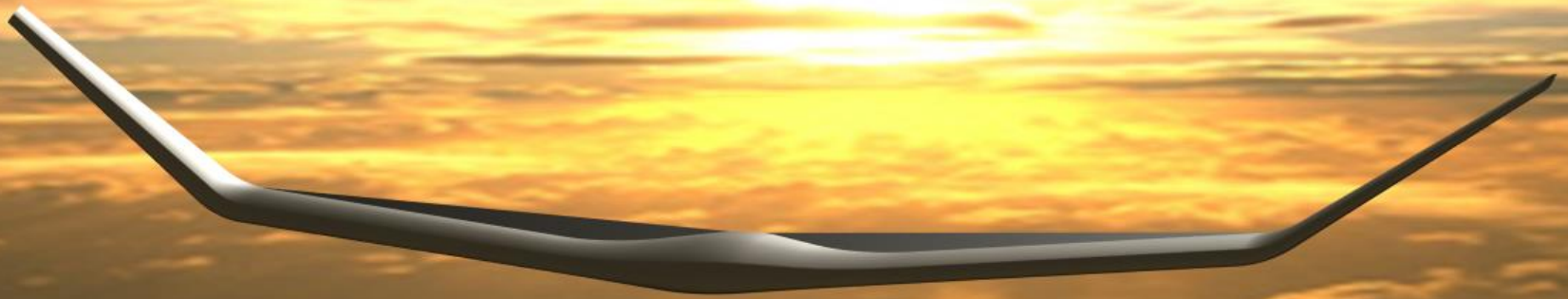


Design Space Exploration of a High-Altitude Aerial Platform “Mothership”



MDAO Webinar hosted by Phoenix Integration

July 22, 2021

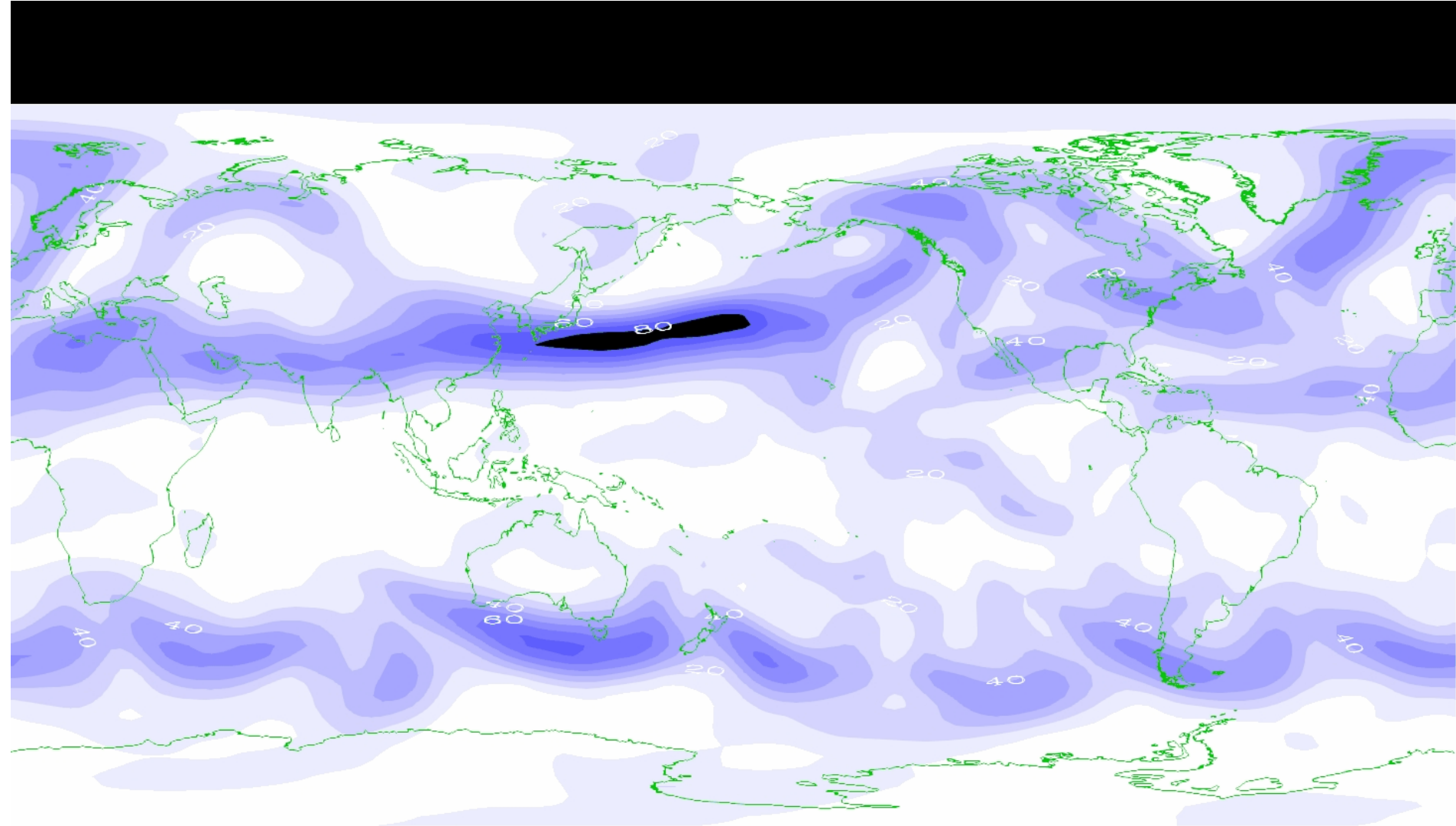
Taewoo Nam

Toyota Research Institute of North America

Outline

- Overview of Toyota High Altitude Aerial Platform Research
- Design Space Exploration through MDA

Wind Speed (m/s) at 10km altitude



Japan has the greatest wind energy resource at high altitudes in the world

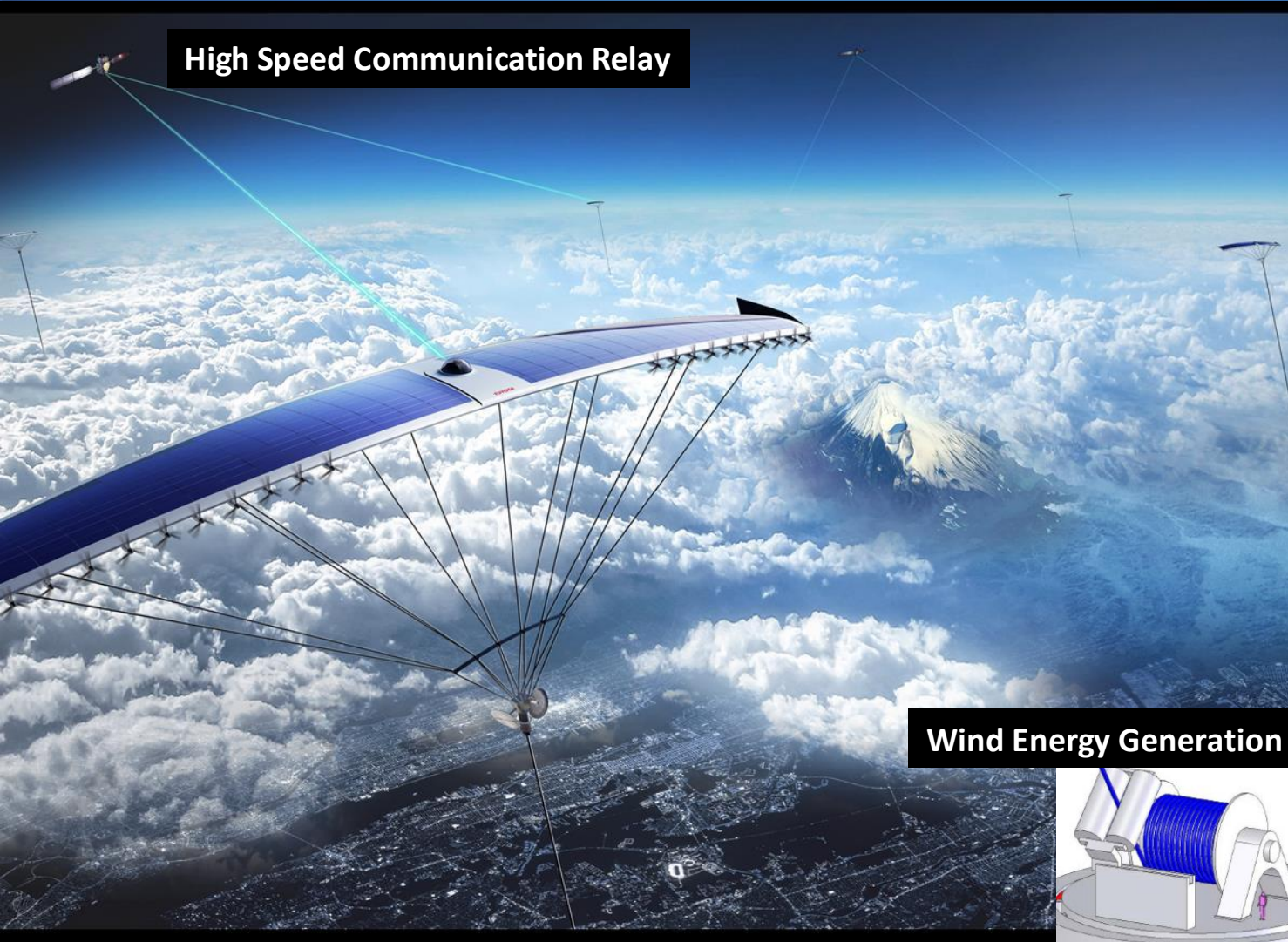
speed color-coded contour map from 2017, 31 to 33,33,332



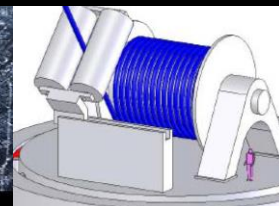
High Altitude Aerial Platform

Mothership

High Speed Communication Relay



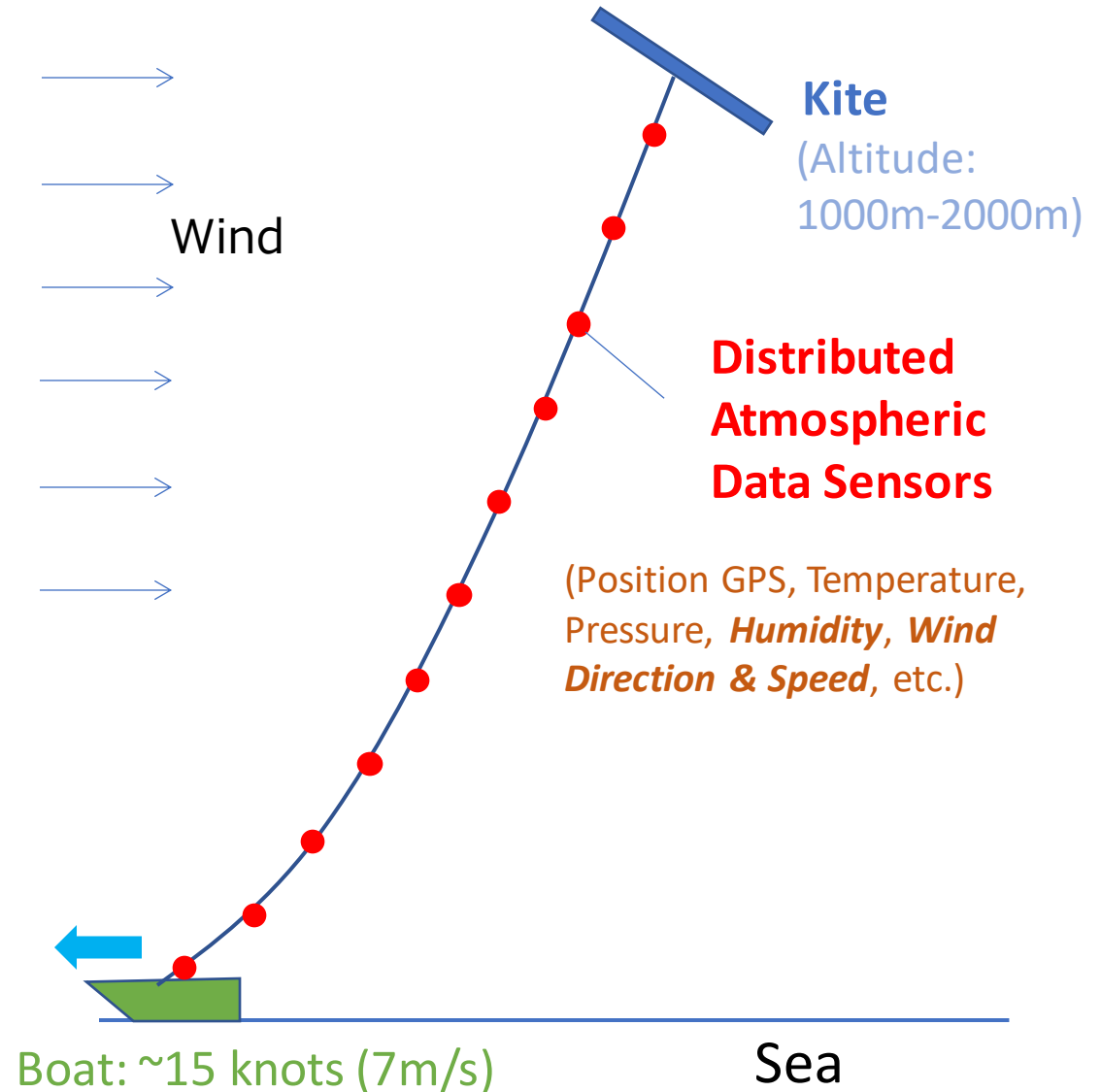
Wind Energy Generation



Transporting goods

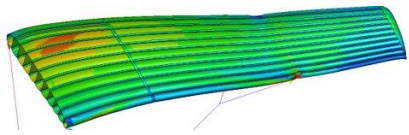


Atmospheric Data Acquisition

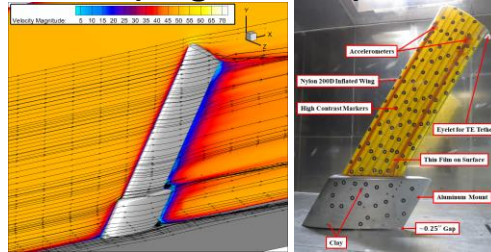


TRINA Mothership Research

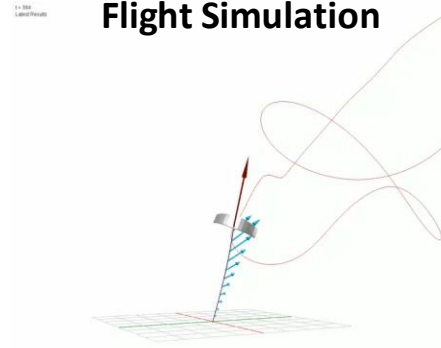
FEM Analysis



Aero-elasticity (Virginia Tech)



Flight Simulation



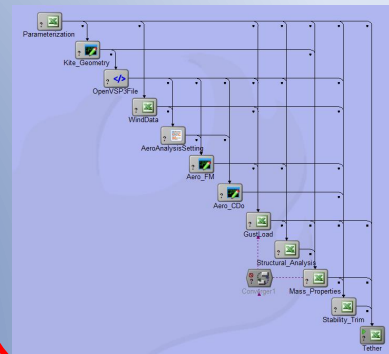
Flight Control Test



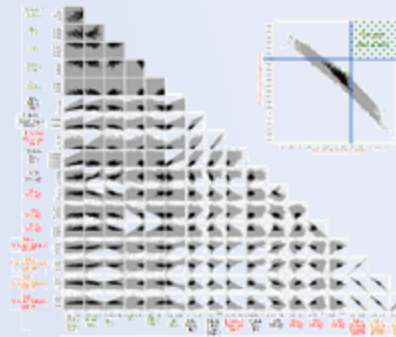
CONOPS



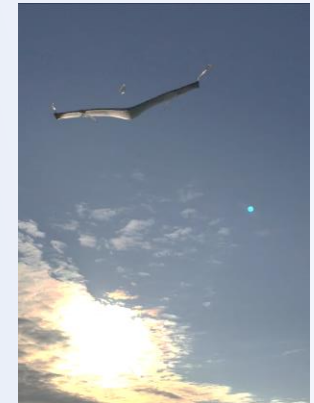
MDA



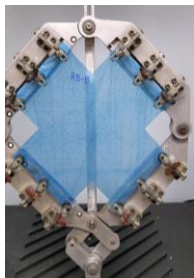
Design Space Exploration



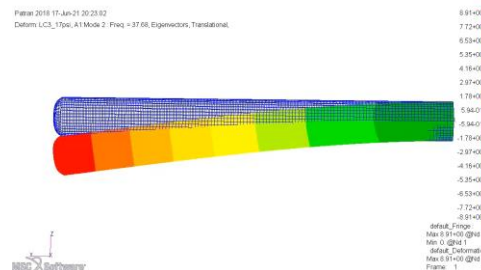
Scale Model Test



Material



Inflatable Structure Dynamics



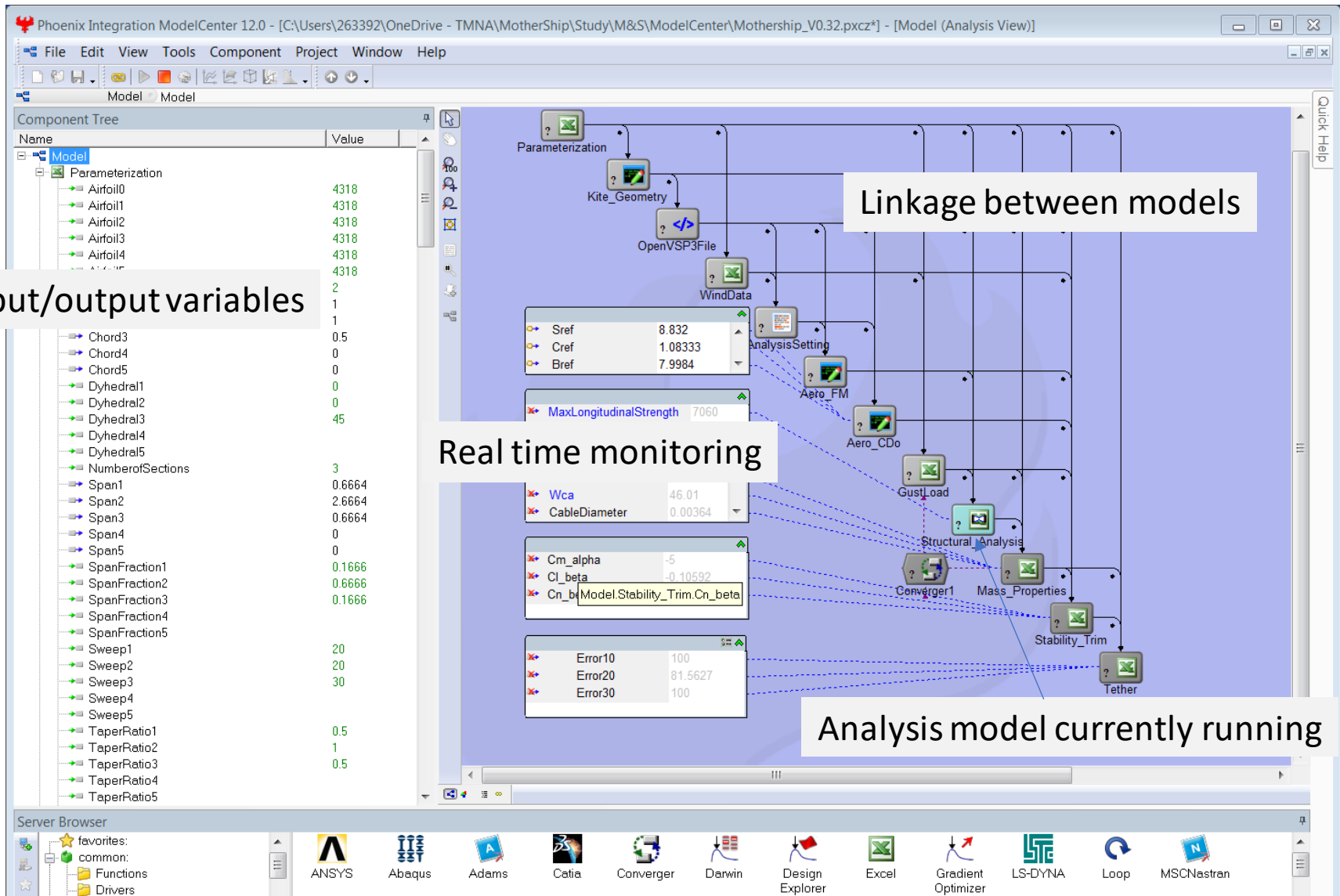
Advanced Actuators and Sensors



(Oklahoma State Univ.)

Integrated Automated Environment V1

Phoenix Integration ModelCenter

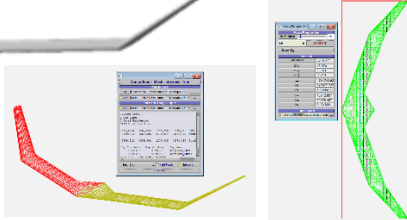


Analysis modules were integrated into an automated environment

Integrated Automated Environment V1

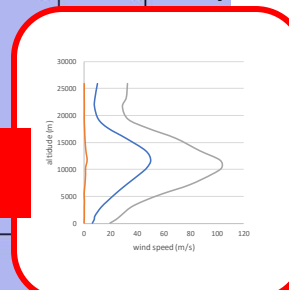
Phoenix Integration ModelCenter

NASA OPENVSP



Kite geometry, Wetted area, CG, Aero Mesh

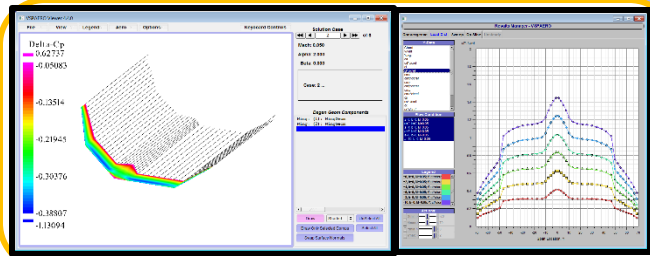
NCEP-DOE Reanalysis 2



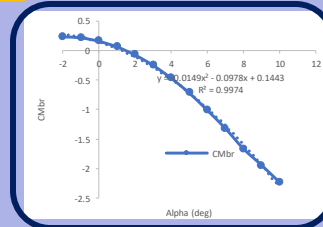
Min. and max wind speed per altitude based on R2 data

Force and Moment
Stability derivatives
Aerodynamic loads

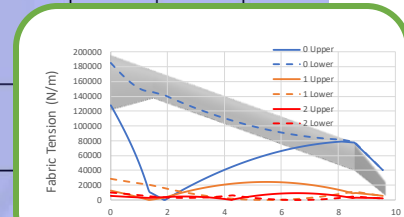
NASA VSPAERO



Limit tension load



Internal loads (shear force,
bending moment, pressure)
required fabric strength



Weight and CG

Static stability and trim

Tether equilibrium using
R2 wind data

Analysis modules were integrated into an automated environment

Reference Configurations

TC100



World Record
Holder
Alt: 5km
Size: 10^1 m^2

TC200



Inflatable Kite
Concept
>5km
 $\sim 10^1 \text{ m}^2$

TC300



Small 10km Kite
(no utility, payload)
10km,
 $10^1 - 10^3 \text{ m}^2$

Baseline Configuration
for Technology Evaluation

TC400



Mothership
10km
 $10^3 - 10^6 \text{ m}^2$

Can fly at favorable wind conditions

Full-year
(10km or above)

Impact of Kite Design
- Inflatable structure
- Higher aspect ratio

Impact of Flight Altitude

**Impact of size, year-round
operation, and utility**

Isolate impact of each dimension for clear understanding

TC200

- Serve as a reference point for sensitivity analysis

Wing Area, $S_{\text{ref}} = 20 \text{ (m}^2\text{)}$

Aspect Ratio, $AR = 20$

Taper Ratio 1, $\gamma_1 = 0.5$

Taper Ratio 2, $\gamma_2 = 1$

Taper Ratio 3, $\gamma_3 = 0.5$

Normalized Span Break, $\eta_1 = 0.15$

Normalized Span Break, $\eta_2 = 0.70$

Normalized Span Break, $\eta_3 = 1$

Leading Edge Sweep, $\Lambda_1 = 20 \text{ (deg)}$

Leading Edge Sweep, $\Lambda_2 = 20 \text{ (deg)}$

Leading Edge Sweep, $\Lambda_3 = 30 \text{ (deg)}$

Dihedral Angle, $DIH_1 = 0 \text{ (deg)}$

Dihedral Angle, $DIH_2 = 0 \text{ (deg)}$

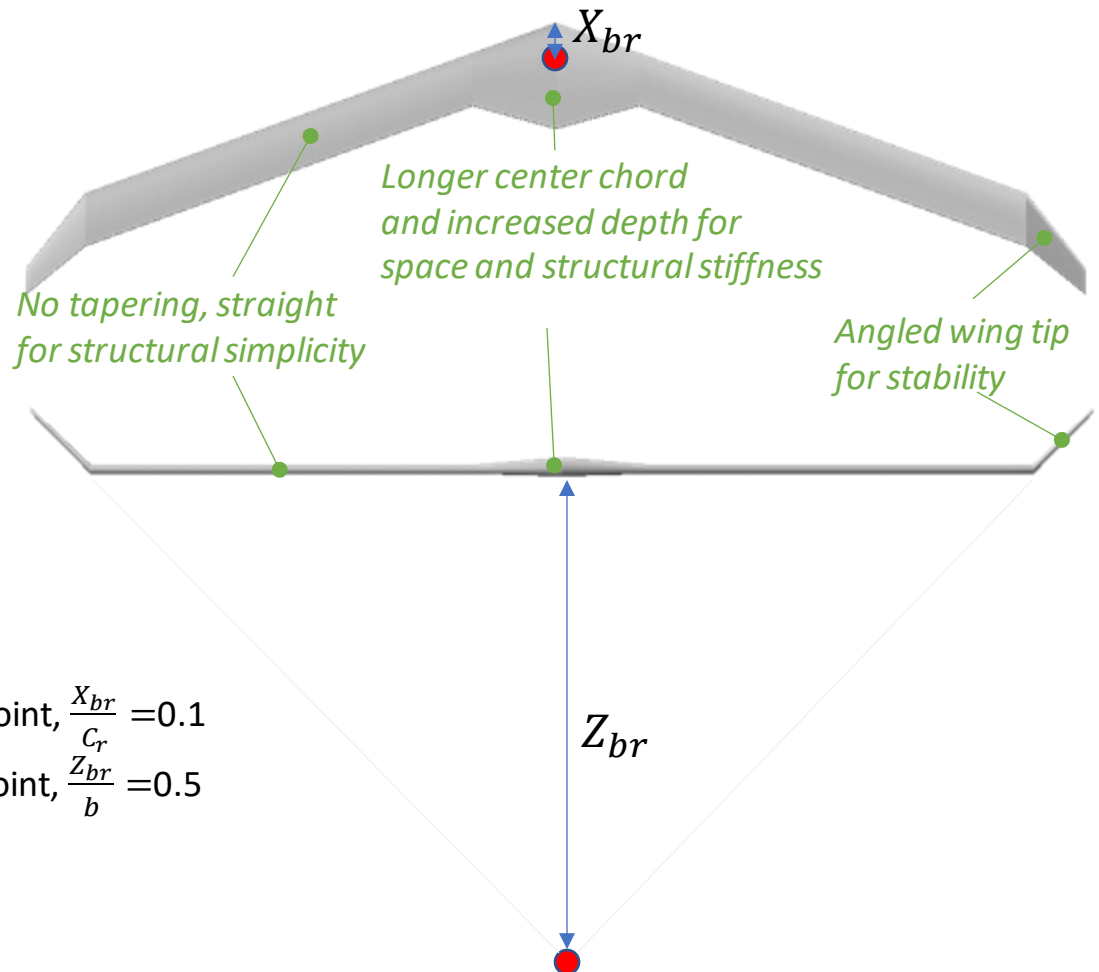
Dihedral Angle, $DIH_3 = 45 \text{ (deg)}$

Normalized X coordinate of the brindle point, $\frac{X_{br}}{C_r} = 0.1$

Normalized Z coordinate of the brindle point, $\frac{Z_{br}}{b} = 0.5$

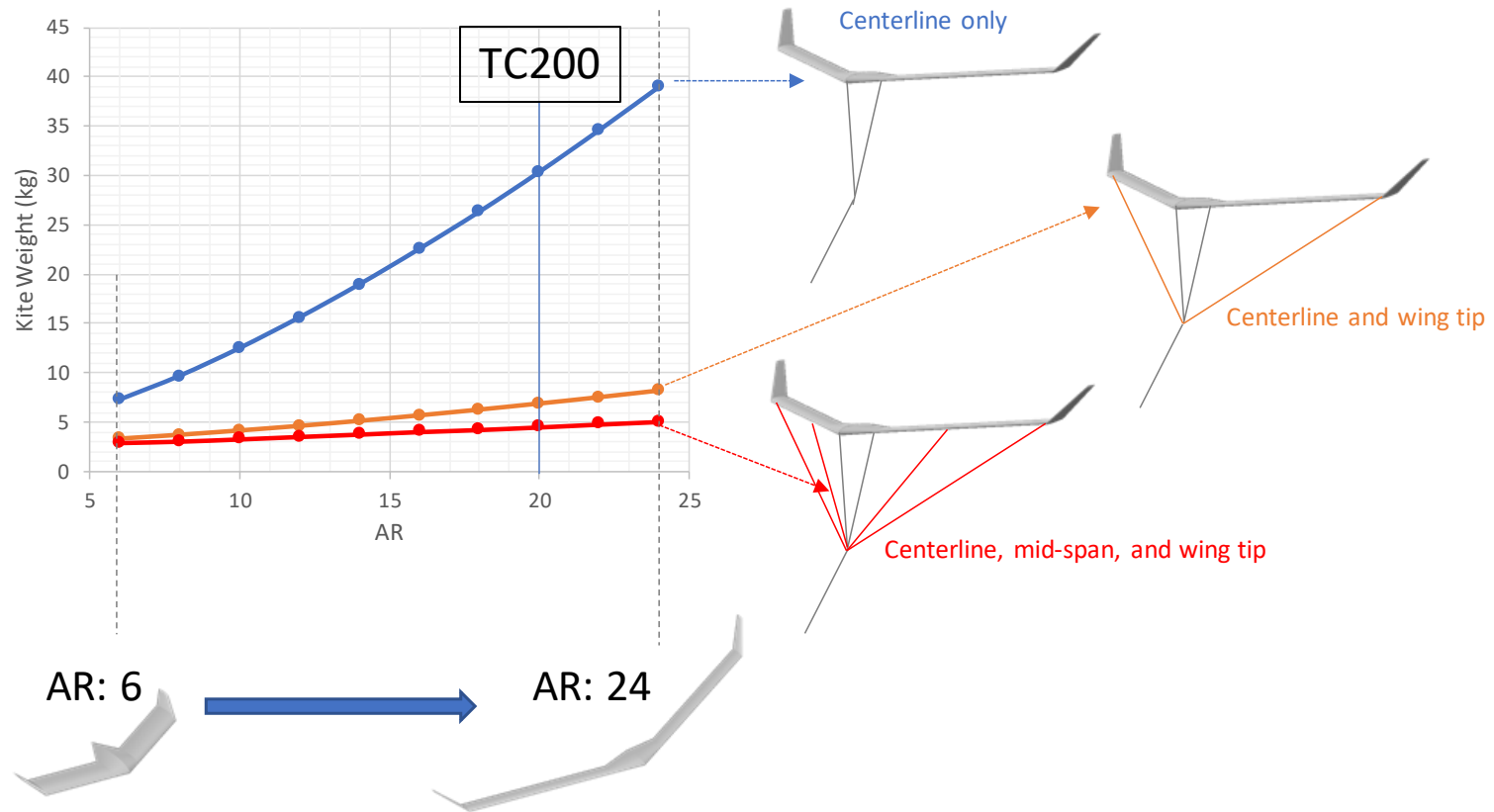
C_r : root chord

b : projected wind span



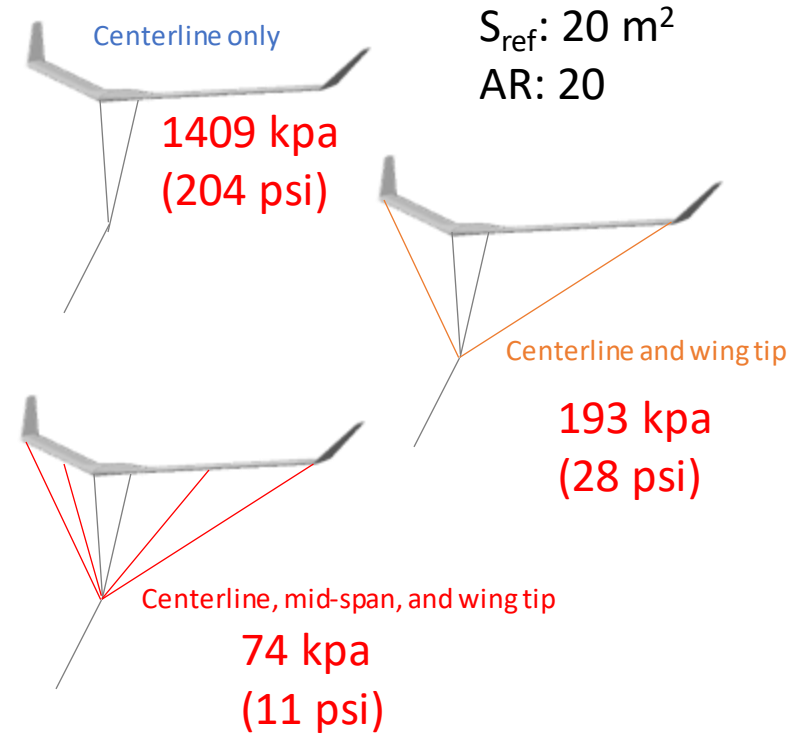
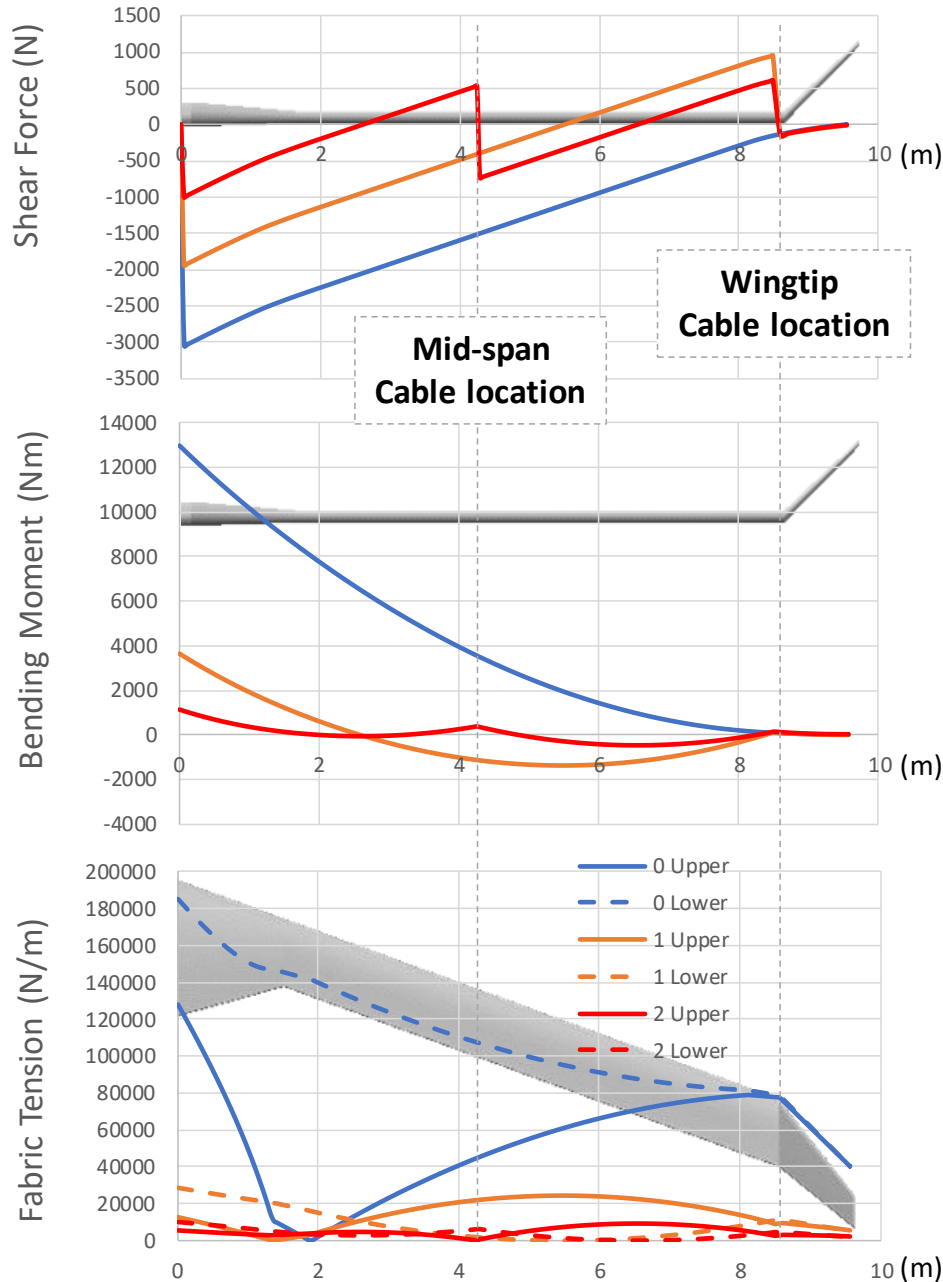
Sensitivity of Aspect Ratio and Wing Support

- Maintain wing area and non-dimensional shape parameters
- Compare three different wing support cable options



Wing tip support cable reduces weight significantly
Additional midspan cable gives marginal benefit

Internal Load Comparison



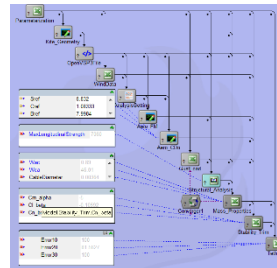
Wing support cable reduces internal loads, leading to lower tension of fabric

Design Space Investigation

Design of Experiment
100~300 cases

	TotalWingArea	TotalAspectRatio	Xbr_cx	SpanFractionX	Dihedral3	BreakPointSpeedRate
1	10	6	0.1	0.5	30	0.3
2	20	6	0.1	0.5	30	0.3
3	10	20	0.1	0.5	30	0.3
4	20	20	0.1	0.5	30	0.3
5	10	6	0.5	0.5	30	0.3
6	20	6	0.5	0.5	30	0.3
7	10	20	0.5	0.5	30	0.3
8	20	20	0.5	0.5	30	0.3
9	10	6	0.1	0.9	30	0.3
10	20	6	0.1	0.9	30	0.3
11	10	20	0.1	0.9	30	0.3
12	20	20	0.1	0.9	30	0.3
13	10	6	0.5	0.9	30	0.3
14	20	6	0.5	0.9	30	0.3
15	10	20	0.5	0.9	30	0.3
16	20	20	0.5	0.9	30	0.3
17	10	6	0.1	0.5	60	0.3
18	20	6	0.1	0.5	60	0.3
19	10	20	0.1	0.5	60	0.3
20	20	20	0.1	0.5	60	0.3
21	10	6	0.5	0.5	60	0.3
22	20	6	0.5	0.5	60	0.3
23	10	20	0.5	0.5	60	0.3
24	20	20	0.5	0.5	60	0.3
25	10	6	0.1	0.9	60	0.3
26	20	6	0.1	0.9	60	0.3
27	10	20	0.1	0.9	60	0.3
28	20	20	0.1	0.9	60	0.3
29	10	6	0.5	0.9	60	0.3
30	20	6	0.5	0.9	60	0.3

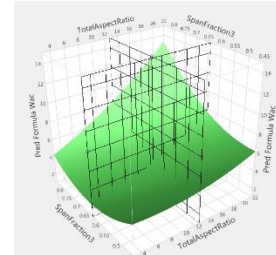
Simulation
(~6 min/case)



Surrogate Model

Check

- Goodness of fits
- Sensitivity



ModelCenter PHOENIX INTEGRATION

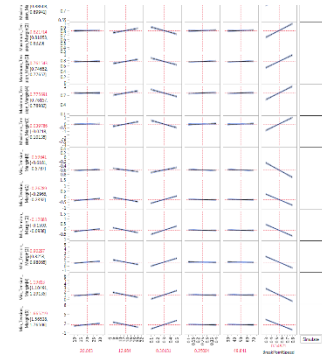
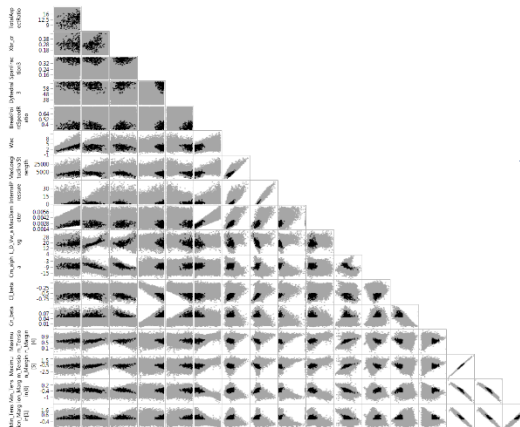
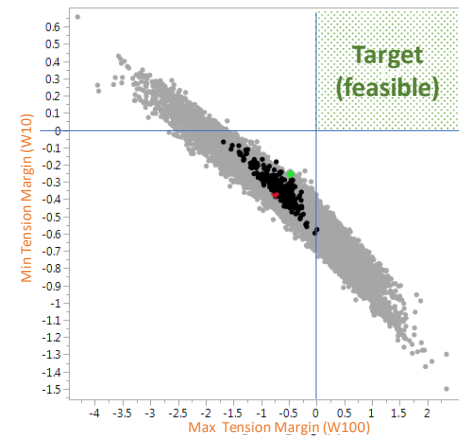
ModelCenter PHOENIX INTEGRATION

jmp
Statistical Discovery™ From SAS

Pareto Optimal

Constraint Analysis via filtering

Monte Carlo Simulation
Using surrogate model
(~1 sec/ 30,000 case)



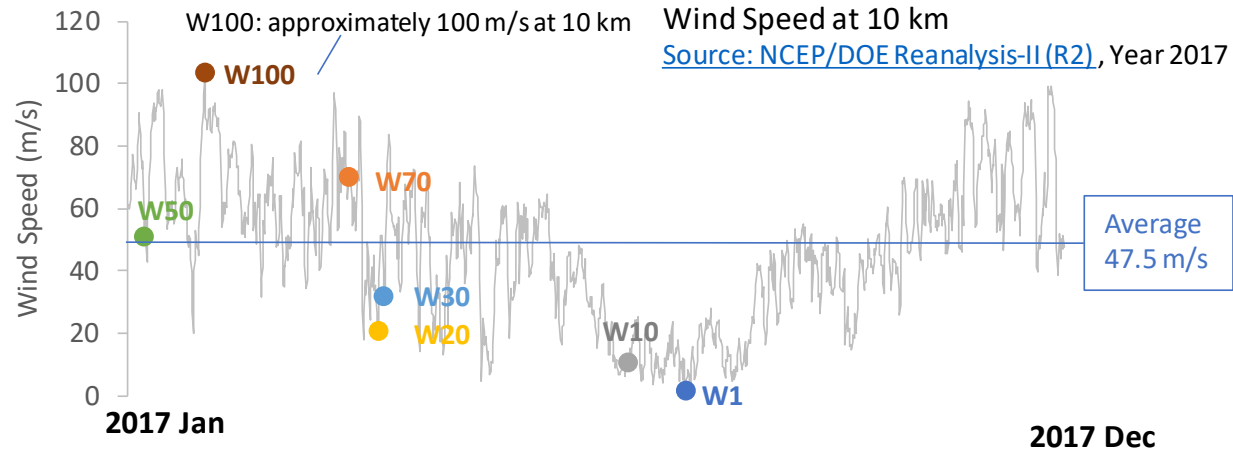
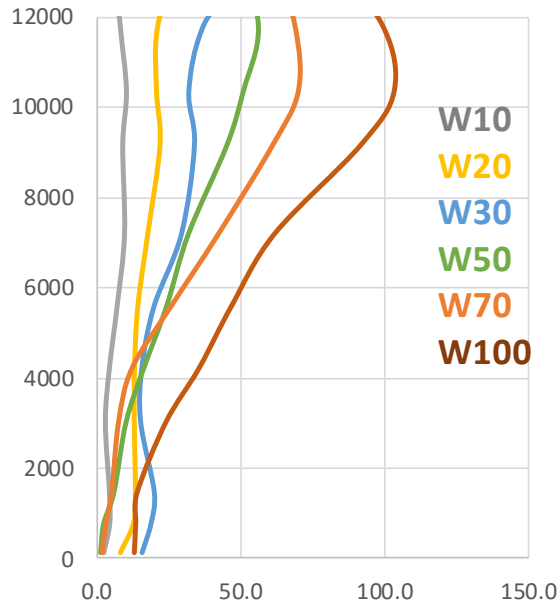
jmp
Statistical Discovery™ From SAS

jmp
Statistical Discovery™ From SAS

jmp
Statistical Discovery™ From SAS

Wind Profile Data and Tension Margin

Selected Wind Speed Profile



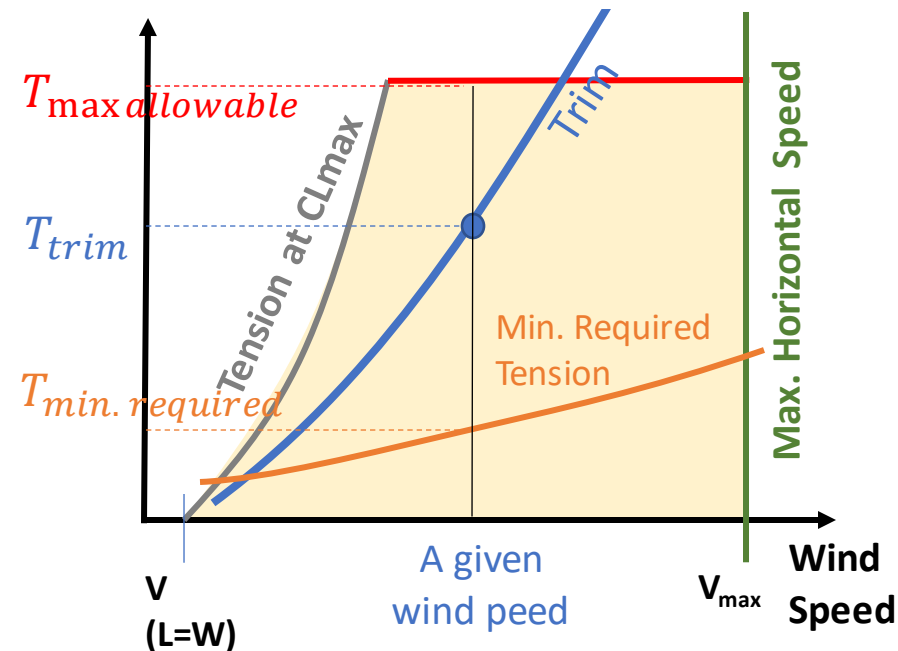
For each wind profile, analyze

$$\text{Min Tension Margin} = \frac{T_{trim}}{T_{min. required}} - 1$$

>0 : Kite can generate enough tension

$$\text{Max Tension Margin} = 1 - \frac{T_{trim}}{T_{max allowable}}$$

>0 : Tether cable will not break at the tension load



Surrogate Model

- 4th order full factorial polynomial functions

Surrogate Model

$$y_1 = f_1(x_1, x_2, \dots, x_6)$$

$$y_2 = f_2(x_1, x_2, \dots, x_6)$$

...

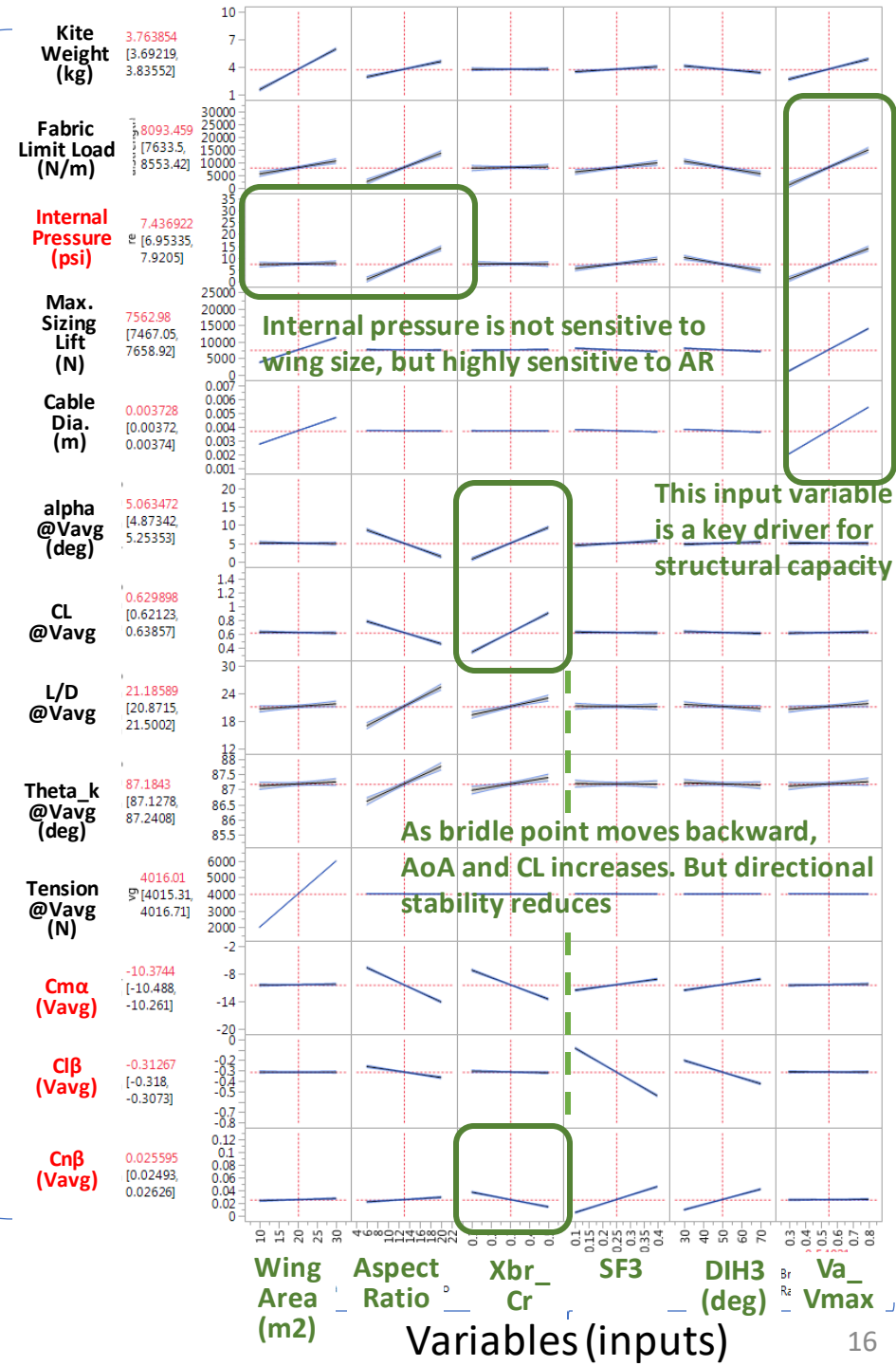
$$y_n = f_n(x_1, x_2, \dots, x_6)$$

Responses
(outputs)

A portion is shown

Prediction Profiler

- Interactive sensitivity matrix built upon the surrogate model
- Good debugging tool



Design Space Exploration via Monte Carlo Simulation

Generate
a random design case



Plot the generated case in Scatter Plot

Random number generator picks
a value of design variables

$x_1 = 21.118$ (Wing Area)
 $x_2 = 11.407$ (Aspect Ratio)
 $x_3 = 0.322$ (Xbr / Cr)
 $x_4 = 0.203$ (Span Fraction Ratio 3)
 $x_5 = 31.892$ (Dihedral Angle 3)
 $x_6 = 0.622$ (Va / Vmax)



Surrogate Model

$$y_1 = f_1(x_1, x_2, \dots, x_6)$$

$$y_2 = f_2(x_1, x_2, \dots, x_6)$$

...

$$y_n = f_n(x_1, x_2, \dots, x_6)$$

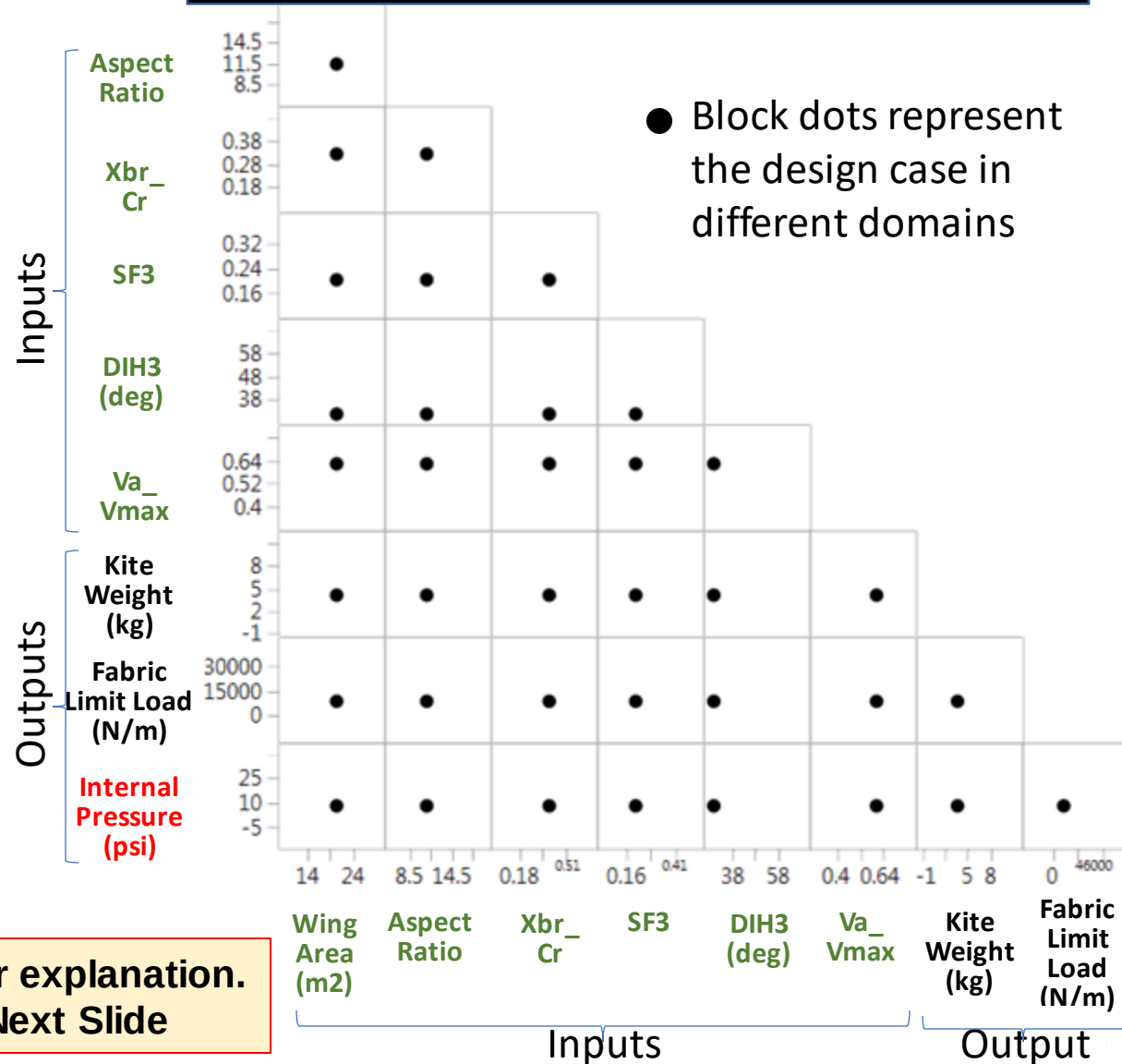


Computed outputs

$y_1 = 4.074$ (Kite Weight)
 $y_2 = 8967$ (Fabric Strength)
 $y_3 = 7.899$ (internal pressure)

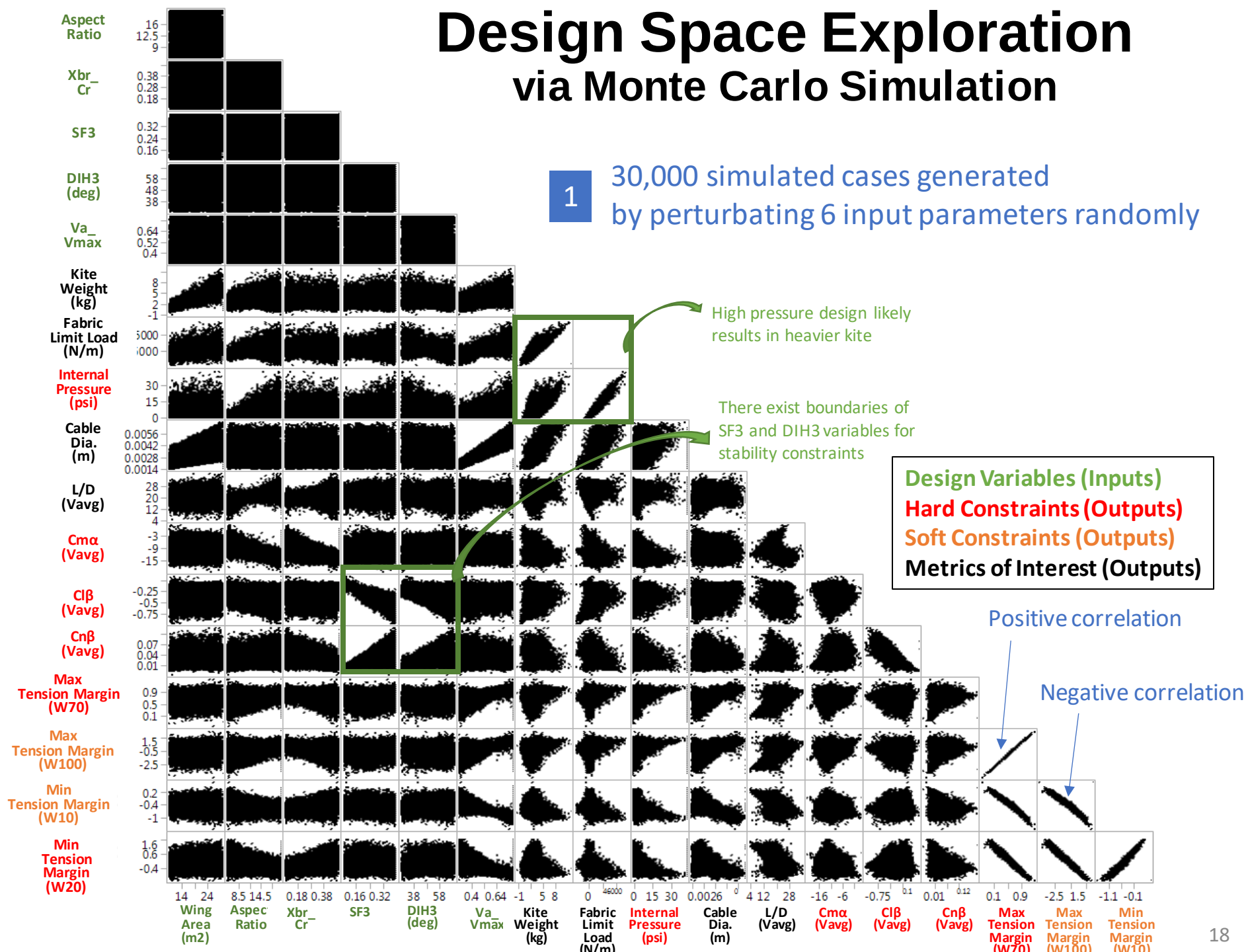
...

This is a single case example for explanation.
Repeat this 30,000 times → Next Slide



Design Space Exploration via Monte Carlo Simulation

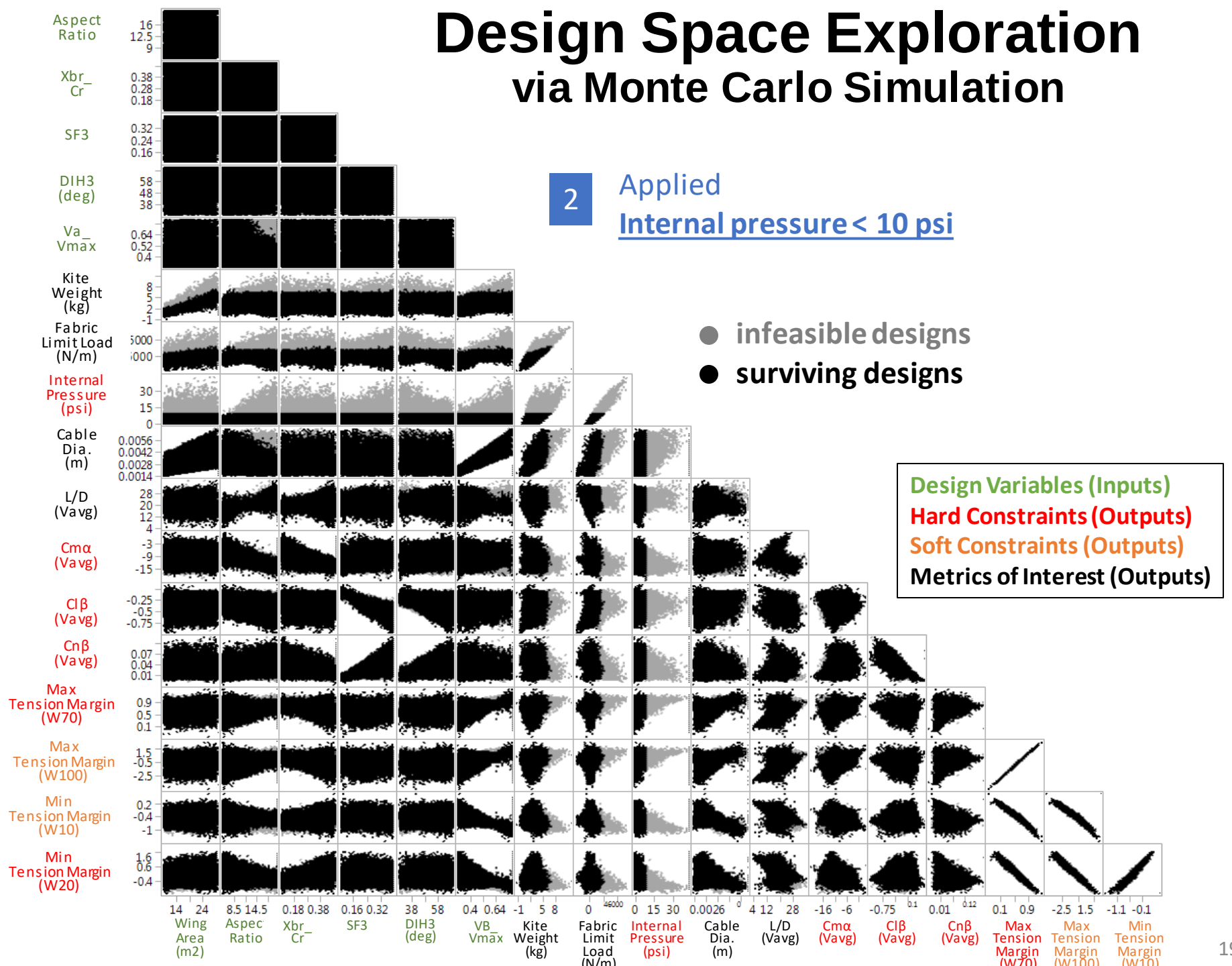
1 30,000 simulated cases generated by perturbing 6 input parameters randomly



Design Space Exploration via Monte Carlo Simulation

2

Applied
Internal pressure < 10 psi



Design Space Exploration via Monte Carlo Simulation

3

Applied

Internal pressure < 10 psi

+ Stability constraints

$Cm\alpha_{br} < -5$

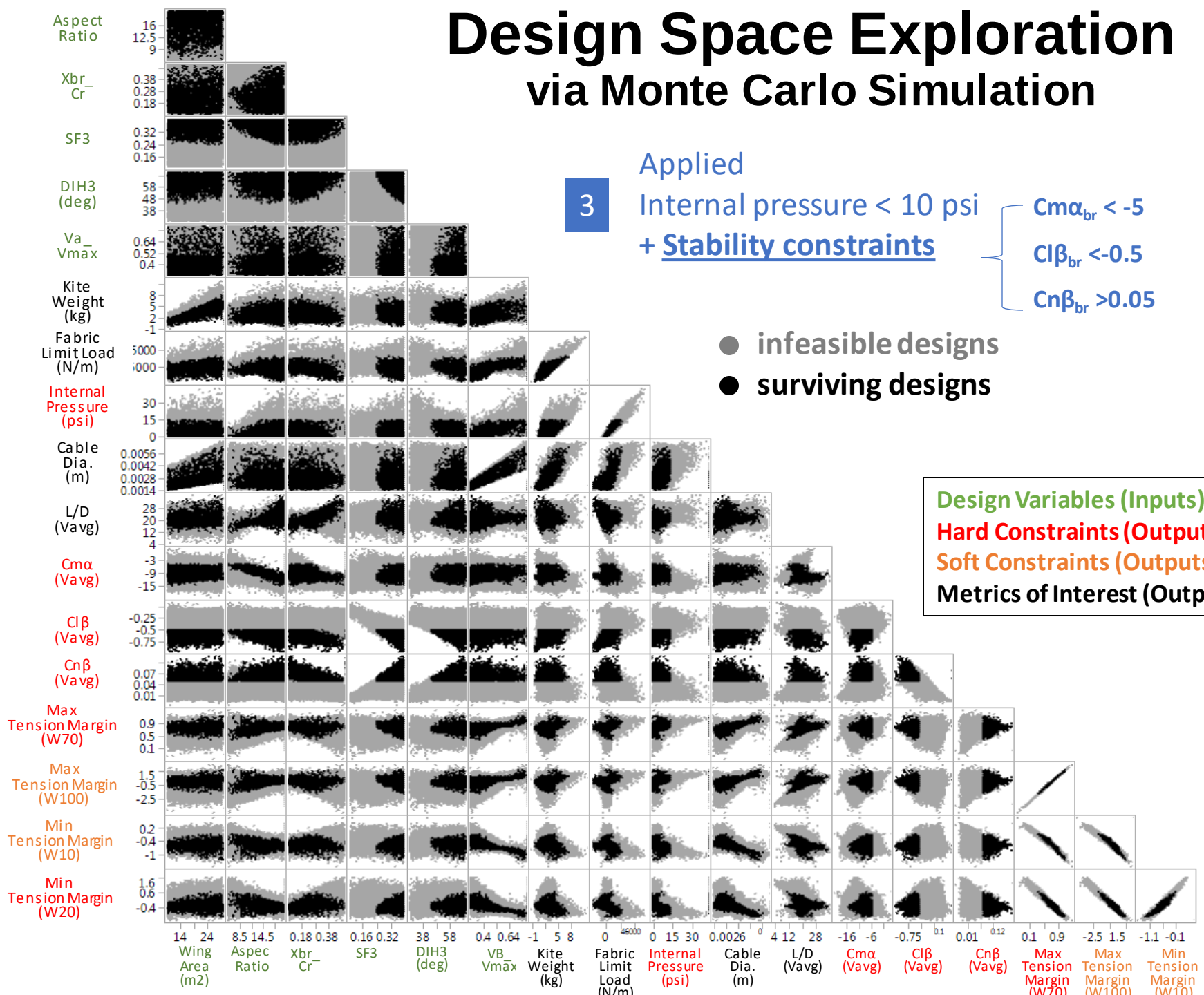
$Cl\beta_{br} < -0.5$

$Cn\beta_{br} > 0.05$

● infeasible designs

● surviving designs

Design Variables (Inputs)
Hard Constraints (Outputs)
Soft Constraints (Outputs)
Metrics of Interest (Outputs)



Design Space Exploration via Monte Carlo Simulation

4

Applied

Internal pressure limit to 10 psi

+ Stability constraints

+ Tether tension margin for W20 and W70

**There is no solution meeting
W10 and W100 simultaneously**

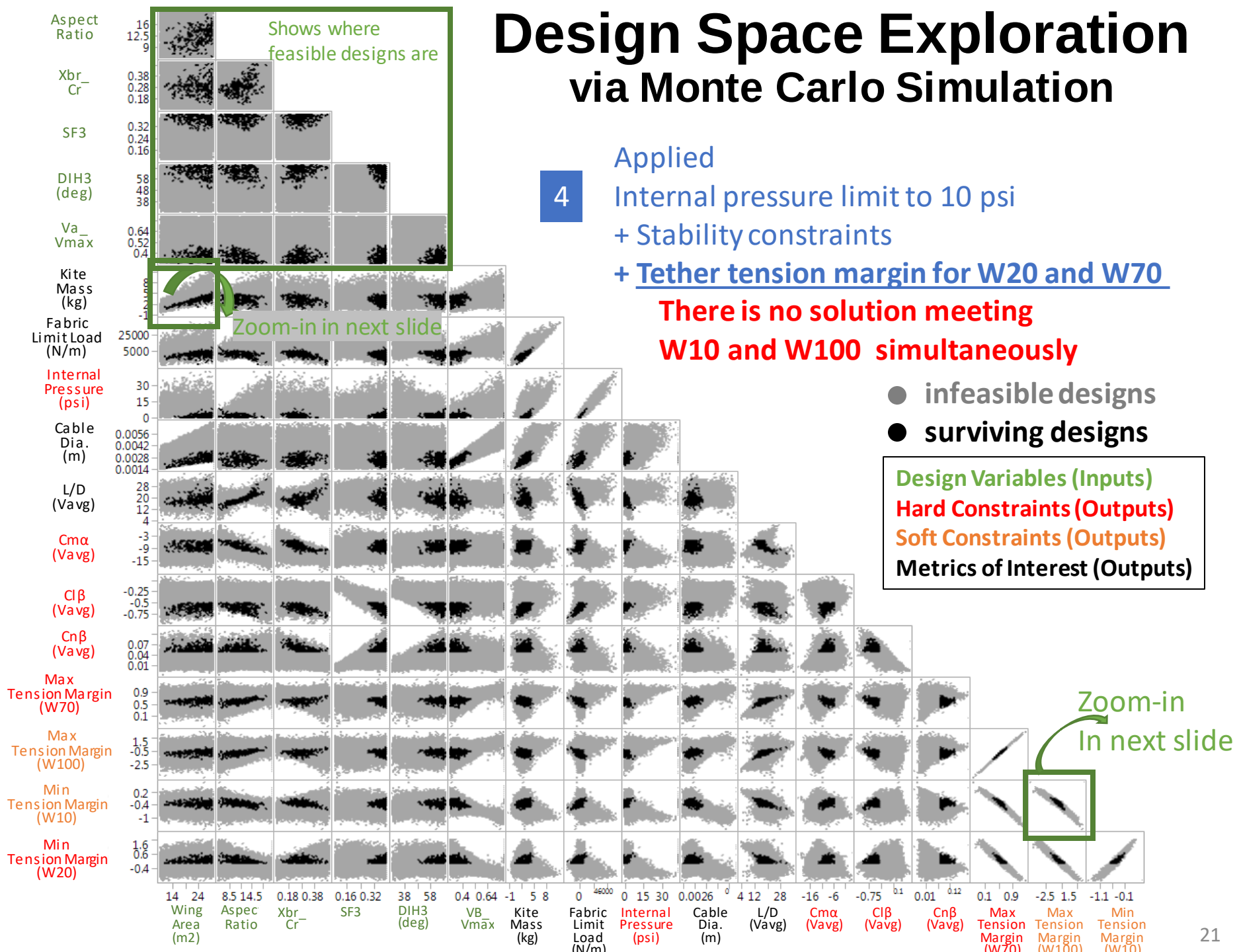
- infeasible designs
- surviving designs

Design Variables (Inputs)

Hard Constraints (Outputs)

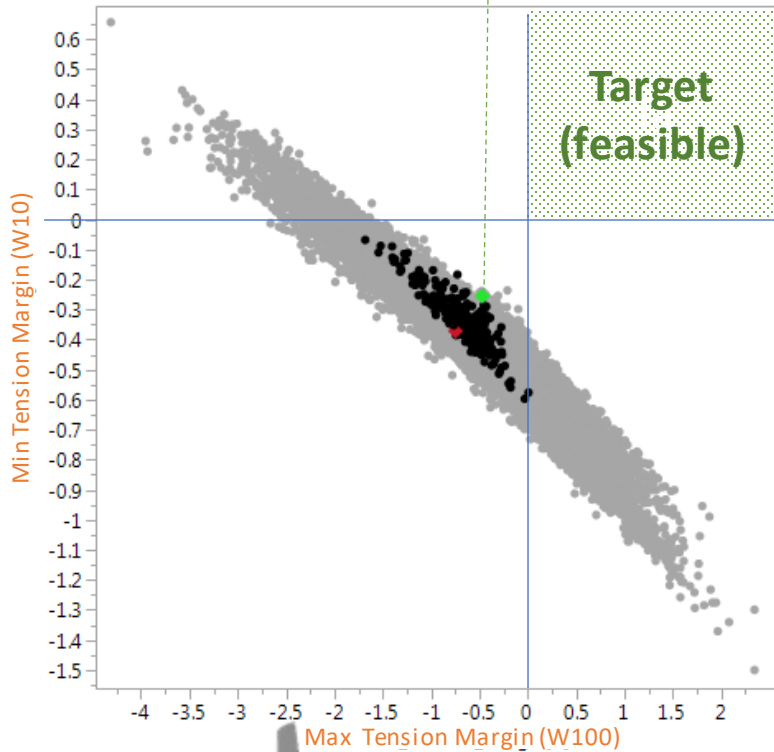
Soft Constraints (Outputs)

Metrics of Interest (Outputs)



Pareto Optimal

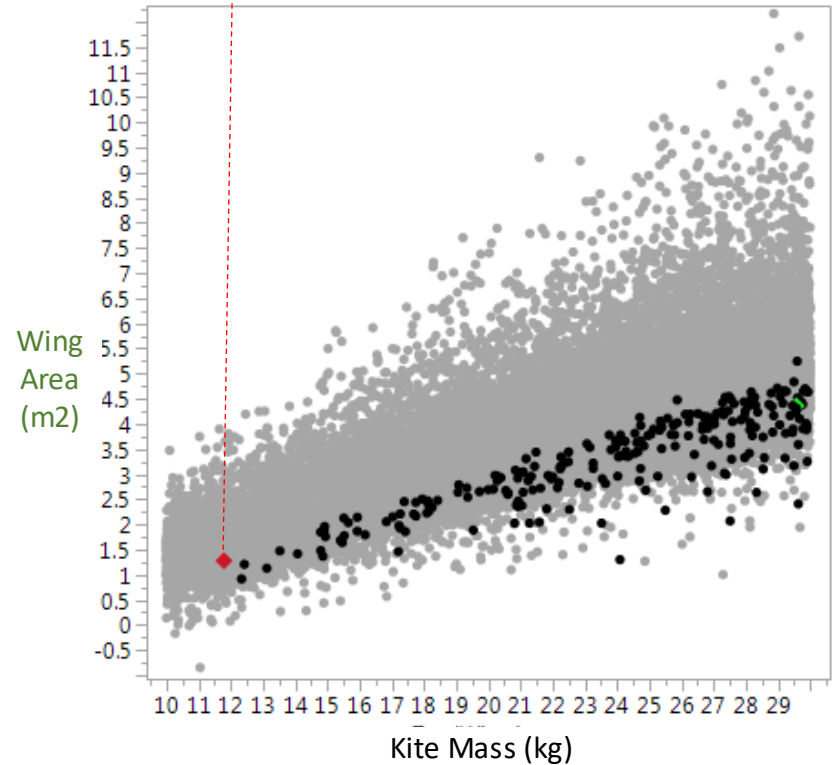
Max feasibility design
(closest to the feasible space)



TC201



Min. cost design
(low weight and small size)



Not good candidate for scaling up to Mothership

Select max feasibility design TC201 for next step

TC201

Wing Area, $S_{\text{ref}} = 30 \text{ (m}^2\text{)}$

Aspect Ratio, $AR = 14$

Taper Ratio 1, $\gamma_1 = 0.5$

Taper Ratio 2, $\gamma_2 = 1$

Taper Ratio 3, $\gamma_3 = 0.5$

Normalized Span Break, $\eta_1 = 0.15$

Normalized Span Break, $\eta_2 = 0.65$

Normalized Span Break, $\eta_3 = 1$

Leading Edge Sweep, $\Lambda_1 = 20 \text{ (deg)}$

Leading Edge Sweep, $\Lambda_2 = 20 \text{ (deg)}$

Leading Edge Sweep, $\Lambda_3 = 30 \text{ (deg)}$

Dihedral Angle, $DIH_1 = 0 \text{ (deg)}$

Dihedral Angle, $DIH_2 = 0 \text{ (deg)}$

Dihedral Angle, $DIH_3 = 55 \text{ (deg)}$

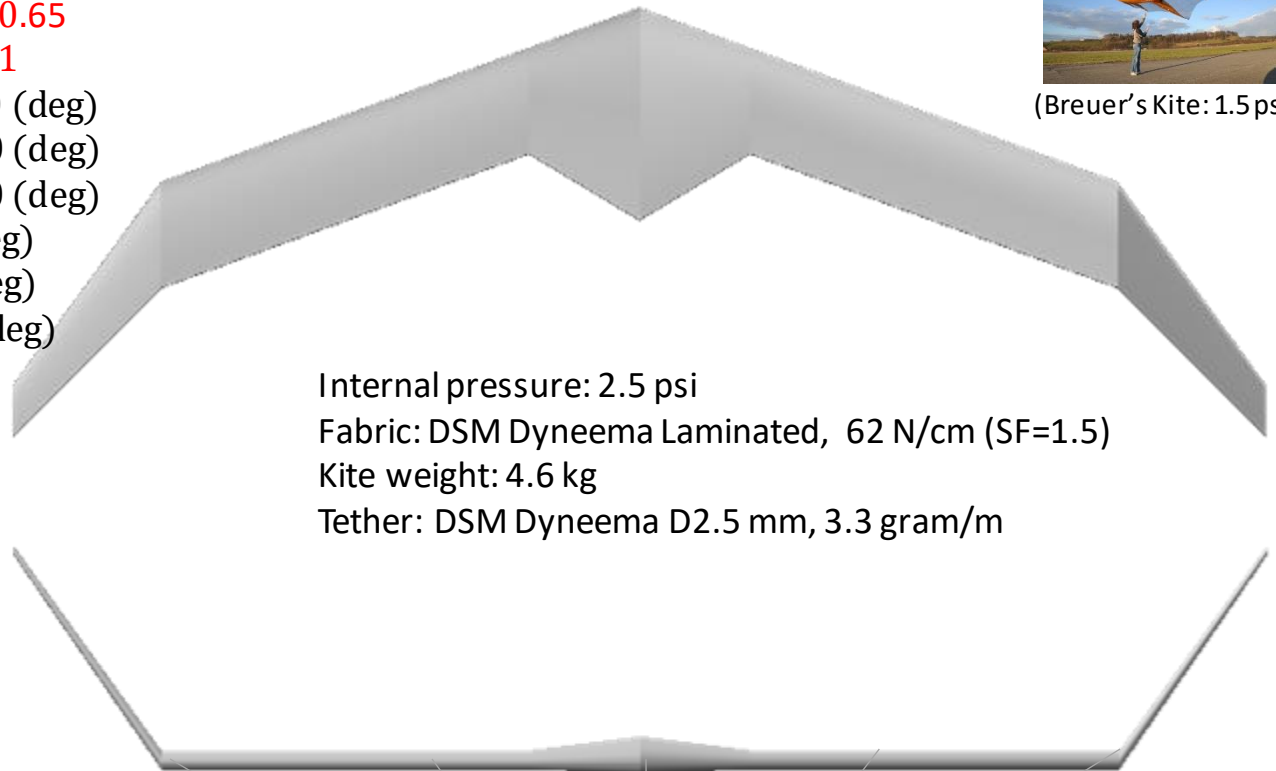
Airfoil: NACA 4318

Normalized X coordinate of the bridle point, $\frac{X_{br}}{C_r} = 0.16$

Normalized Z coordinate of the bridle point, $\frac{Z_{br}}{b} = 0.5$



(Breuer's Kite: 1.5 psi)



Internal pressure: 2.5 psi

Fabric: DSM Dyneema Laminated, 62 N/cm (SF=1.5)

Kite weight: 4.6 kg

Tether: DSM Dyneema D2.5 mm, 3.3 gram/m



Reference Configurations

Baseline Configuration
for Technology Evaluation

TC100



World Record
Holder
Alt: 5km
Size: 10^1 m^2

TC200



Inflatable Kite
Concept
>5km
 $\sim 10^1 \text{ m}^2$

TC300



Small 10km Kite
(no utility, payload)
10km,
 $10^1 - 10^3 \text{ m}^2$

TC400



Mothership
10km
 $10^3 - 10^6 \text{ m}^2$

← Can fly at favorable wind conditions → Full-year
(10km or above)

Impact of Kite Design
- Inflatable structure
- Higher aspect ratio

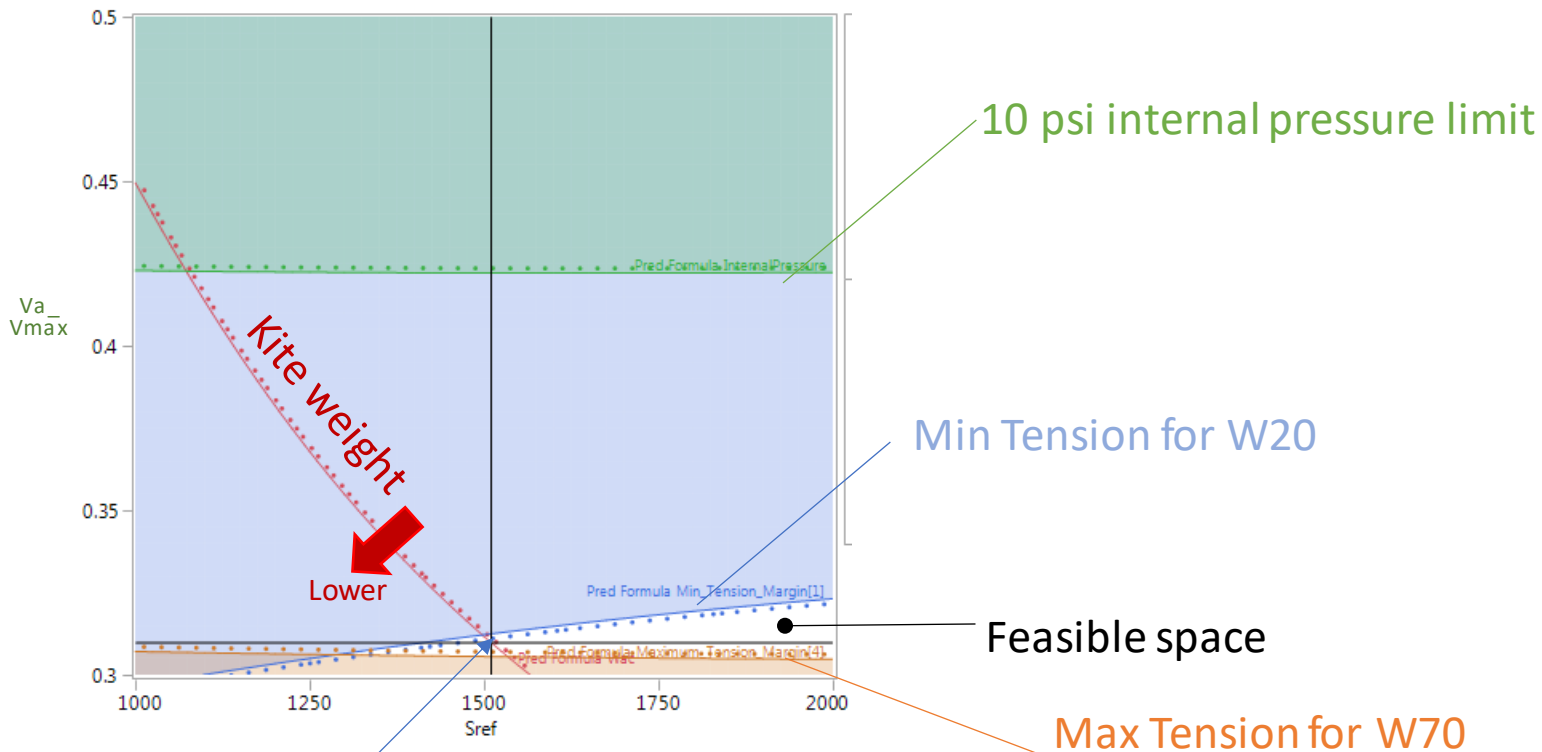
Impact of Flight Altitude

**Impact of size, year-round
operation, and utility**

Isolate impact of each dimension for clear understanding

TC300: 10km Kite

- Determine wing size and V_a/V_{max} through constraint analysis
- Keep shape parameters such as aspect ratio and dihedral angle



TC301

S_{ref} : 1500 m ² (TC201: 30 m ²)
V_b/V_{max} =0.31 (TC201: 0.30)

Kite size needs to grow by X50 to ascend from 5km to 10km

TC301

Wing Area, $S_{\text{ref}} = 1500 \text{ (m}^2\text{)}$

Aspect Ratio, $AR = 14$

Taper Ratio 1, $\gamma_1 = 0.5$

Taper Ratio 2, $\gamma_2 = 1$

Taper Ratio 3, $\gamma_3 = 0.5$

Normalized Span Break, $\eta_1 = 0.15$

Normalized Span Break, $\eta_2 = 0.65$

Normalized Span Break, $\eta_3 = 1$

Leading Edge Sweep, $\Lambda_1 = 20 \text{ (deg)}$

Leading Edge Sweep, $\Lambda_2 = 20 \text{ (deg)}$

Leading Edge Sweep, $\Lambda_3 = 30 \text{ (deg)}$

Dihedral Angle, $DIH_1 = 0 \text{ (deg)}$

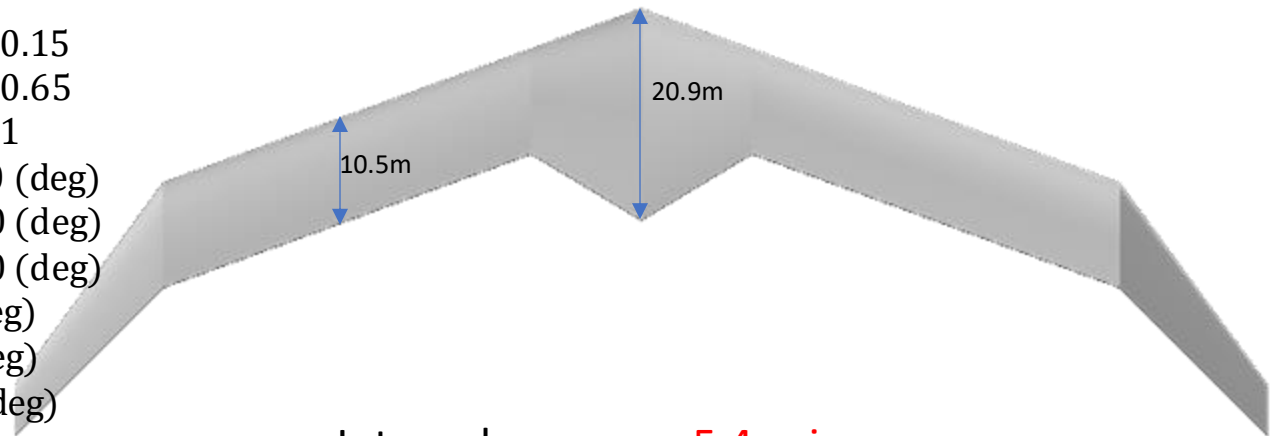
Dihedral Angle, $DIH_2 = 0 \text{ (deg)}$

Dihedral Angle, $DIH_3 = 55 \text{ (deg)}$

Airfoil: NACA 4318

Normalized X coordinate of the bridle point, $\frac{X_{br}}{c_r} = 0.16$

Normalized Z coordinate of the bridle point, $\frac{Z_{br}}{b} = 0.5$

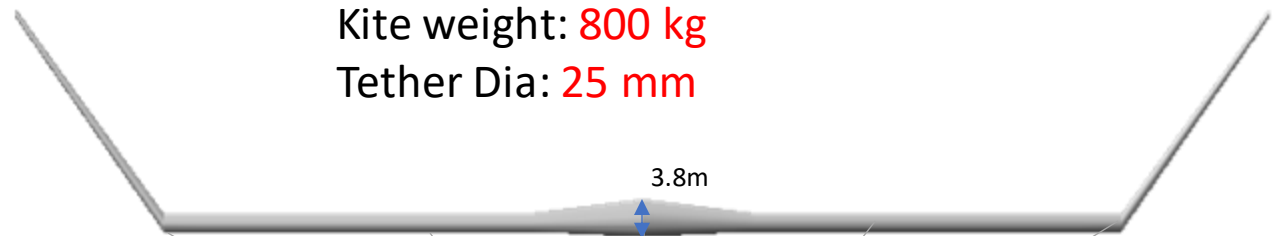


Internal pressure: **5.4 psi**

Fabric strength: **848 N/cm** (SF=1.5)

Kite weight: **800 kg**

Tether Dia: **25 mm**



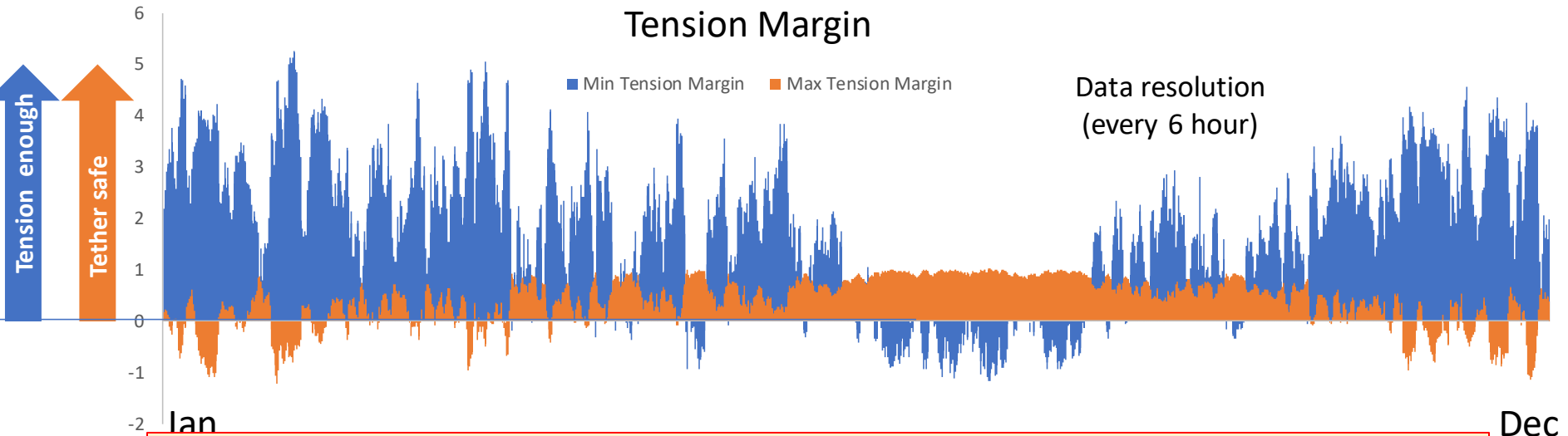
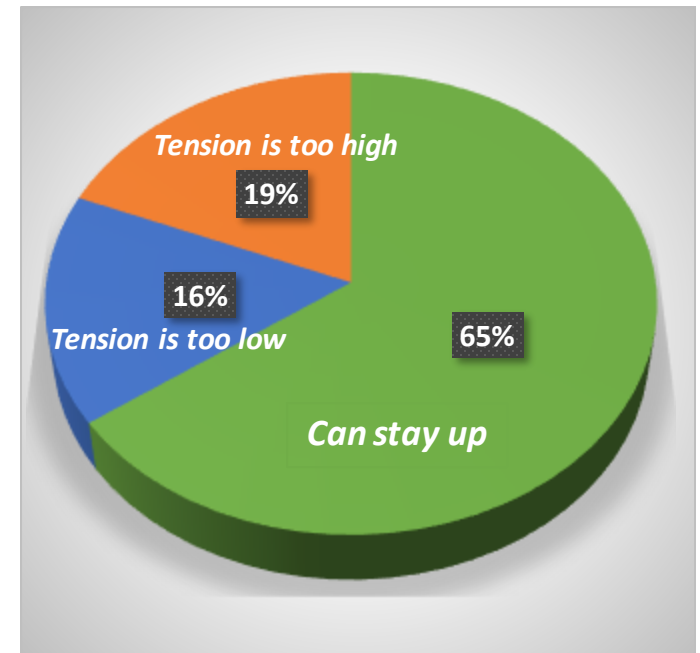
Full Year Simulation

- If TC301 was put at 10km above Higashifuji area in 2017...



Sized to fly W20 and W70
Wind profile.

- Simulated NCEP/DOE R2 data of 2017 (1460 wind profiles)



TC301 can stay up at 10km for 65% of year

Reference Configurations

TC100



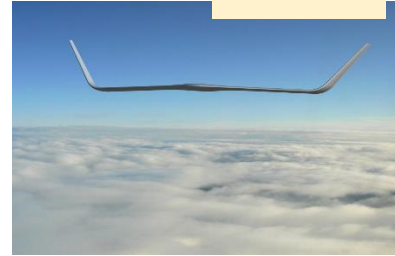
World Record
Holder
Alt: 5km
Size: 10^1 m^2

TC200



Inflatable Kite
Concept
>5km
 $\sim 10^1 \text{ m}^2$

TC300



Small 10km Kite
(no utility, payload)
10km,
 $10^1 - 10^3 \text{ m}^2$

Baseline Configuration
for Technology Evaluation

TC400



Mothership
10km
 $10^3 - 10^6 \text{ m}^2$

← Can fly at favorable wind conditions → Full-year

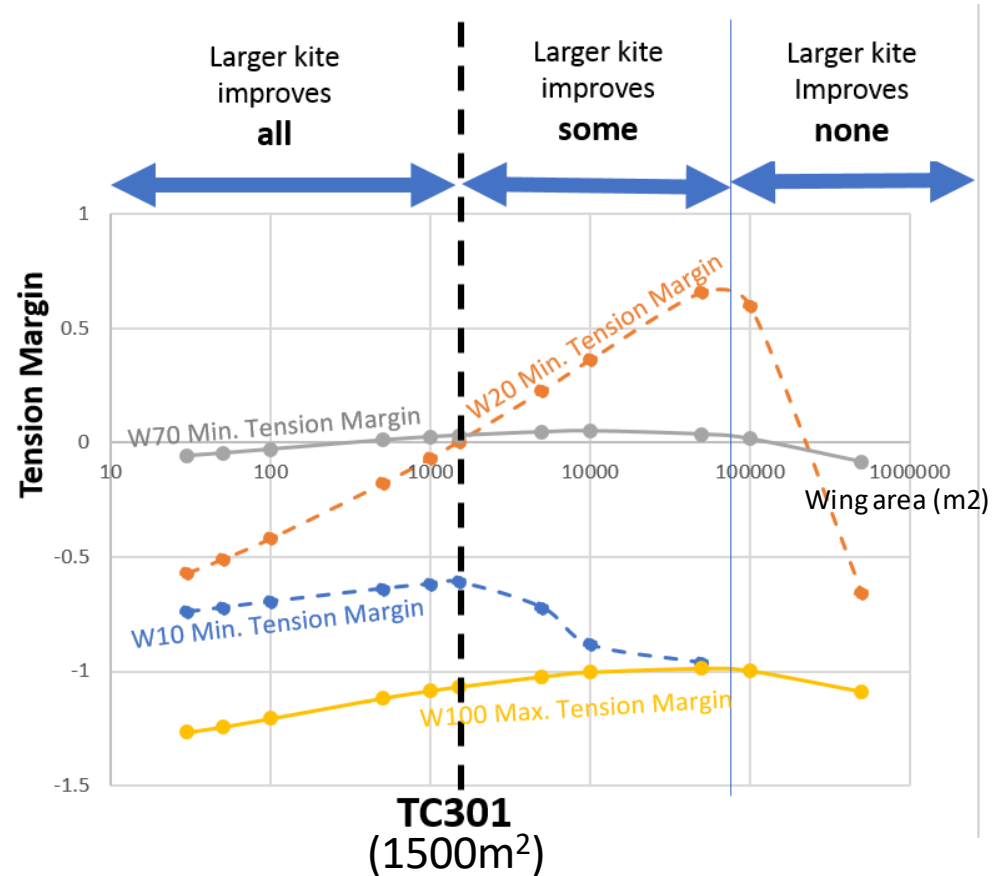
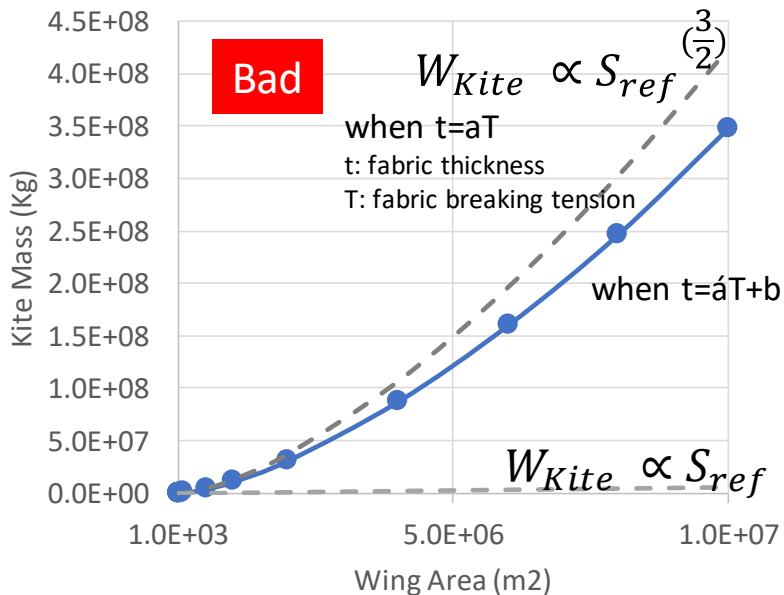
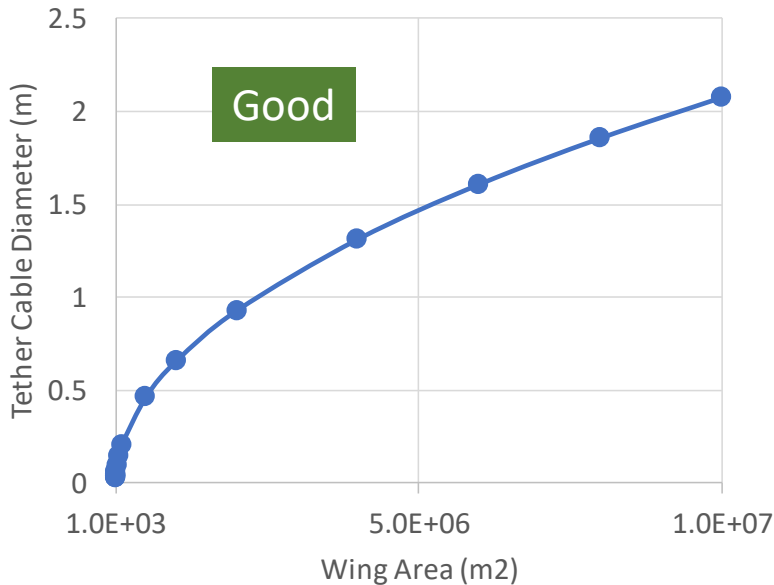
Impact of Kite Design
- Inflatable structure
- Higher aspect ratio

Impact of Flight Altitude

**Impact of size, year-round
operation, and utility**

Isolate impact of each dimension for clear understanding

Sensitivity w.r.t. Wing Area



- There exists a wing size that maximizes feasibility for current technology and assumptions
- TC301 size (1500m²) appears to be a good starting point for Mothership(TC400 series)

TC401

- Add utility items on TC300 (*No resizing*)
- Later, we will revisit larger size Motherships with technologies

TC301



Wing Area, $S_{\text{ref}} = 1500 \text{ (m}^2\text{)}$
Aspect Ratio, $AR = 14$
Gross Weight: 800 kg

Internal pressure: 5.4 psi
Fabric strength: 848 N/cm
(SF=1.5)
Tether Dia: 25 mm, 0.353kg/m

+

Utility

Wind Turbine

- 4 X D3.4m
- Rated power: 3.0MW (@100m/s wind)
- + 1052 kg
- + Cdo: 0.0215

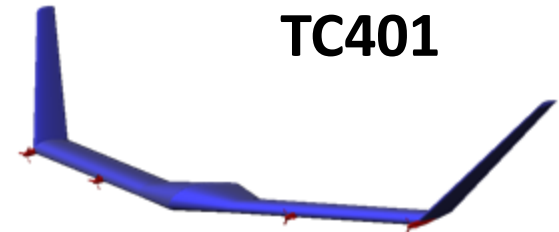
Solar Panels

- 90% of upper surface
- Rated power: 0.4MW
- + 1129 kg
- + Cdo: 0

Conductive Wire

- Cu wire (2X10.2mm², max 45A)

TC401



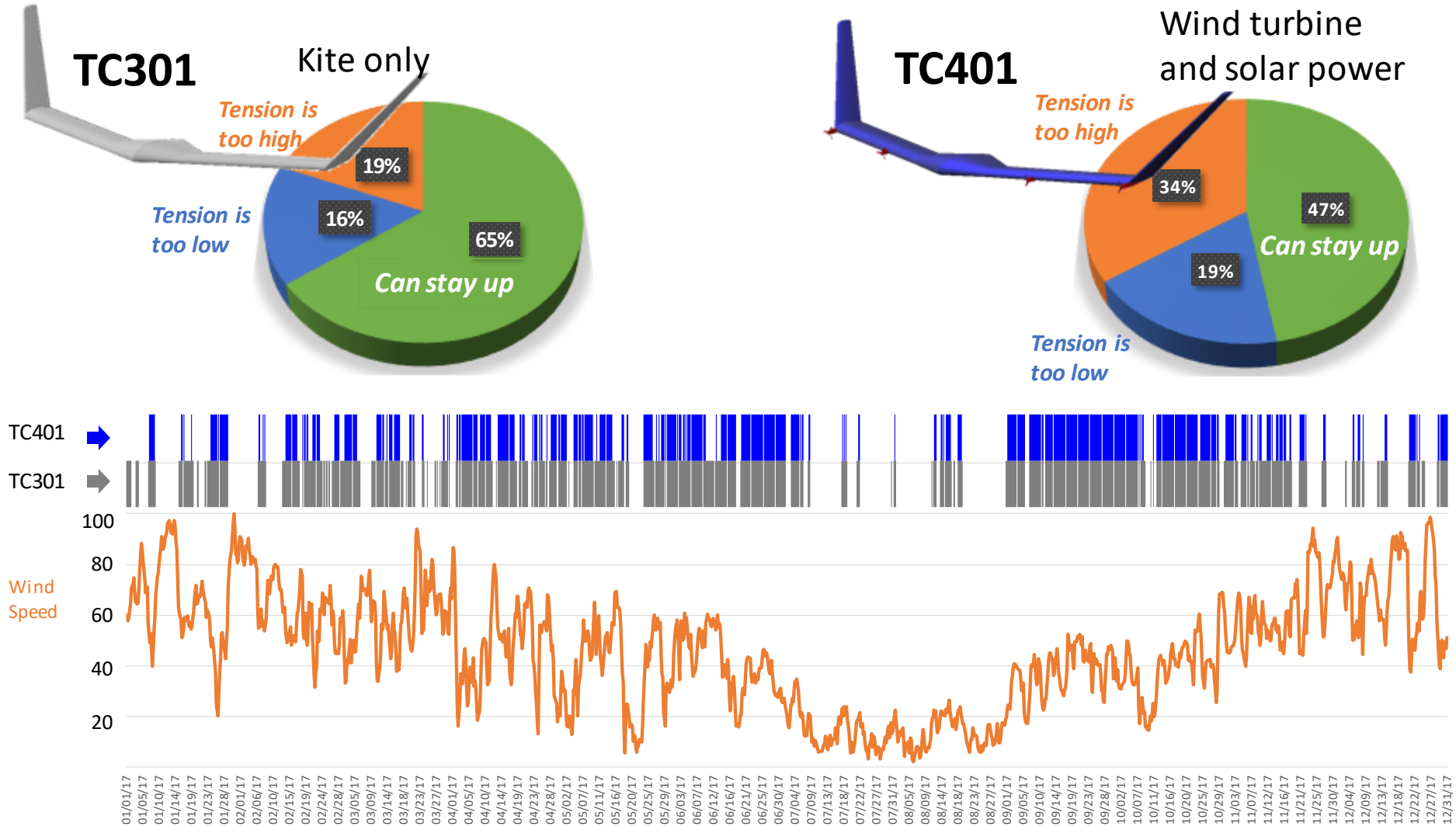
Wing Area, $S_{\text{ref}} = 1500 \text{ (m}^2\text{)}$
Aspect Ratio, $AR = 14$
Gross weight: **2,981 kg***

Internal pressure: 5.4 psi*
Fabric strength: 848 N/cm*
(SF=1.5)

**Tether Dia: 26 mm, 0.528kg/m
including conductor**

* Inertia relief effect gives only 1% weight reduction. It is assumed that wind turbine and solar panel does not affect kite structural sizing

TC401 Full Year Simulation



Installing energy harvesting system reduces flyable period at 10km by 18%
Now, we are searching for technologies for full year operation capability

MDA study in early phase

- Found to be very beneficial, answering
 - Estimate of system key attributes
 - Feasibility of proposed concept
 - Key technical challenges and countermeasures
- Requires right balance between fidelity and cost
- Needs to evolve continuously as design matures and more experiment data become available
 - Modular and flexible MDA environment is essential

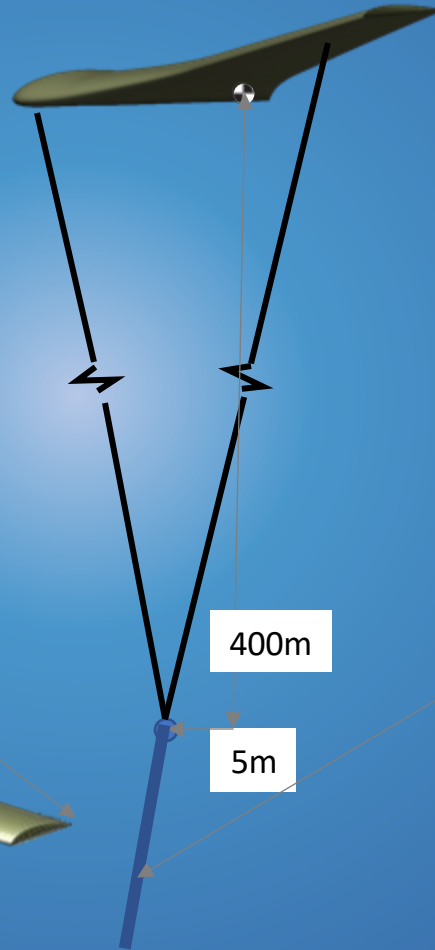
Back Up

High Altitude Wind Energy Harvesting

Wing Area: 1500 m²
Kite Weight: 800kg
Aspect Ratio: 6.92

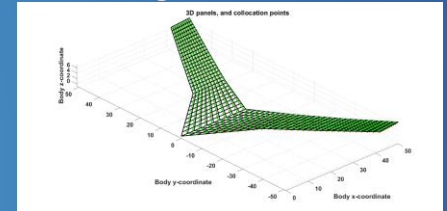
101.9 m

Inflatable structure made of
laminated fabrics



Kite Aerodynamic

- Vortex Lattice Method with viscos drag correction

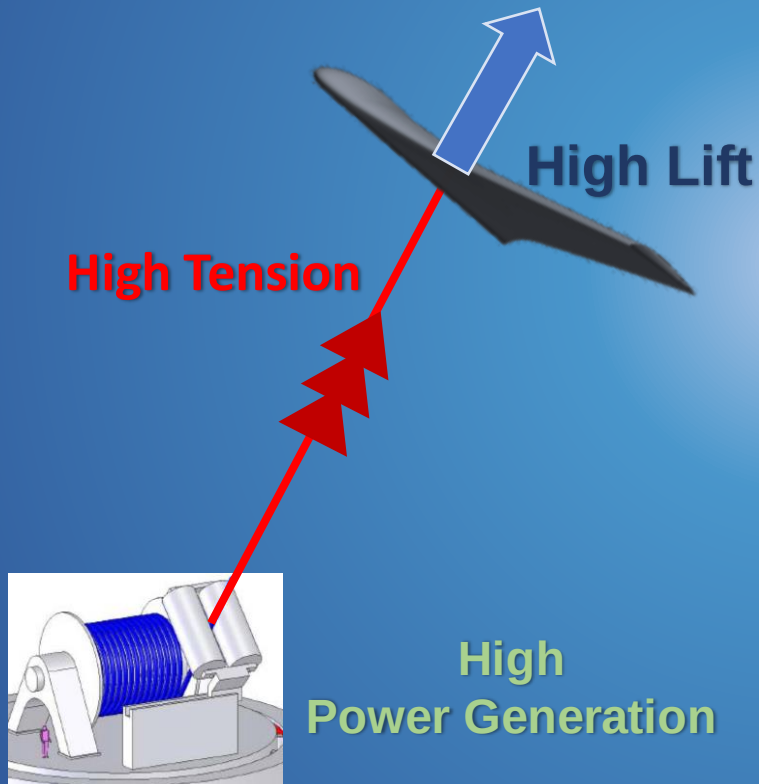


Tether

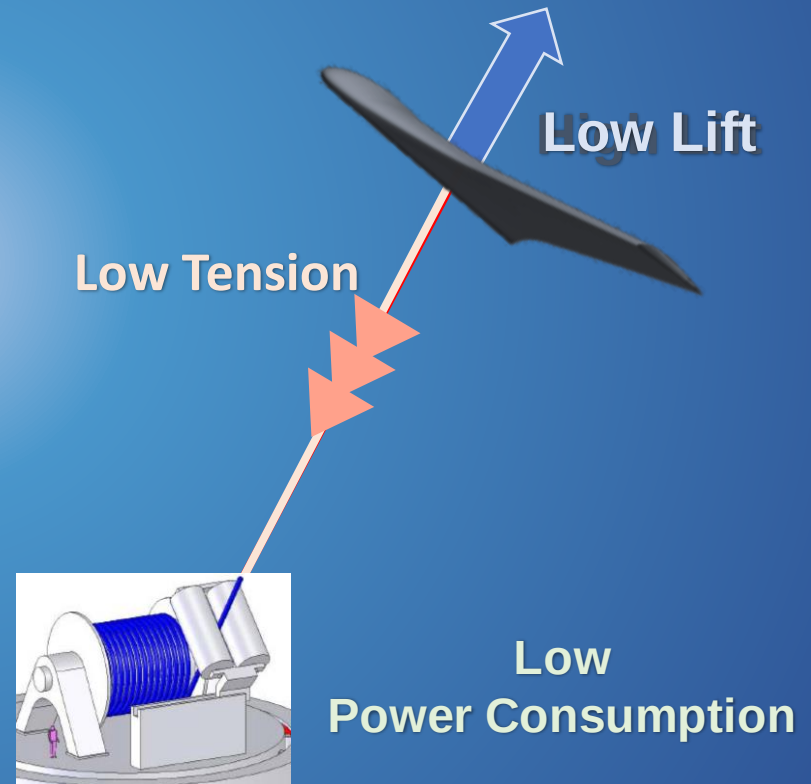
- Braid rope made of DSM DM-20 fiber (high creep resistance)
- Diameter and weight estimated from Samson Rope EVERSTEEL™-X data (<https://samsonrope.com/mooring/evers-teel-x>)

How Can The Kite Harvest Wind Energy

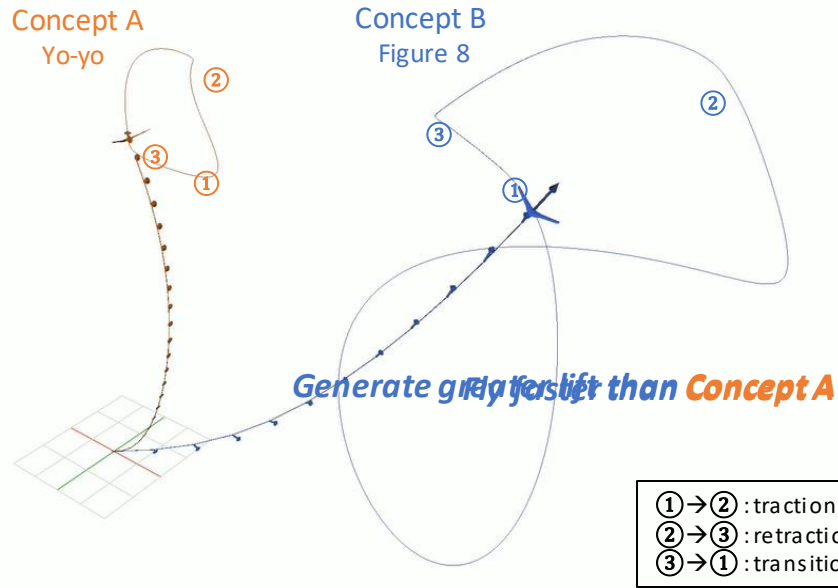
Traction Phase



Retraction Phase

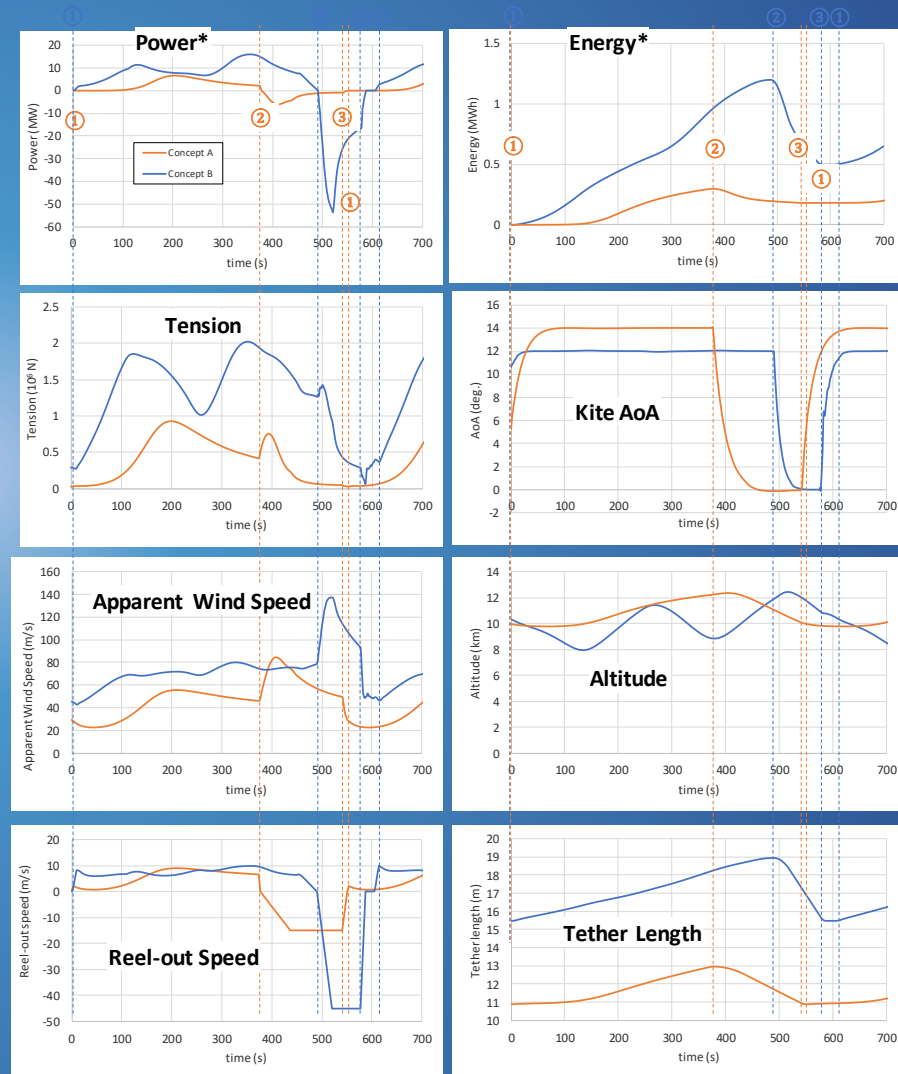


Simulation Results



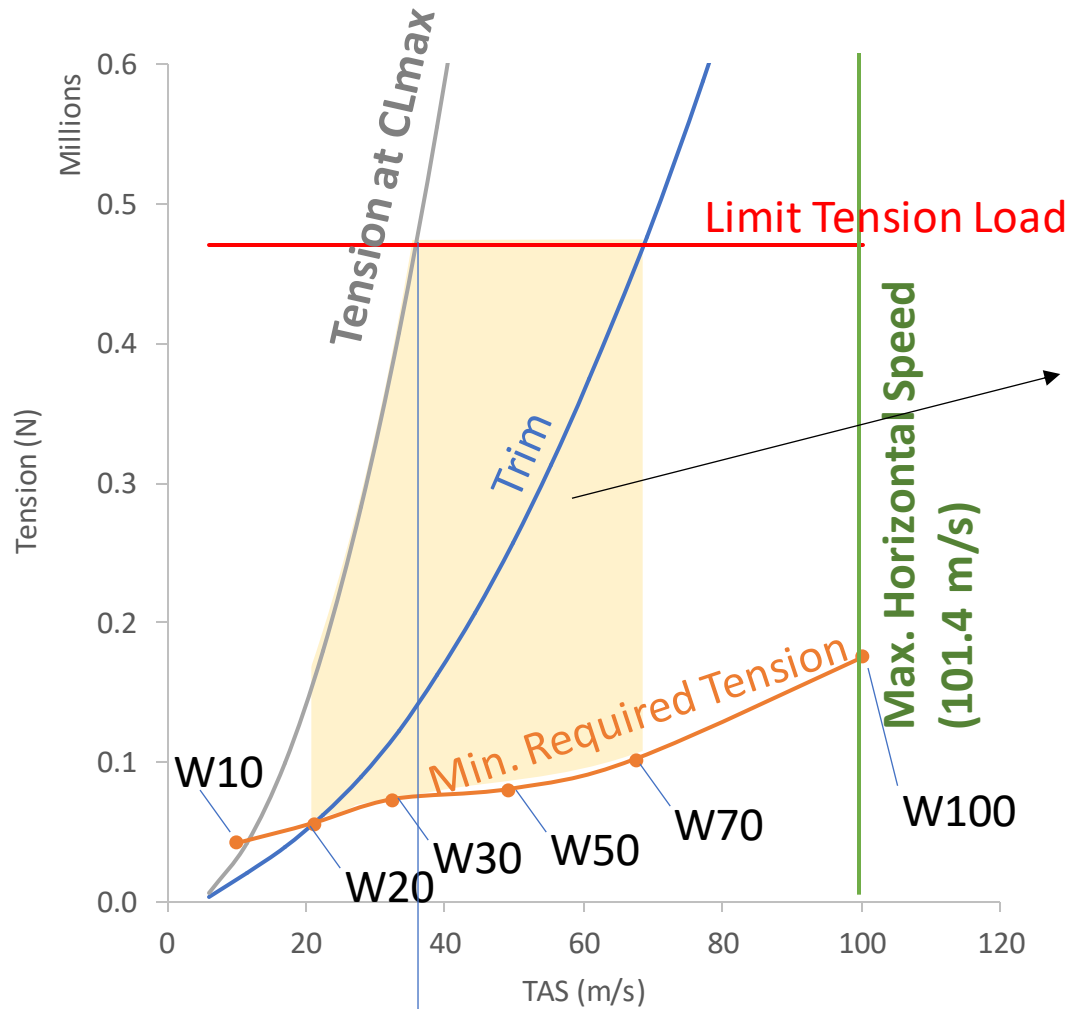
	Concept A	Concept B
Average net of full cycle* (MW)	1.2	3.0
Average mechanical power of traction phase (MW)	3.5	11.1
Peak mechanical power of traction phase (MW)	6.7	19.6

* Motor and generator efficiencies are assumed to be 0.8



TC301 Tension Load Envelope

10km Altitude



This envelope is only valid for W20, W30, W50, and W70 (W10 and W100 were excluded: too stringent)

Worth to look at how many days it can fly at 10km

$$V_A = aV_{\max} = 31.5 \text{ (m/s)}$$

Where $a=0.31$