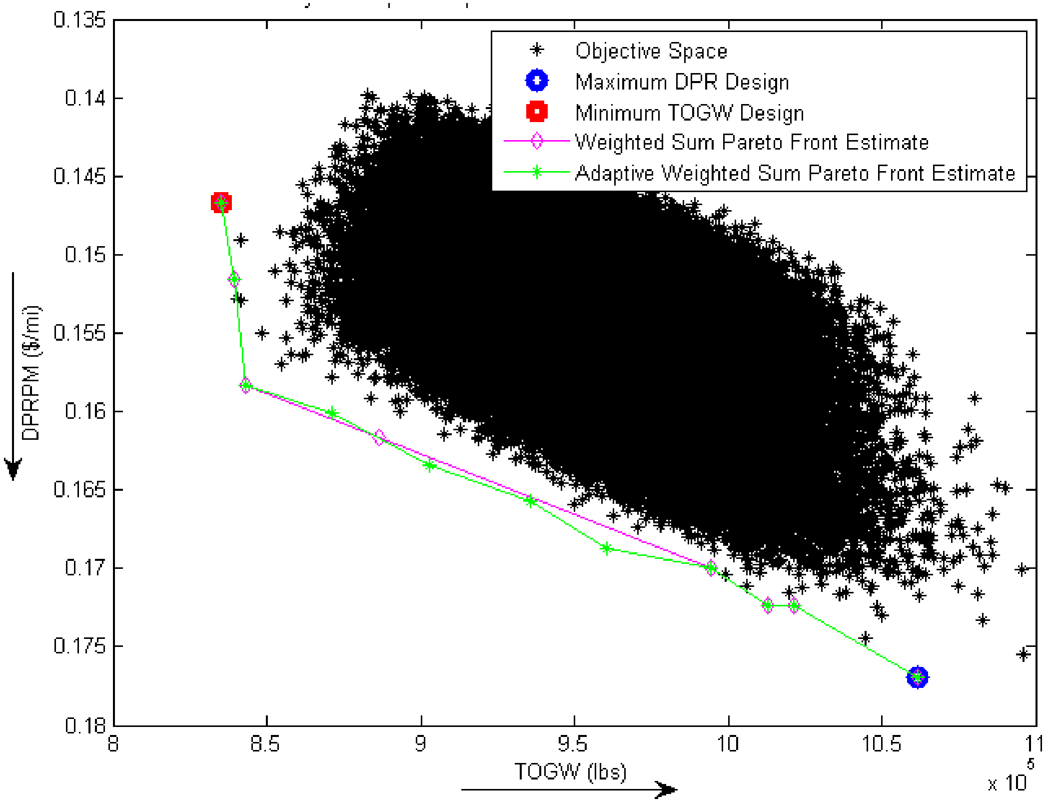
Scaled Output Sensitivity at Optimal Design

Post Optimality

Pareto Front and Trade-off Analysis

- TOGW, FUELWT, and ACQCST are all mutually supportive
- The trades occur with DPRPM
- Pareto front: Using AWS approach

$$J = \lambda \frac{TOGW}{750000} - (1-\lambda)\frac{DPRPM}{0.12}.$$



Conclusions and Recommendations

- Fairly confident that we have found global optimal design for our weight selection
  - Consistent heuristic convergence to the optimal design
  - Need to get a better understanding of the "customer" wants
    - Include additional performance metrics and constraints
      - Stability
      - Emissions
      - Range
      - Altitude
      - Speed
- Refine model around optimal solution
  - Limited domain of RSE
  - Go back to high fidelity model
  - Consider higher order model
  - Re-evaluate constraints
    - "black box" leads to a poor understanding of assumptions, parameters, etc.
  - Include additional parameters (e.g. wing thickness)

References

1. B. Chudoba & Al., “What Price Supersonic Speed ? – An Applied Market Research Case Study – Part 2”, AIAA paper, AIAA 2007-848, *45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, 2007*.
2. C. Trautvetter, “Aerion : A viable Market for SSBJ”, *Aviation International News, Vol. 37 , No. 16, 2005.*
3. Deremaux, Y., Nicolas, P., Négrier, J., Herbin, E., and Ravachol, M., “Environmental MDO and Uncertainty Hybrid Approach Applied to a Supersonic Business Jet,” AIAA-2008-5832, 2008.
4. Briceño, S.I., Buonanno, M.A., Fernández, I., and Mavris, D.N., “A Parametric Exploration of Supersonic Business Jet Concepts Utilizing Response Surfaces,” AIAA-2002-5828, 2002.
5. Federal Aviation Administration (FAA), “Federal Aviation Regulations (FAR)”, FAR91.817
6. *Cox, S.E., Haftka, R.T., Baker, C.A., Grossman, B.G., Mason, W.H., and Watson, L.T., “A Comparison of Global Optimization Methods for the Design of a High-speed Civil Transport,” Journal of Global Optimization, Vol. 21, No. 4, Dec. 2001, pp. 415-432.*
7. B. Chudoba & Al., “What Price Supersonic Speed ? – A Design Anatomy of Supersonic Transportation– Part 1”, AIAA paper, AIAA 2007-848, *45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, 2007*.
8. *Chung, H.S., Alonso, J.J., “Comparison of Approximation Models with Merit Functions for Design Optimization,” AIAA 2000-4754, 200.*

Backup

Post Optimality

Scaling

- Objective function was scaled to be O(1)
- Since the response surface does not have any second order terms, the diagonal of the Hessian is 0