Multidisciplinary System Design Optimization (MSDO)

A General Aviation Aircraft Conceptual Design using Multidisciplinary Optimization

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Outline

- Problem formulation
- Design space exploration
- Single objective SQP optimization
- Sensitivity analysis, scaling
- Genetic Algorithm optimization
- Multiobjective SQP optimization
- Conclusion

Project Definition

- Objective: design a general aviation aircraft in order to:
  - increase Range
  - decrease Gross Take-Off Weight (GTOWeight)
- Motivation: study the performance tradeoff
- Reference aircraft *Cessna 172R Skyhawk:*
  - used to validate the algorithm
  - used as a starting point for gradient-based algorithms

Master Table

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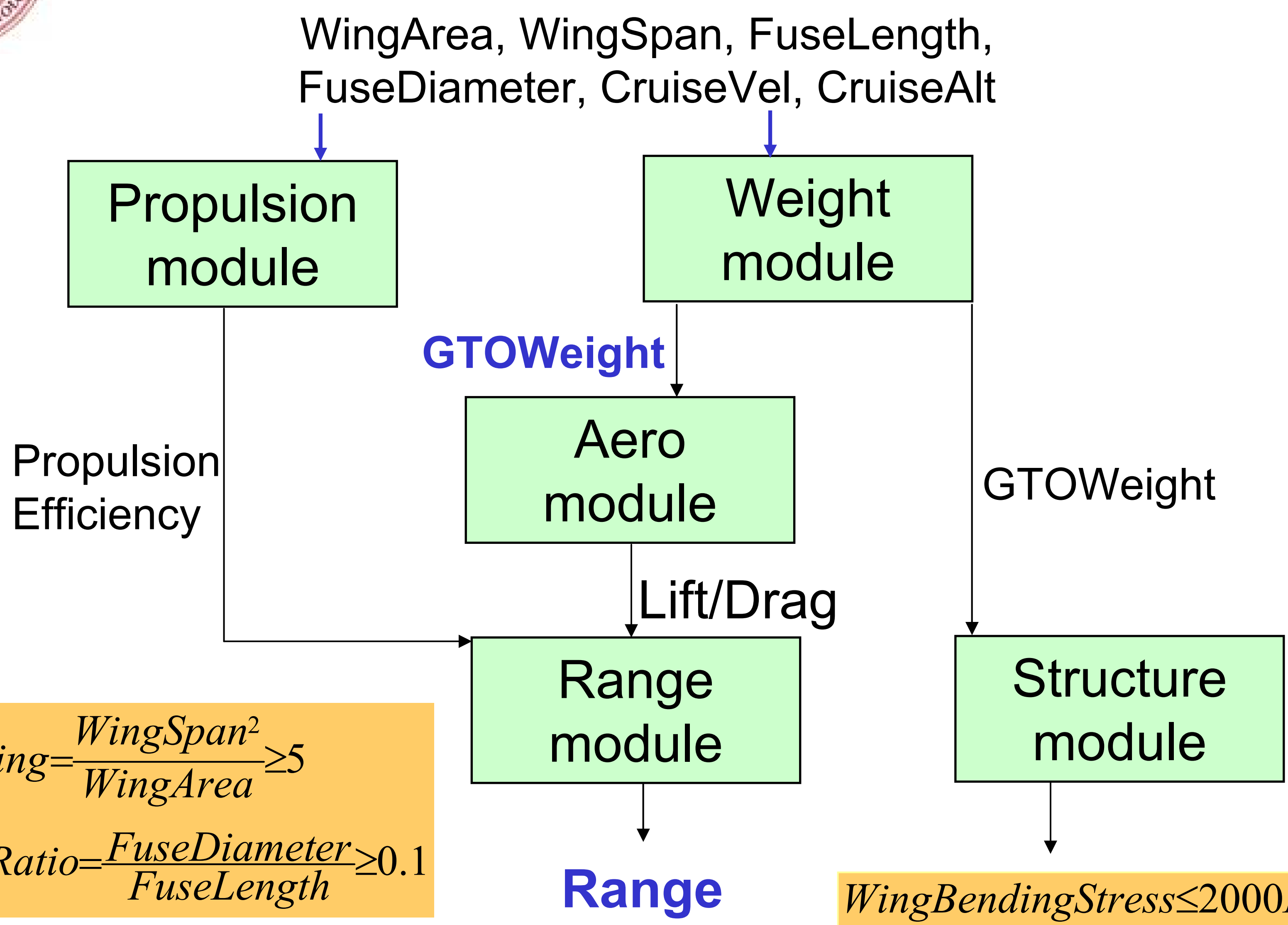
Variables	Description	Units	Min	Cessna *(real performances)*	Max
WingArea	Wing Area	[m^2]	0	16.2	-
WingSpan	Wing Span	[m]	0	11	20
FuseLength	Fuselage Length	[m]	3	8.28	20
FuseDiameter	Fuselage Diameter	[m]	1	1.22	4
CruiseVel	Cruise Velocity	[m/s]	0	62.78	-
CruiseAlt	Cruise Altitude	[m]	0	2438	6000
Range	Range	[km]		1218 *(1074, +13.4%)*	
GTOWeight	Gross Take-Off Weight	[kg]		1309 *(1111, +17.8%)*	
BendStress	Wing Bending Stress	[MPa]			2000
ARWing	Wing Aspect Ratio	[]	5	7.47	
FuseRatio	Fuselage Ratio	[]	0.1	0.147	

Fixed Parameter Values

Fixed Parameters	Description	Units	Value
EngPower	Engine power	[W]	119312 (160 BHP)
EngineWeight	Engine weight	[kg]	70
Sfc	Specific fuel comsumption	$[m^{-1}]$	5.10^{-6}
FracPowerCruise	Fraction of power used at cruise	[]	80%
rotationvelocity	Propeller rotation velocity	[rpm]	2400
propellerdiameter	Propeller blade diameter	[m]	1.91
EngineNum	Number of Engines	[]	1
PayloadWeight	Payload weight	[kg]	100
PassNum	Number of passengers	[]	2

Values of parameters: *Cessna 172R Skyhawk*

Simulation Modules



$$ARWing = \frac{WingSpan^2}{WingArea} \geq 5$$

$$FuseRatio = \frac{FuseDiameter}{FuseLength} \geq 0.1$$

$$WingBendingStress \leq 2000MPa$$

Design Space Exploration: Parameter Study of Range

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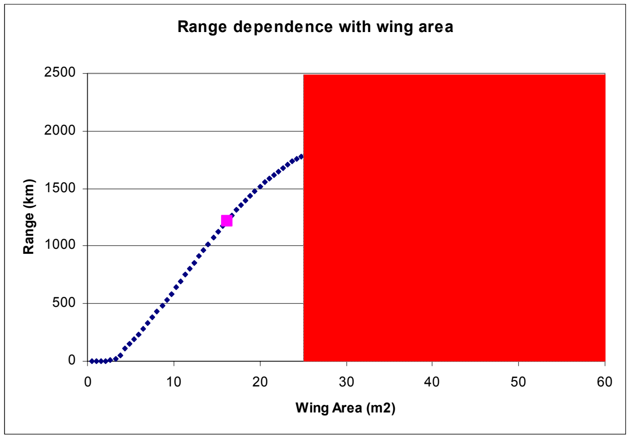
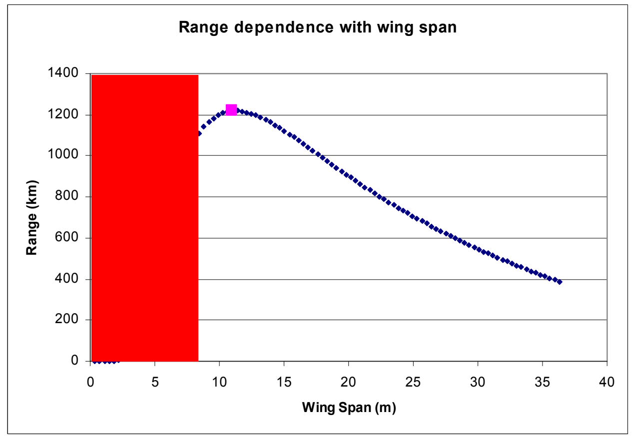
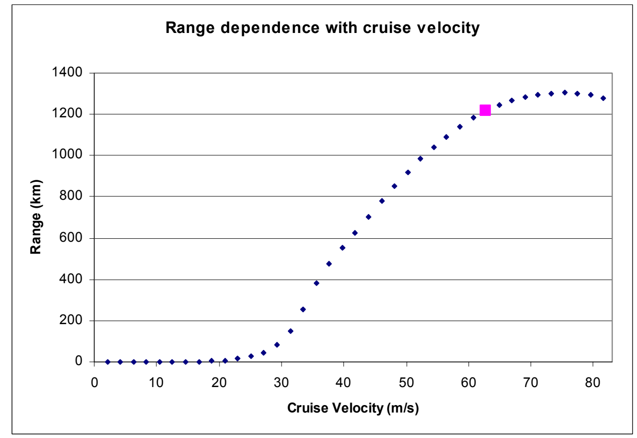
Wing Area



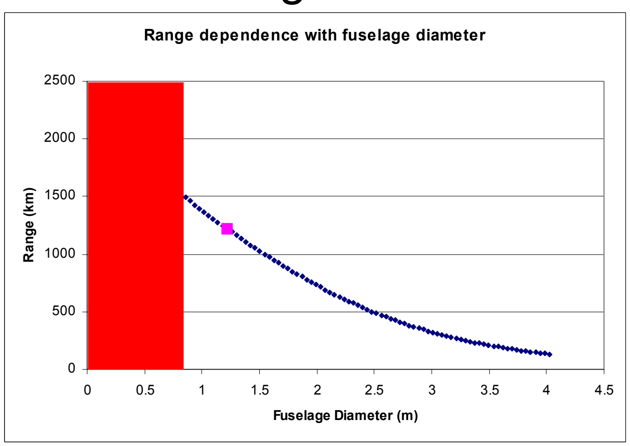
Wing Span



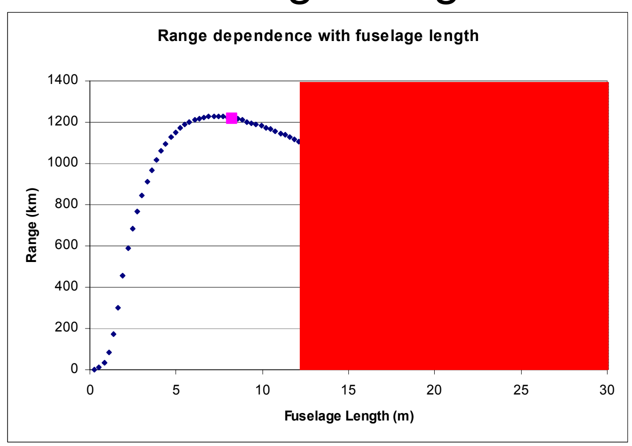
Cruise Velocity



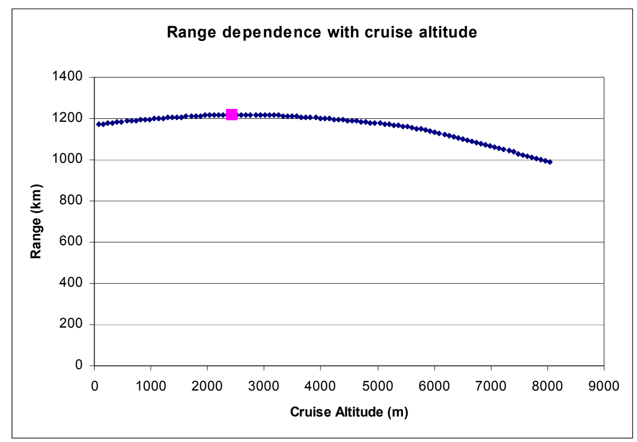
Fuselage Diameter



Fuselage Length



Cruise Altitude



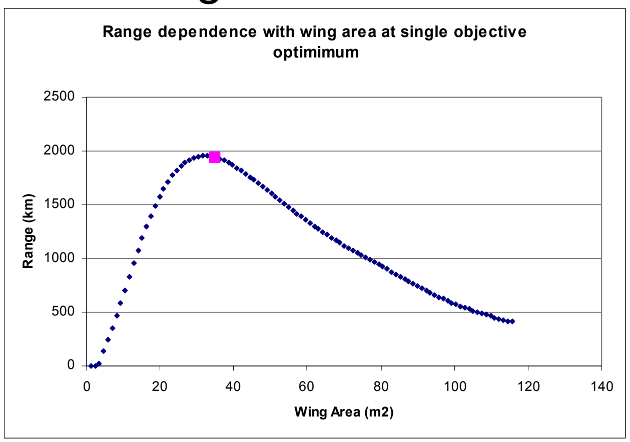
■ *Cessna 172R Skyhawk*

Gradient-based iSIGHT SQP-NLPQL optimization results

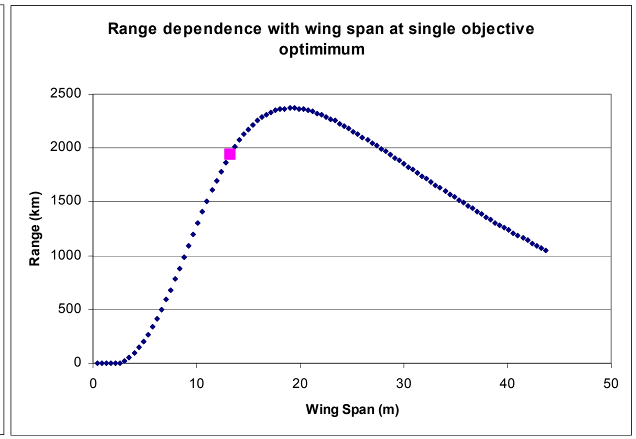
Variables	Units	Min	Cessna	Optimum	Max
WingArea	[m^2]	0	16.2	35.0	-
WingSpan	[m]	0	11	13.2	20
FuseLength	[m]	3.	8.28	5.74	20
FuseDiameter	[m]	1.0	1.22	**1.0**	4
CruiseVel	[m/s]	0	62.78	58.4	-
CruiseAlt	[m]	0	2438	2448	6000
Range	[km]		1218	1940	
GTOWeight	[kg]		1309	1829	
BendStress	[MPa]			**2000**	2000
ARWing	[]	5.0	7.47	**5.0**	
FuseRatio	[]	0.1	0.147	0.174	

Reduced Sensitivity

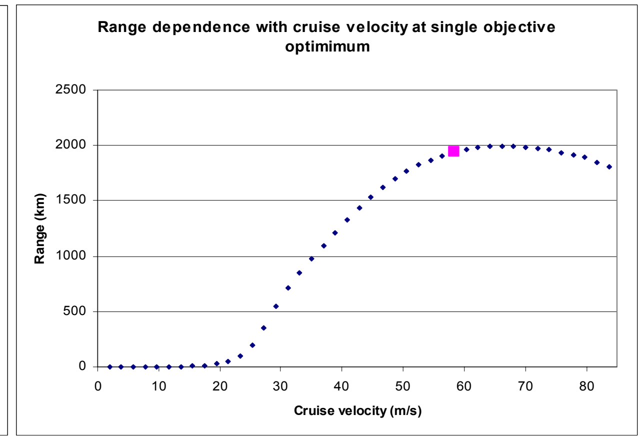
WingArea: -0.1775



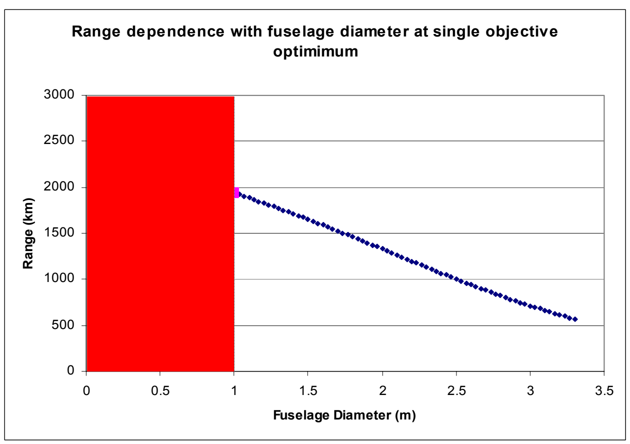
WingSpan: 1.1121



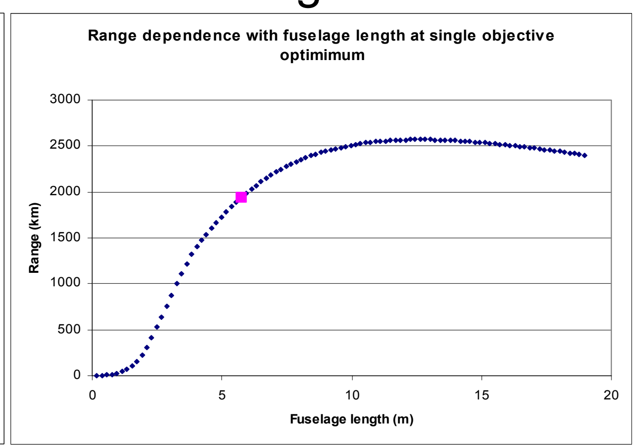
CruiseVelocity: 0.4353



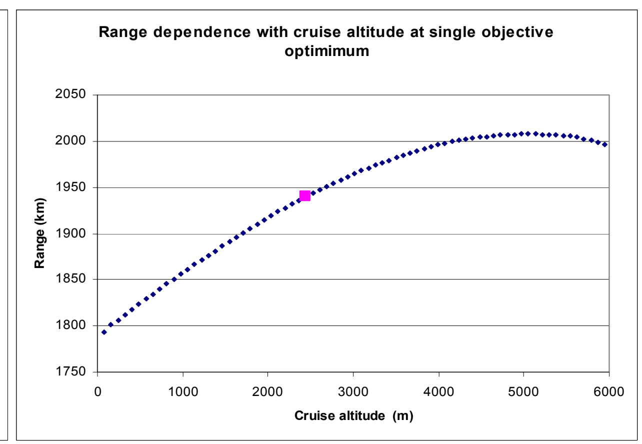
FuseDiameter: -0.2794



FuseLength: 0.7376



CruiseAlt: 0.0602



■ SQP optimum

Sensitivity - Constraint Relaxation

Variables	Min	SQP Optimum	BendStress +25%	FuseDiameter –25%	ARWing –25%	Max
WingArea	0	35.0	62.22	35.05	106.5	-
WingSpan	0	13.2	17.64	13.25	**20**	20
FuseLength	3.	5.74	10	6.45	14.34	20
FuseDiameter	1	**1.0**	**1.0**	**0.75**	1.43	4
CruiseVel	0	58.4	64.97	58.4	73.3	-
CruiseAlt	0	2448	4693	2448	2450	6000
Range		1940	3664	2258	3905	
GTOWeight		1829	3384	1777	6925	
BendStress		**2000**	**2500**	**2000**	**2000**	2000
ARWing	5	**5.0**	**5.0**	**5.0**	**3.75**	
FuseRatio	0.1	0.174	**0.1**	0.116	**0.1**	

Single-Objective Scaling

- We evaluate the Hessian using finite differencing:

$$\frac{\partial^2 J}{\partial x_i^2}(x^*) = \frac{J(x_1,\ldots,x_i+\delta x_i,\ldots,x_n) - 2J(x_1,\ldots,x_j,\ldots,x_i,\ldots,x_n) + J(x_1,\ldots,x_i-\delta x_i,\ldots,x_n)}{\delta x_i^2}$$

Original Hessian coefficients	Scale factors	New Hessian coefficients
$\lambda_{WingArea} = -3.05$	$sf_{WingArea} = 1$	$\lambda_{WingArea} = -3.05$
$\lambda_{WingSpan} = -38.59$	$sf_{WingSpan} = 10$	$\lambda_{WingSpan} = -0.386$
$\lambda_{FuseLength} = -79.28$	$sf_{FuseLength} = 10$	$\lambda_{FuseLength} = -0.773$
$\lambda_{FuseDiameter} = -139.1$	$sf_{FuseDiameter} = 10$	$\lambda_{FuseDiameter} = -1.378$
$\lambda_{CruiseVelocity} = -1.564$	$sf_{CruiseVelocity} = 1$	$\lambda_{CruiseVelocity} = -1.564$
$\lambda_{CruiseAlt} = 0.0136$	$sf_{CruiseAlt} = 0.1$	$\lambda_{CruiseAlt} = 0.0045$

157 iterations to reach optimum

54 iterations to reach optimum

Multi-island Genetic Algorithm results for 40 generations

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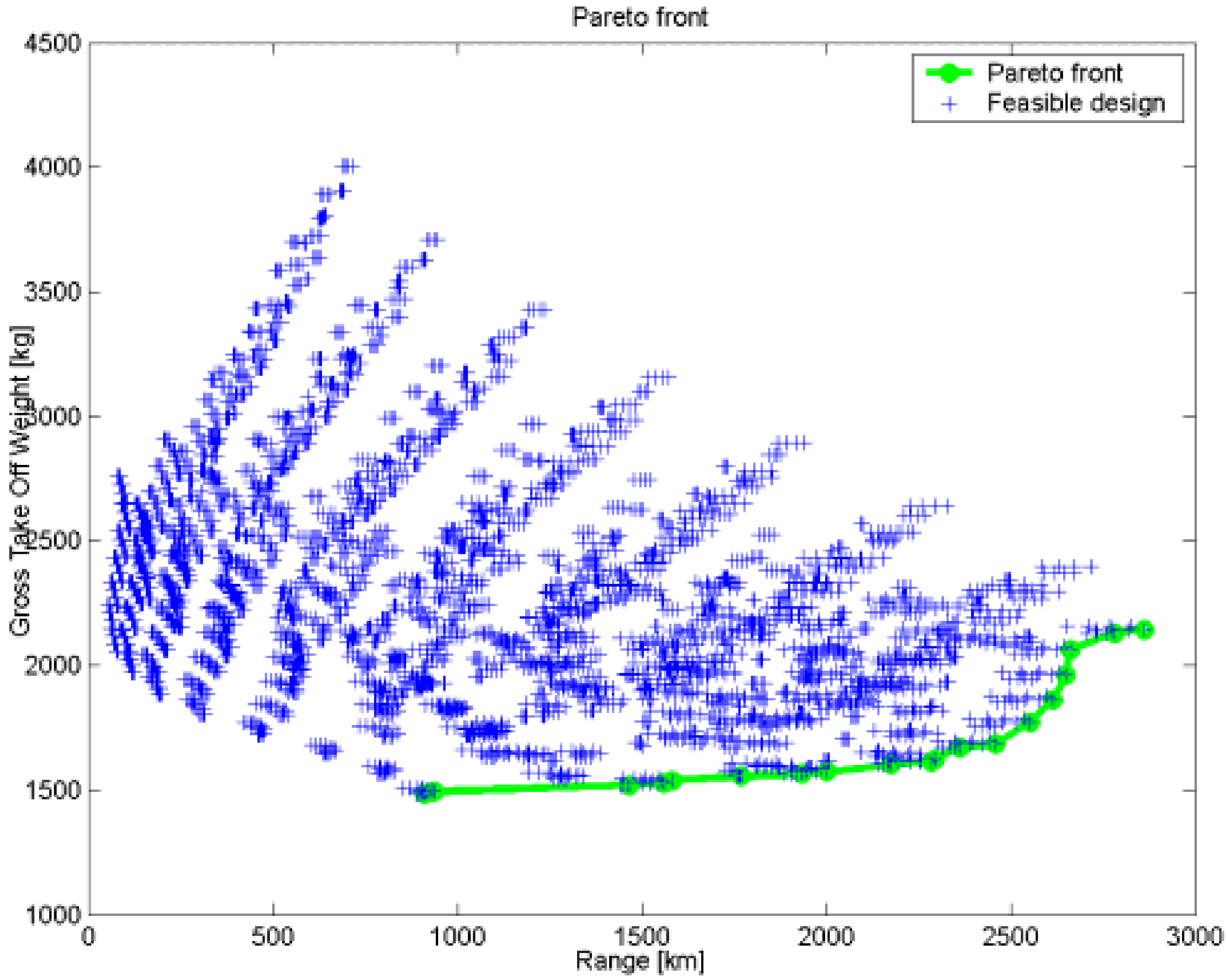
Population	SQP Optim	5 islands of 5	10 islands of 5	10 islands of 10	5 islands of 5	5 islands of 5
Mutation rate	-	0.01	0.01	0.01	0.001	0.1
Wing Area	35.0	21.03	63.39	73.68	58.22	19.61
Wing Span	13.2	10.33	15.97	16.93	16.48	10.10
Fuselage Length	5.74	3.63	14.00	17.22	4.42	3.84
Fuselage Diameter	**1.0**	2.73	1.05	1.02	1.37	3.98
Cruise Velocity	58.4	49.10	67.49	78.78	57.38	22.61
Cruise Altitude	2448	2579.58	5132.50	101.02	1089.86	5331.79
Range	1940	254.13	3821.96	5426.72	1326.00	3.68
Bending Stress	**2000**	1952.07	1862.45	1959.03	1883.36	1741.06
Wing Aspect Ratio	**5.0**	5.08	**4.02**	**3.89**	**4.67**	5.20
Fuselage Ratio	0.174	0.76	**0.075**	**0.059**	0.31	1.04

Multiobjective SQP Optimization

Variables	Cessna	Optim	Case1	Case2	Case3	Case4	Case5
RangeWeight	-	1	2	2.25	2.50	1.50	1
GTOWWeight	-	0	1	1	1	1	2
WingArea	16.2	35.04	30.74	31.18	31.50	29.30	18.5
WingSpan	11	13.24	12.39	12.49	12.55	12.10	9.62
FuseLength	8.28	5.75	5.83	5.82	5.742	5.81	4.758
FuseDiameter	1.22	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
CruiseVel	62.78	58.37	61.24	61.03	62.36	62.13	63.03
CruiseAlt	2438	2445	2447	2445	2998	2447	2447
Range	1074	1940	1893	1902	1937	1858	1265
GTOWeight	1111	1830	1655	1672	1686	1596	1156
BendStress		**2000**	**2000**	**2000**	**2000**	**2000**	**2000**
ARWing	7.47	**5**	**5**	**5**	**5**	**5**	**5**
FuseRatio	0.147	0.174	0.172	0.172	0.174	0.172	0.21

Pareto Front



Conclusions

- Single objective SQP optimization is successful. Scaling and sensitivity analysis are efficient.
- Because of the topology of the design space (too many infeasible designs), the GA approach failed.
- The multi-objective approach illustrates the importance of the weight factors, and is consistent with the real Cessna case.
- Future work:
  - A stability module could be added.
  - The knowledge of the topology of the feasible design space would be valuable.