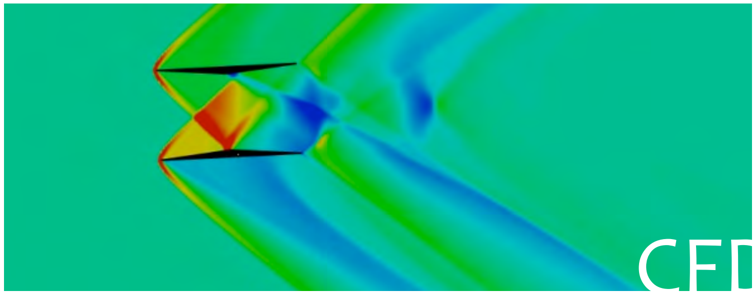
Multi-Objective Design Exploration (MODE) and Its Applications

Shigeru Obayashi
Institute of Fluid Science, Tohoku University
東北大学流体科学研究所
大林　茂

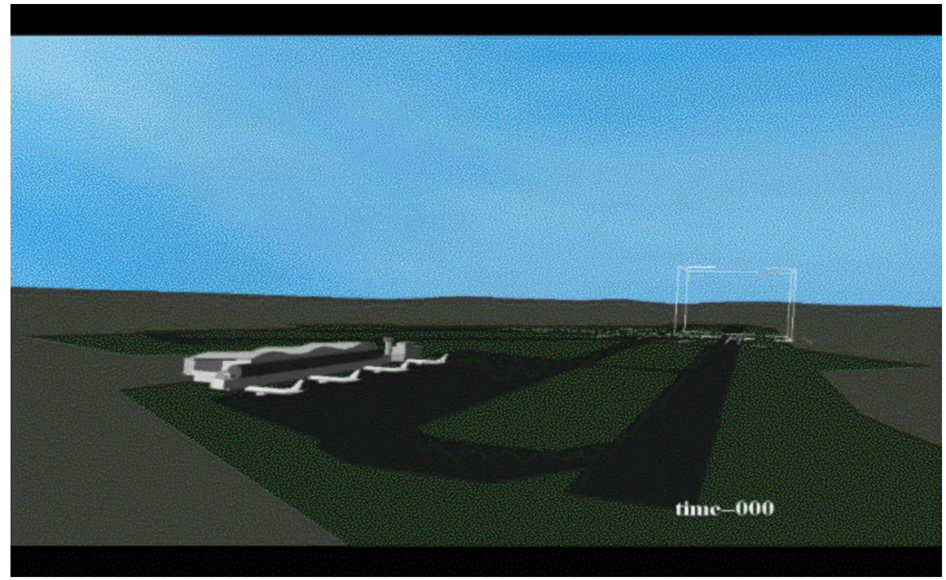
100 Years of Powered Flight

Research Topics in Laboratory

1. Supersonic Biplane

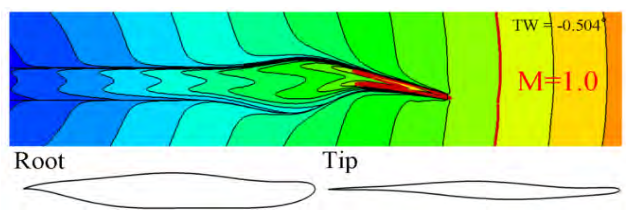


3. Measurement-Integrated Simulation

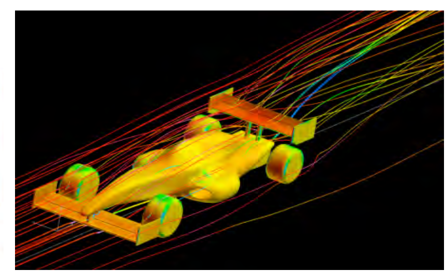


2. Multi-Objective Design Exploration (MODE)

Mitsubishi Regional Jet (MRJ)

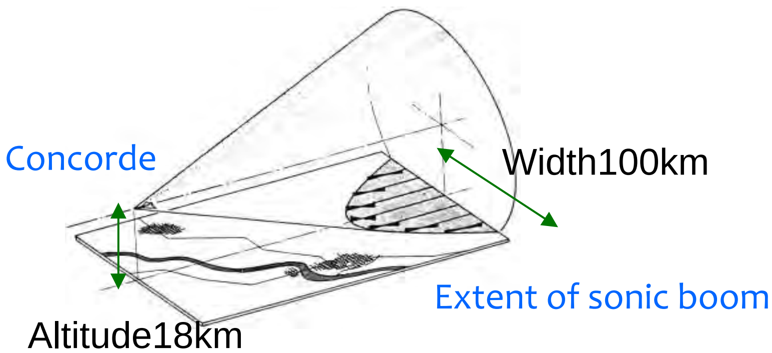


Helicopter Blade



Racing Car

Mitigation of Sonic Boom



Sonic boom noise is a bottleneck in the development of the next generation SST

environmental standard for 2016~2019

Conventional Low Boom Technology

Approx. 30% Reduction of sonic boom

<u>Axisymmetric linear theory</u>

1. Rounded nose shape
2. Slender body

Innovative Low Boom Technology

100% reduction in linear theory!

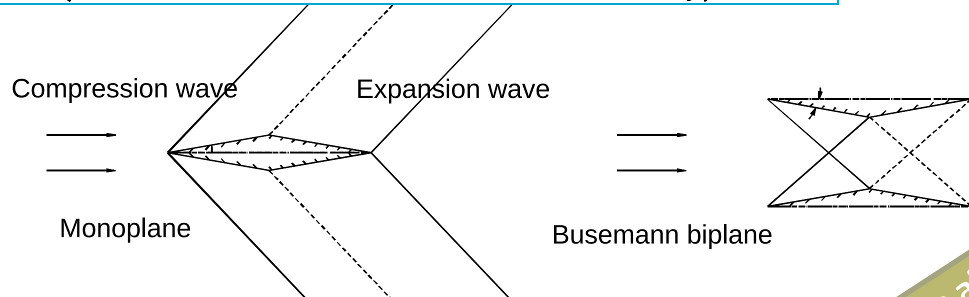
<u>Supersonic biplane theory</u>

- Busemann biplane!

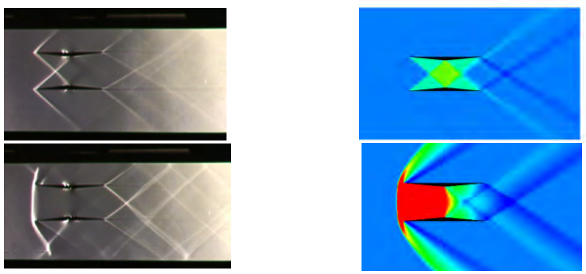
<u>Breakthrough for larger SST</u>

Development of Supersonic Biplane Theory

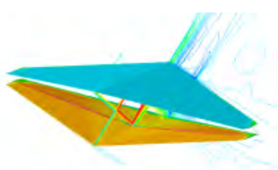
Busemann airfoil that cancels sonic boom (1930s)
(limited to two-dimensional linear theory)



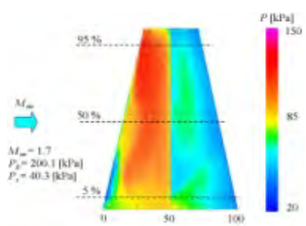
Research of supersonic biplane started from 2003 for the realization of silent SST



Investigation using EFD and CFD

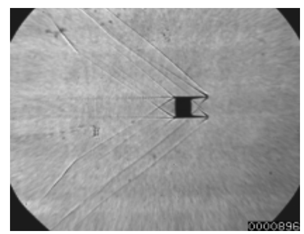


CFD for Three-dimensional biplane



PSP measurement of three-dimensional shock interference

From airfoil theory to aircraft



Ballistic-range supersonic free flight experiment
(model size: 25mm)

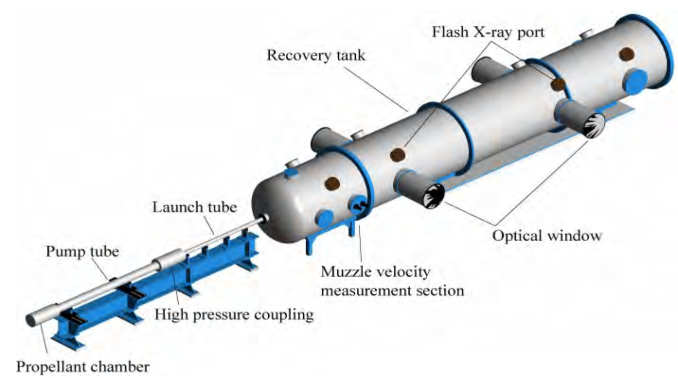
Low speed radio controlled flight experiment

Evaluation of non-linearity and three-dimensionality of sonic boom on the ground

Aircraft Integration
Unsteady CFD Simulation, Supersonic wind tunnel experiment

+

Sonic boom ground experiment
Supersonic free flight experiment
(model size: 50mm)

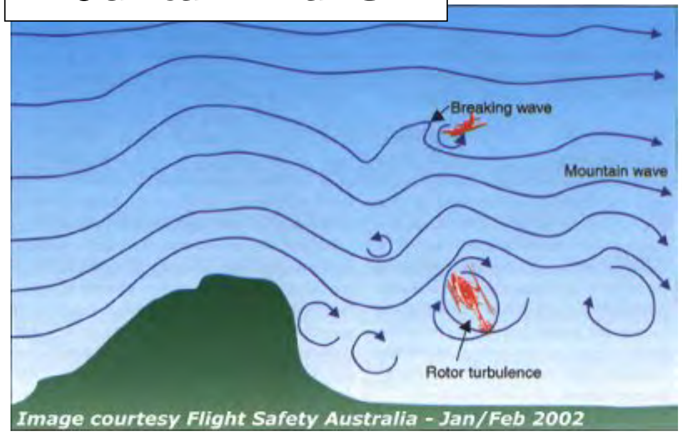


Measurement-Integrated Simulation of Atmospheric Turbulence

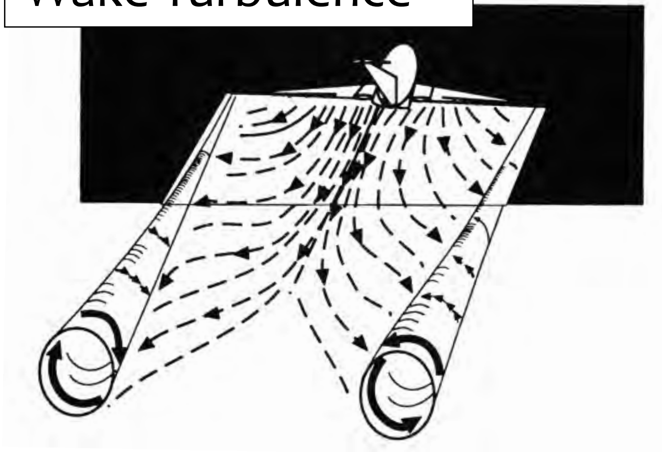
- Uncomfortable shake of aircraft
- Operational error
- Sometimes serious accidents

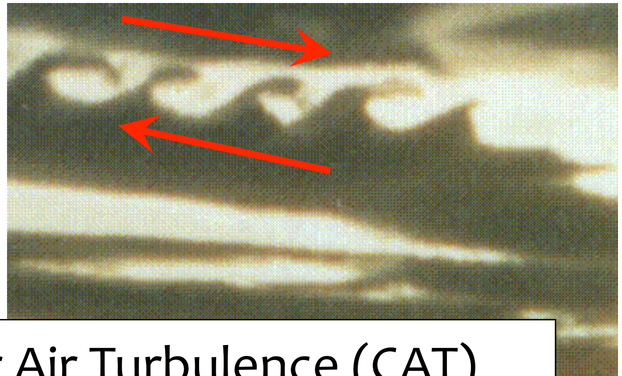
Thunderstorm

Mountain Wave



Wake Turbulence

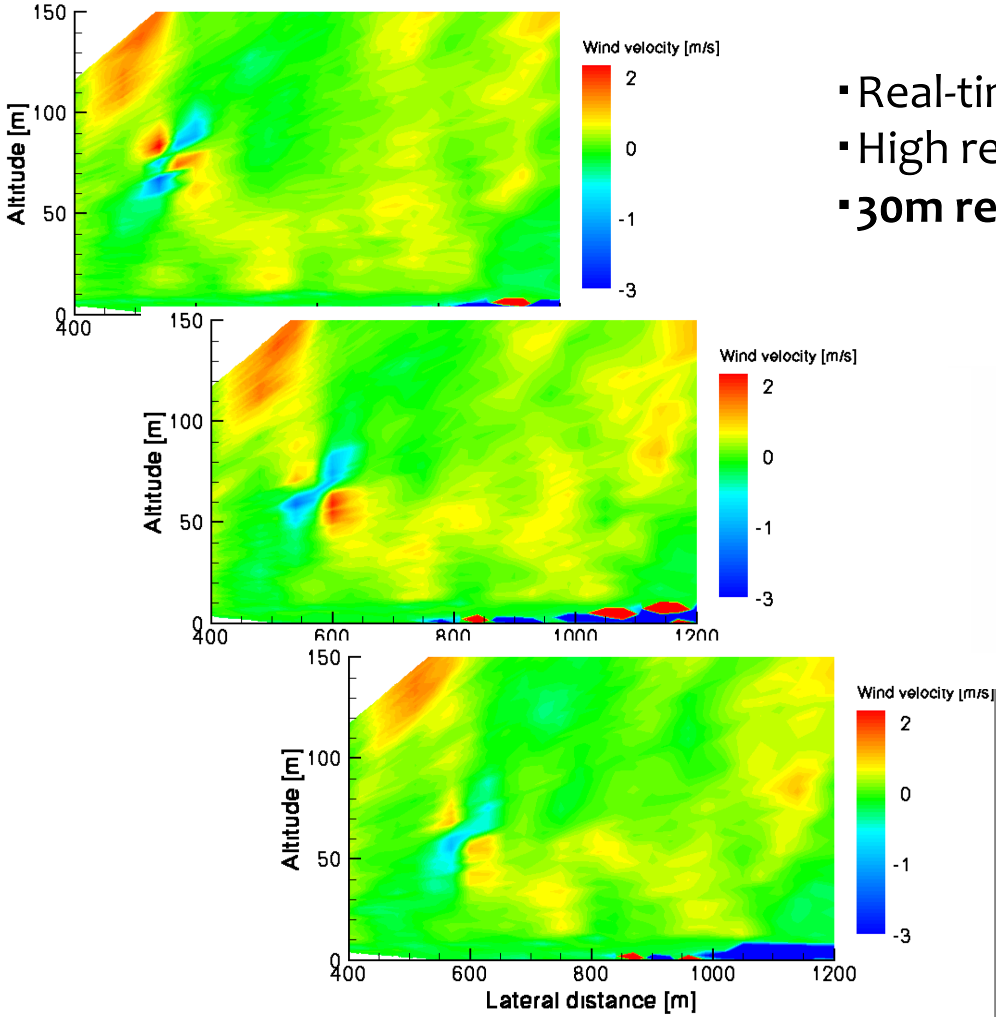




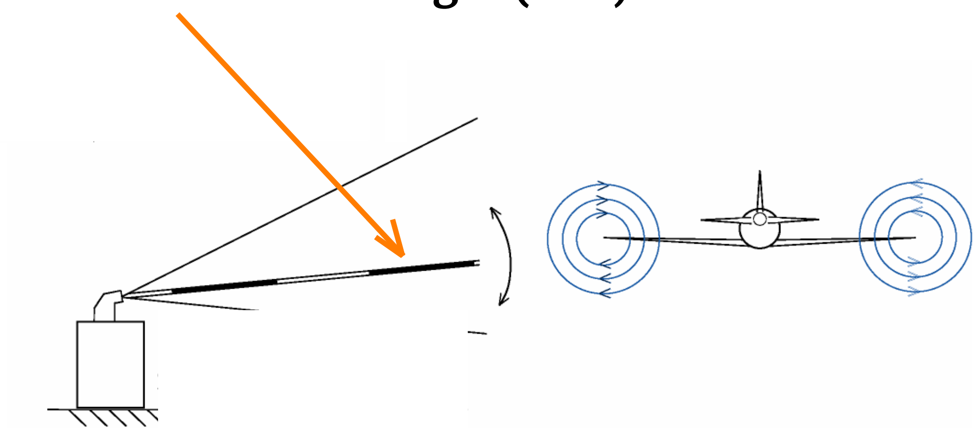
Clear Air Turbulence (CAT)

Measurement of Wake Turbulence

➢ Lidar measurement at Sendai airport



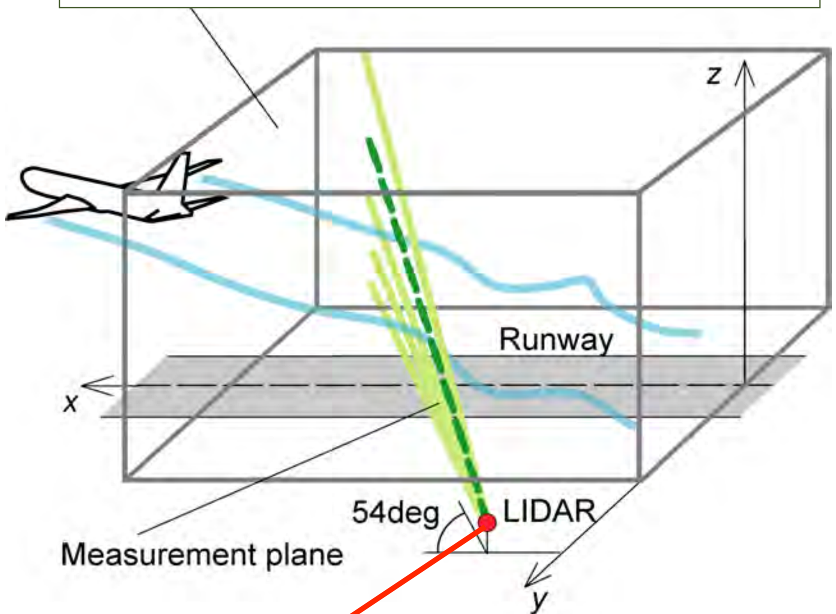
- Real-time measurement and visualization
- High resolution in elevator angle direction
- **30m resolution in line of sight (LOS) direction**



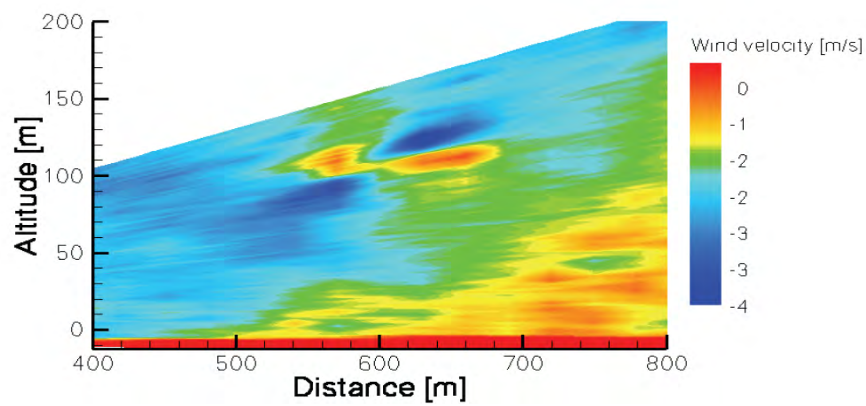
➢ **Lack of spatial resolution and 3D information!!**

Integrated-Simulation at Sendai Airport

Reproduce realistic wake vortices in supercomputer



Data assimilation using four-dimensional variational method (4D-Var)

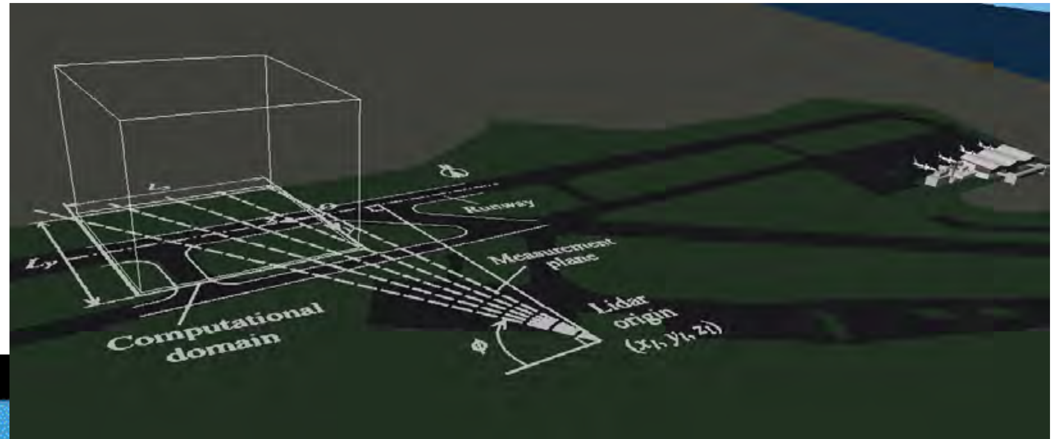


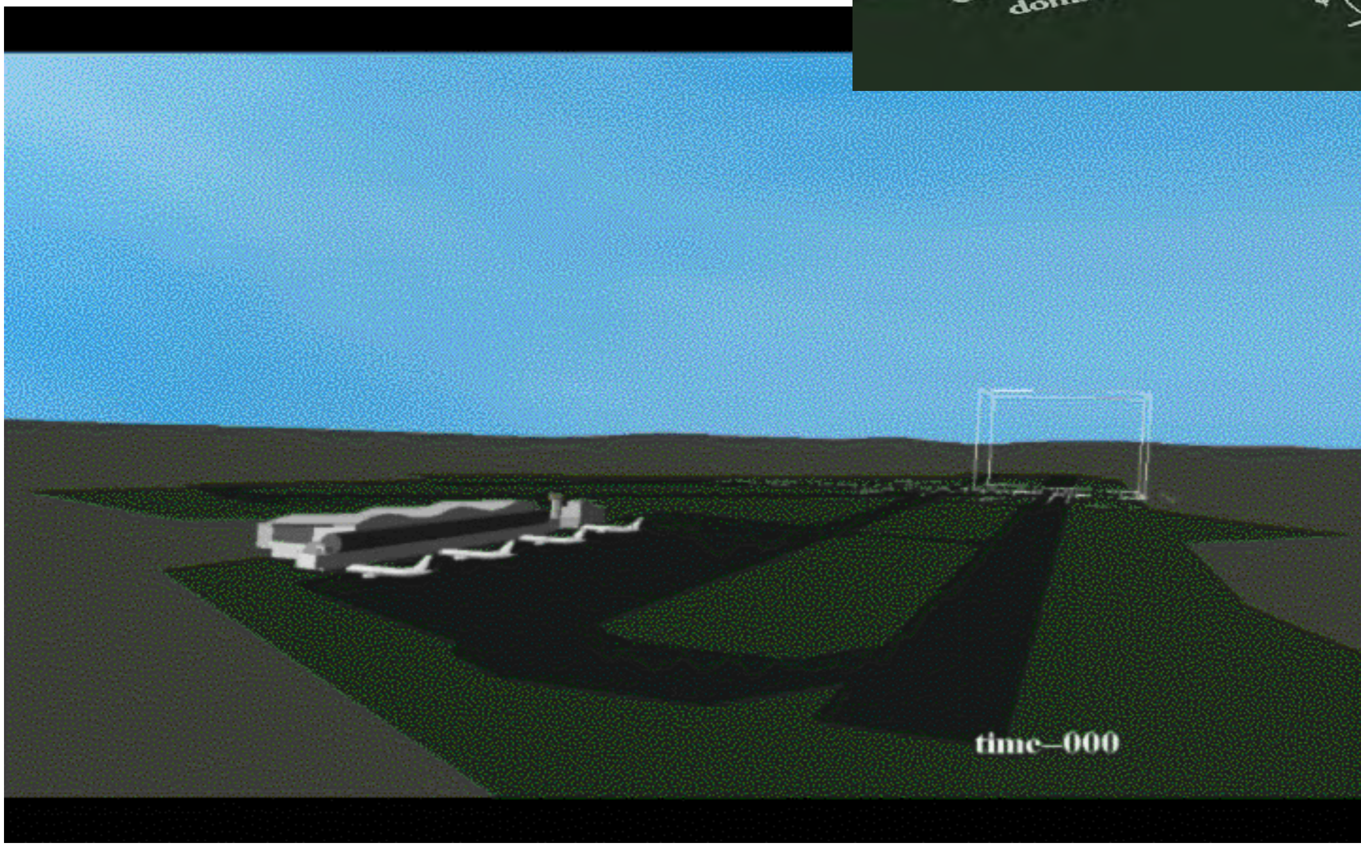
Lidar (ENRI)

Lidar measurements of departing aircraft at Sendai airport

Wake Turbulence at Sendai Airport

✓ Reproduced flow field is superimposed on the virtual reality model of Sendai airport



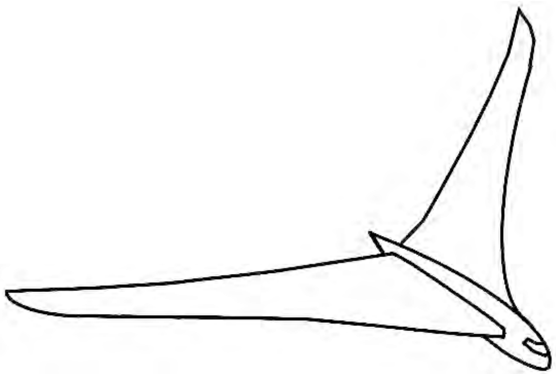


Outline

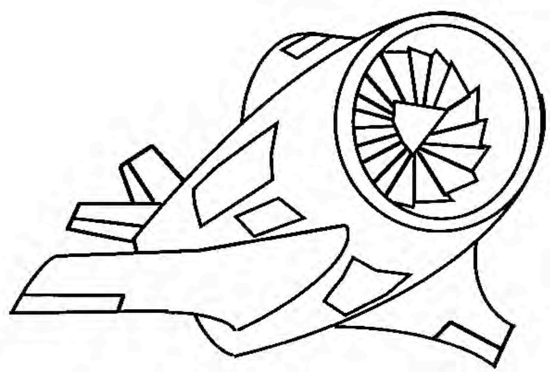
Multidisciplinary Design Optimization (MDO) for Regional Jet

- Multi-Objective Design Exploration (MODE)
  - SOM
- R&D Project and Resulting MRJ
- Applications to Regional-Jet MDO Problems
  - Wing-body configuration
  - Wing-nacelle-pylon-body configuration
  - Winglet design
  - Horizontal tail structural design
- Lessons Learned

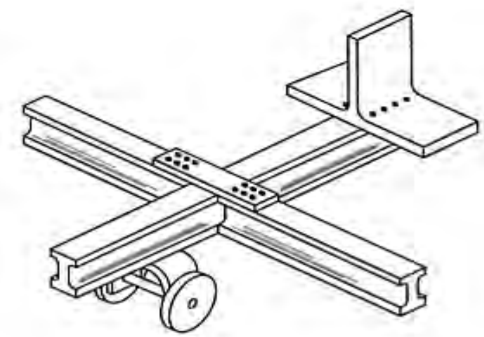
Aircraft Design



Aerodynamics



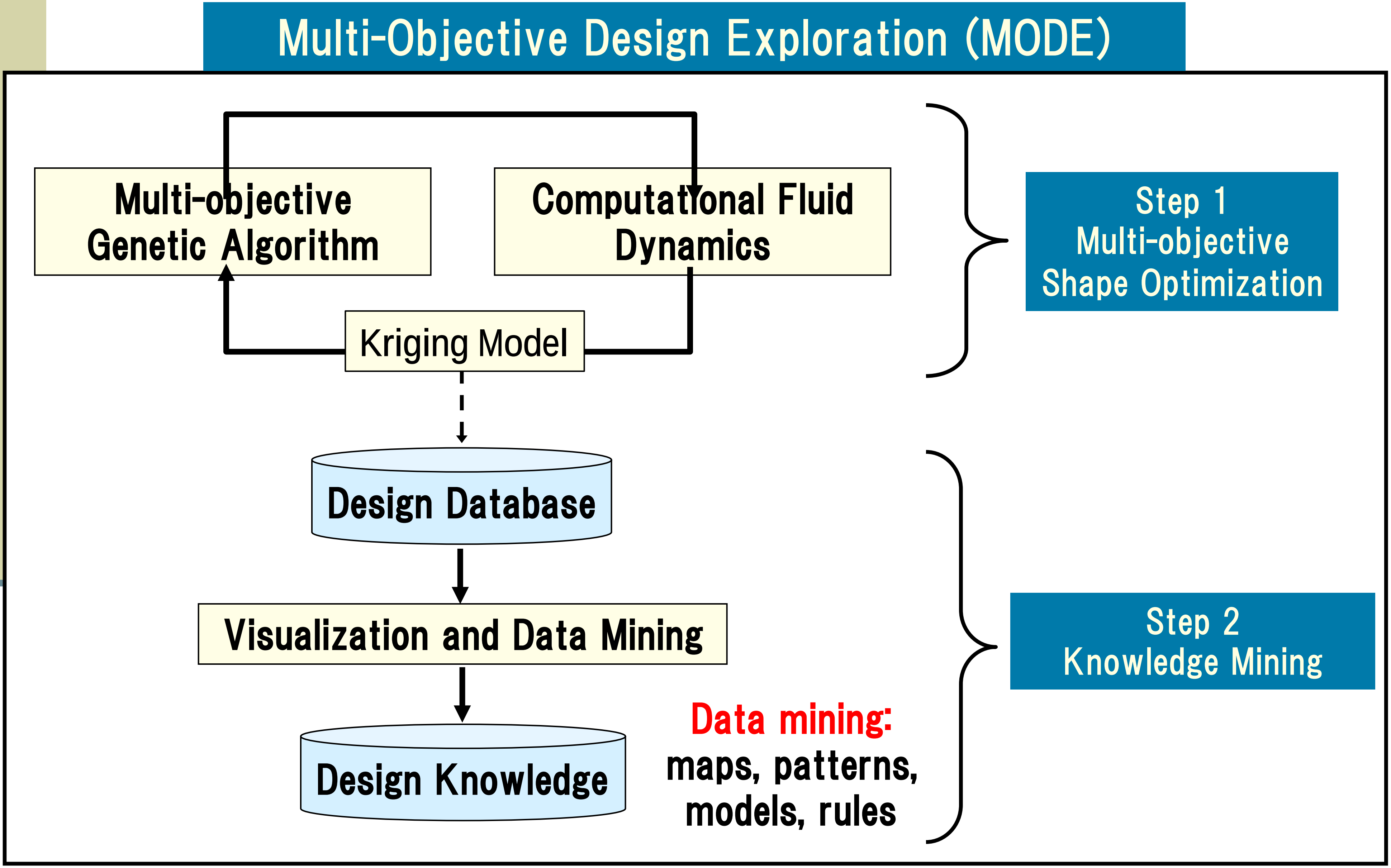
Propulsion



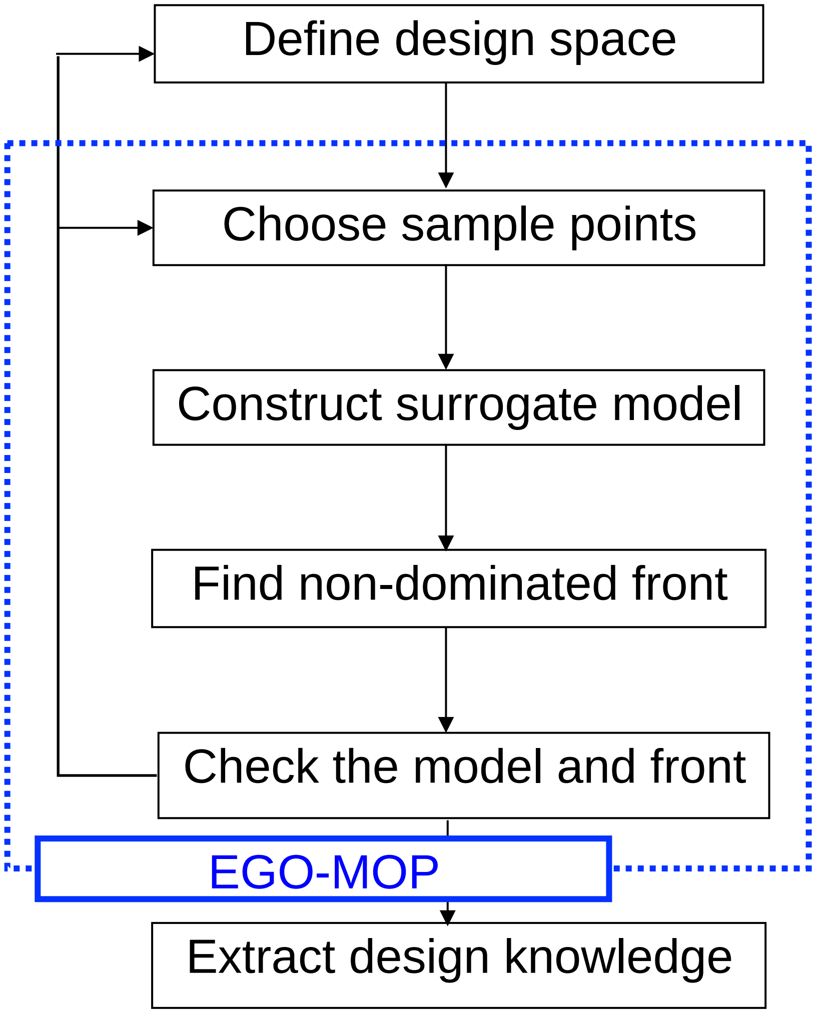
Structure

- Compromise of all disciplines
- Multidisciplinary Design Optimization (MDO) as Multi-Objective Optimization (MOP)

MODE to Solve MOP



Incorporating EGO to MODE



Parameterization: PARSEC, B-Spline, etc.

Design of Experiment: Latin Hypercube

EGO-MOP Using Kriging Model

Optimization: Evolutionary Algorithms (Genetic Algorithms

Uncertainty Analysis: Expected Improvement based on Kriging Model, statistics of design variables, etc.

Data Mining: Analysis of Variance, Scatter Plot Matrix, Self-Organizing Map, Rough Set, etc.

Present MDO Problems

1. Wing-body configuration
2. Wing-nacelle-pylon-body configuration
3. Winglet design
4. Horizontal tail structural design

Optimization of Wing-Body Configuration

Objective functions

Minimize

1. Drag at the cruising condition
2. Drag divergence between the cruising and off-design condition
3. Pitching moment at the cruising condition
4. Structural weight of main wing

✓ Function evaluation tools

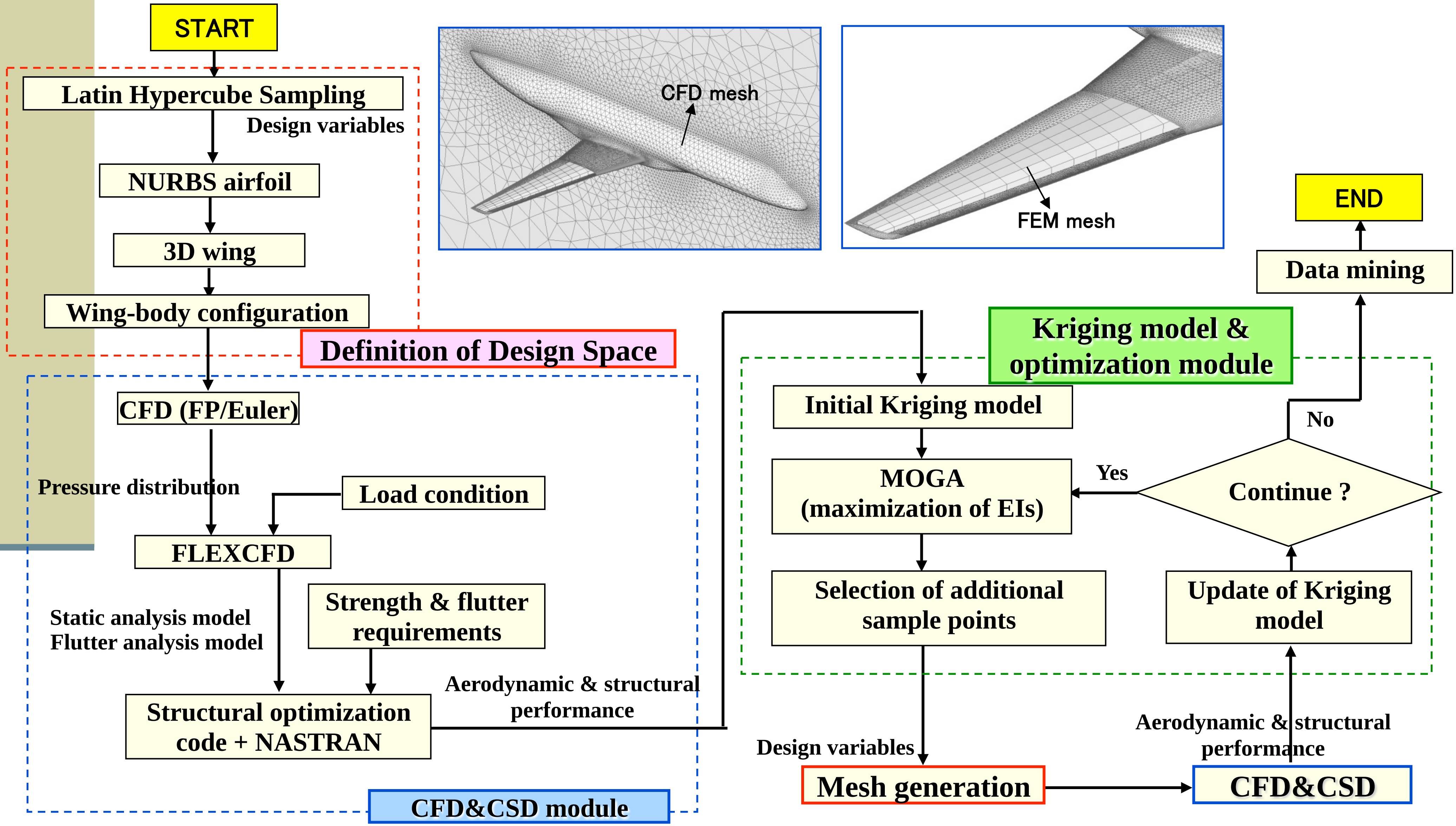
- CFD: Full Potential code (MHI in-house), Euler code (TAS-code)
- CSD/Flutter analysis: MSC. NASTRAN

Design variables

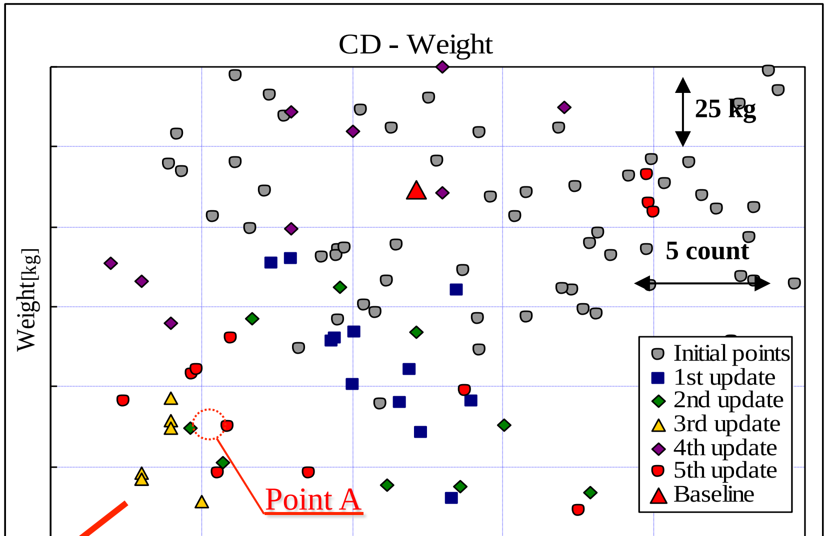
- Airfoil shapes at 4 spanwise sections (η = 0.1, 0.35, 0.7 and 1.0)
  → 26 variables (NURBS) × 4 sections = 104 variables
- Twist angles at 5 sections = 5 variables

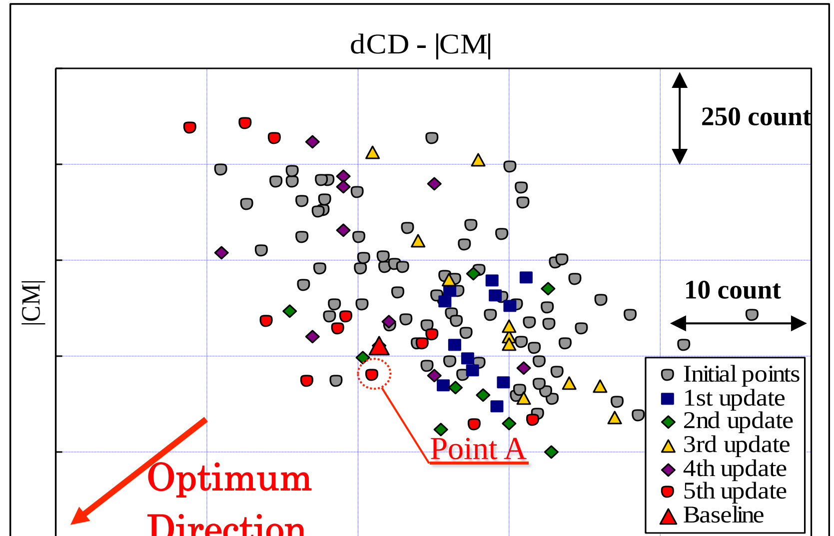
109 variables in total

MODE System for Regional Jet Design

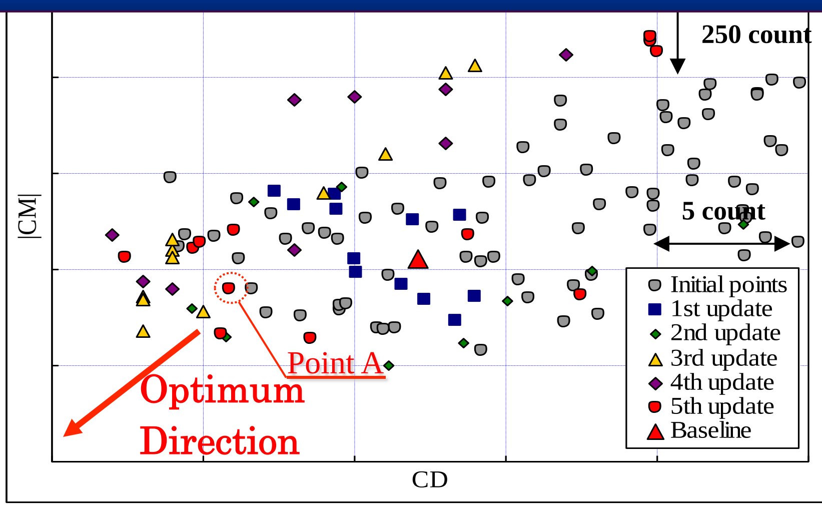


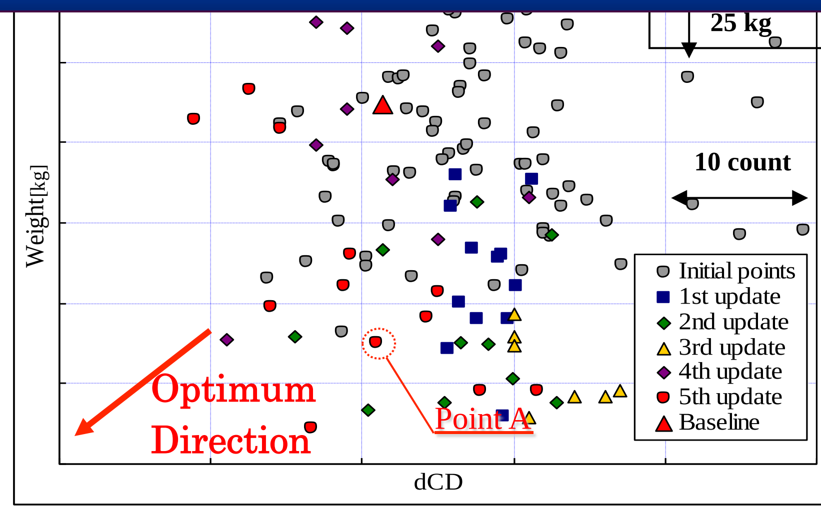
Comparison of Baseline Shape and Sample Points





Point A is improved by 6.2 counts in CD, 0.4 counts in ΔCD, 79.4 counts in |CM|, and 74.0 kg in wing weight compared with the baseline





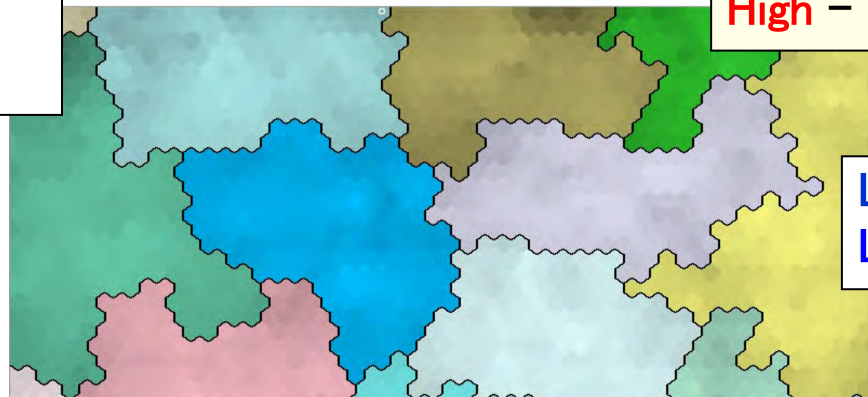
TOHOKU UNIVERSITY

Visualization of Design Space

(SOM made from the data uniformly distributed in design space)

High – Drag
High – Pitching moment

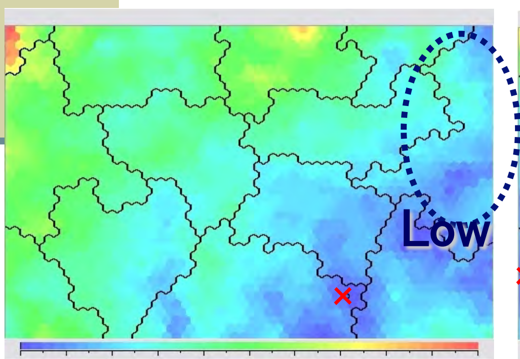
High – Drag divergence



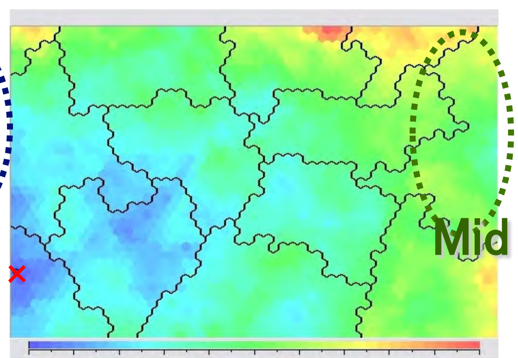
Low – Pitching moment
Low – Wing weight

High – Wi
Low – Dra

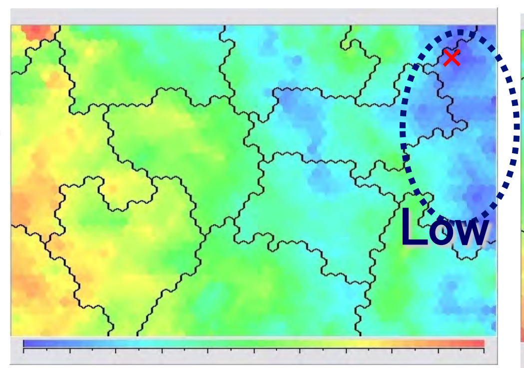
If ΔCD is tolerable, this region is SWEET SPOT for design



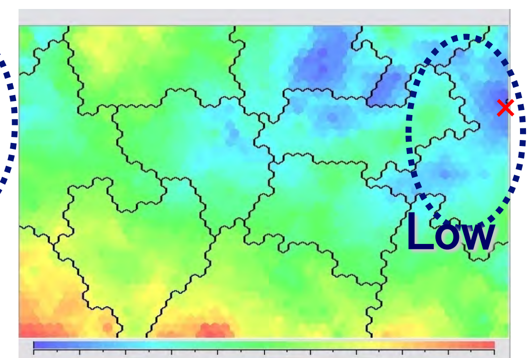
C_D



ΔC_D



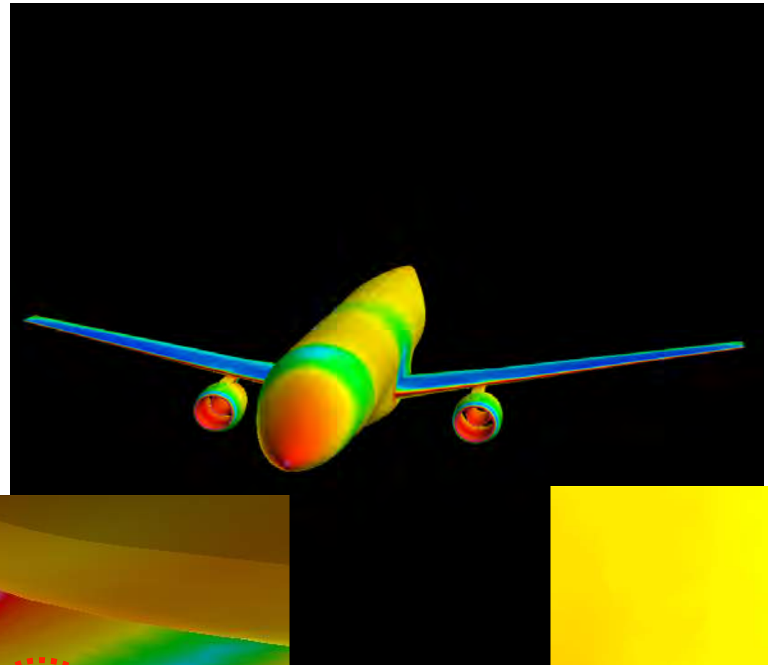
$|C_M|$

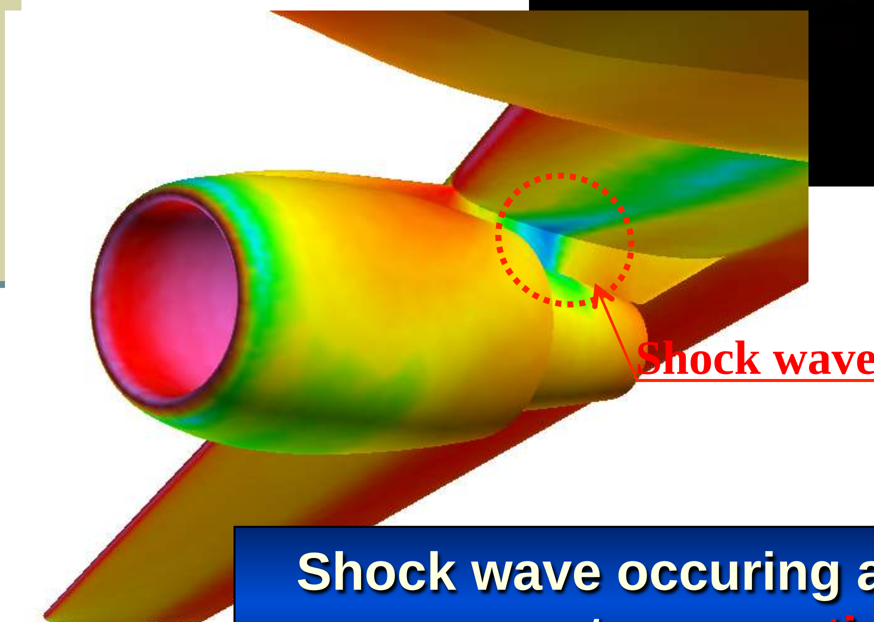


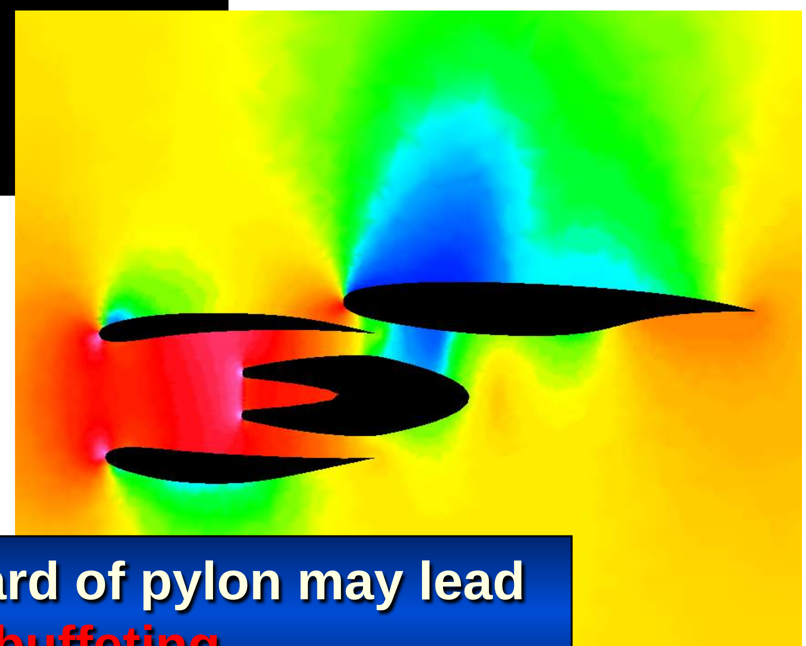
Wing weight

×: Minimum Point

Optimization of Wing-Nacelle-Pylon-Body Configuration







Shock wave occuring at inboard of pylon may lead to separation and buffeting

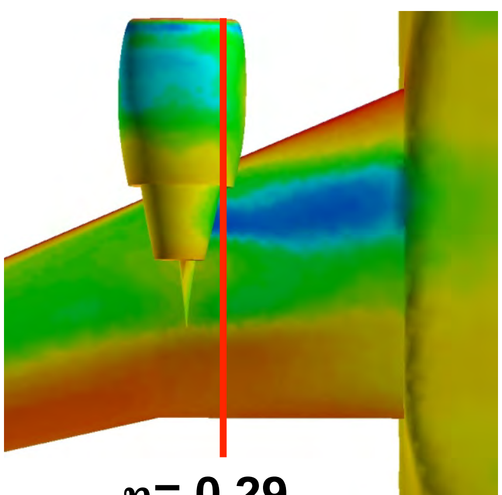
Definition of Optimization Problem -1
- Objective Functions -

Minimize

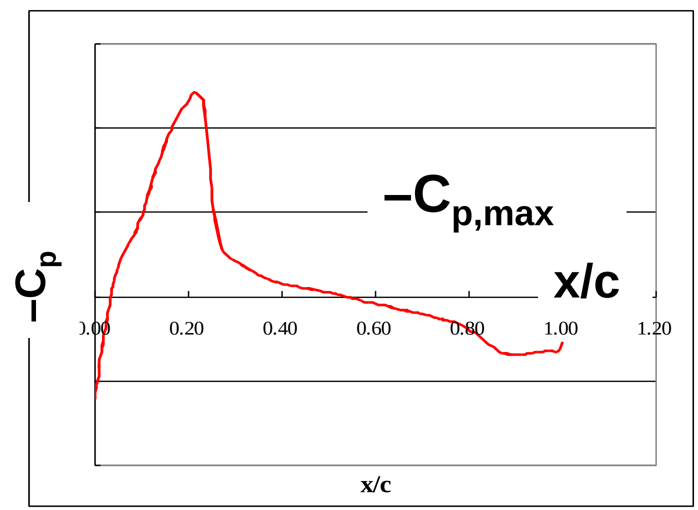
1. **Drag** at the cruising condition (C_D)
2. **Shock strength** near wing-pylon junction ($-C_{p,max}$)
3. **Structural weight** of main wing (wing weight)

✓ Function evaluation tools

- CFD : Euler code (TAS-code)
- CSD/Flutter analysis : MSC. NASTRAN



η= 0.29



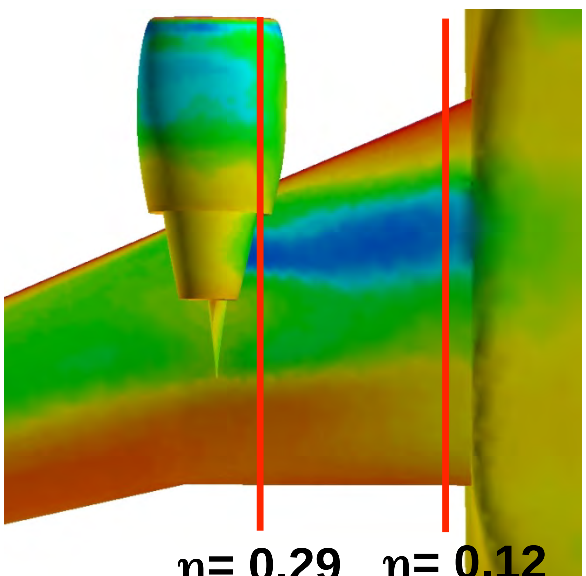
$-C_P$ distribution of lower surface @η=0.29

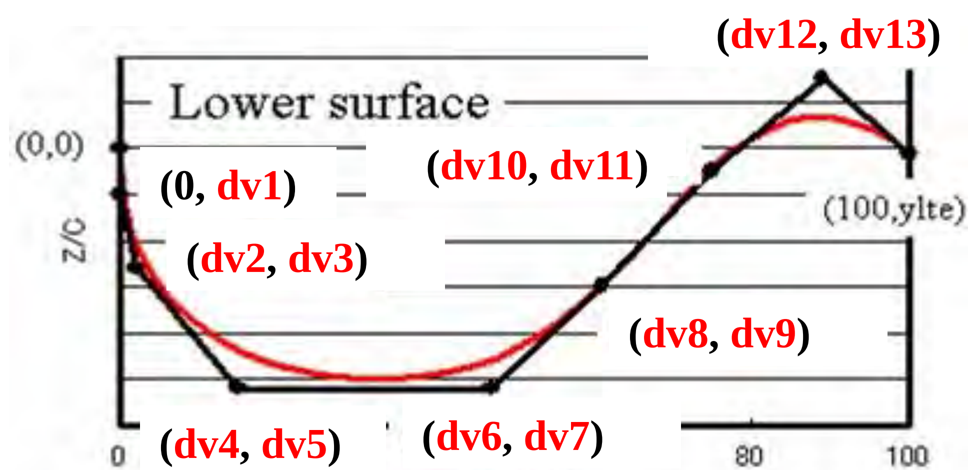
Definition of Optimization Problem -2
- Design Variables -

- **Lower surface of Airfoil shapes at 2 spanwise sections (η= 0.12, 0.29)**
  → 13 variables (NURBS) × 2 sections = 26 variables

- **Twist angles at 4 sections = 4 variables**

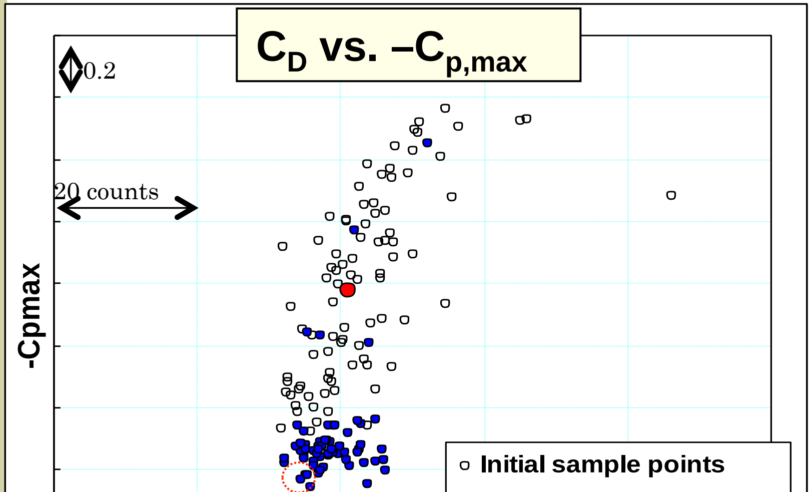
30 variables in total

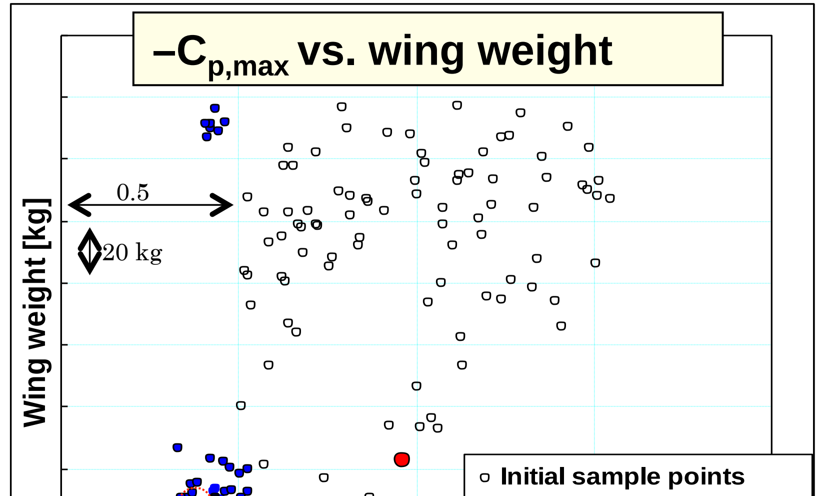




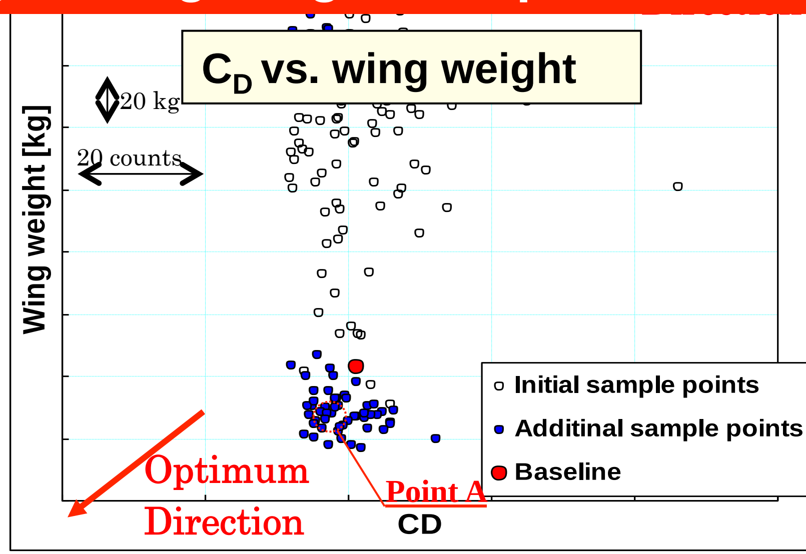
NURBS control points

Comparison of Baseline Shape and Sample Points



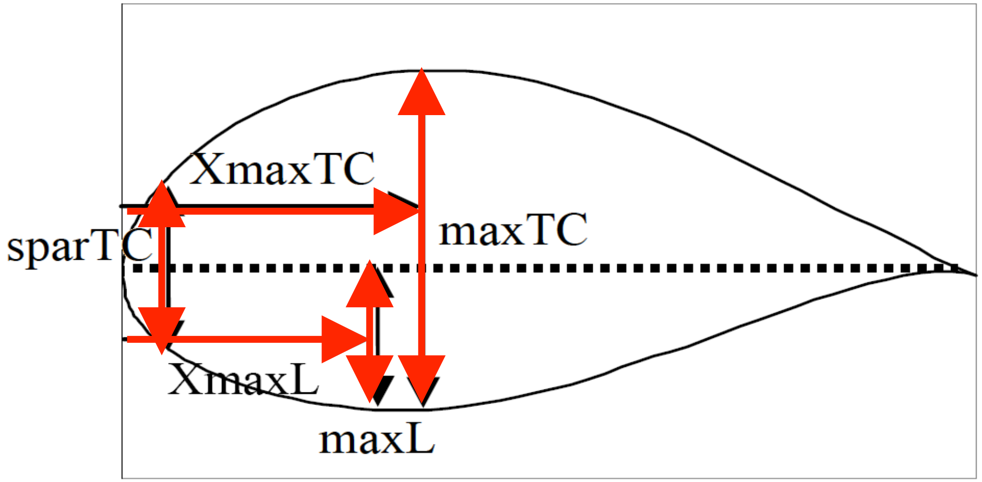


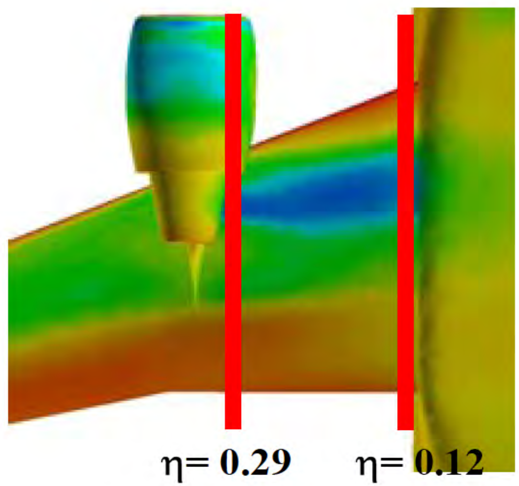
Point A is improved by 6.7 counts in C_D, 0.61 in $–C_{p,max}$, and 12.2 kg in wing weight compared with the baseline



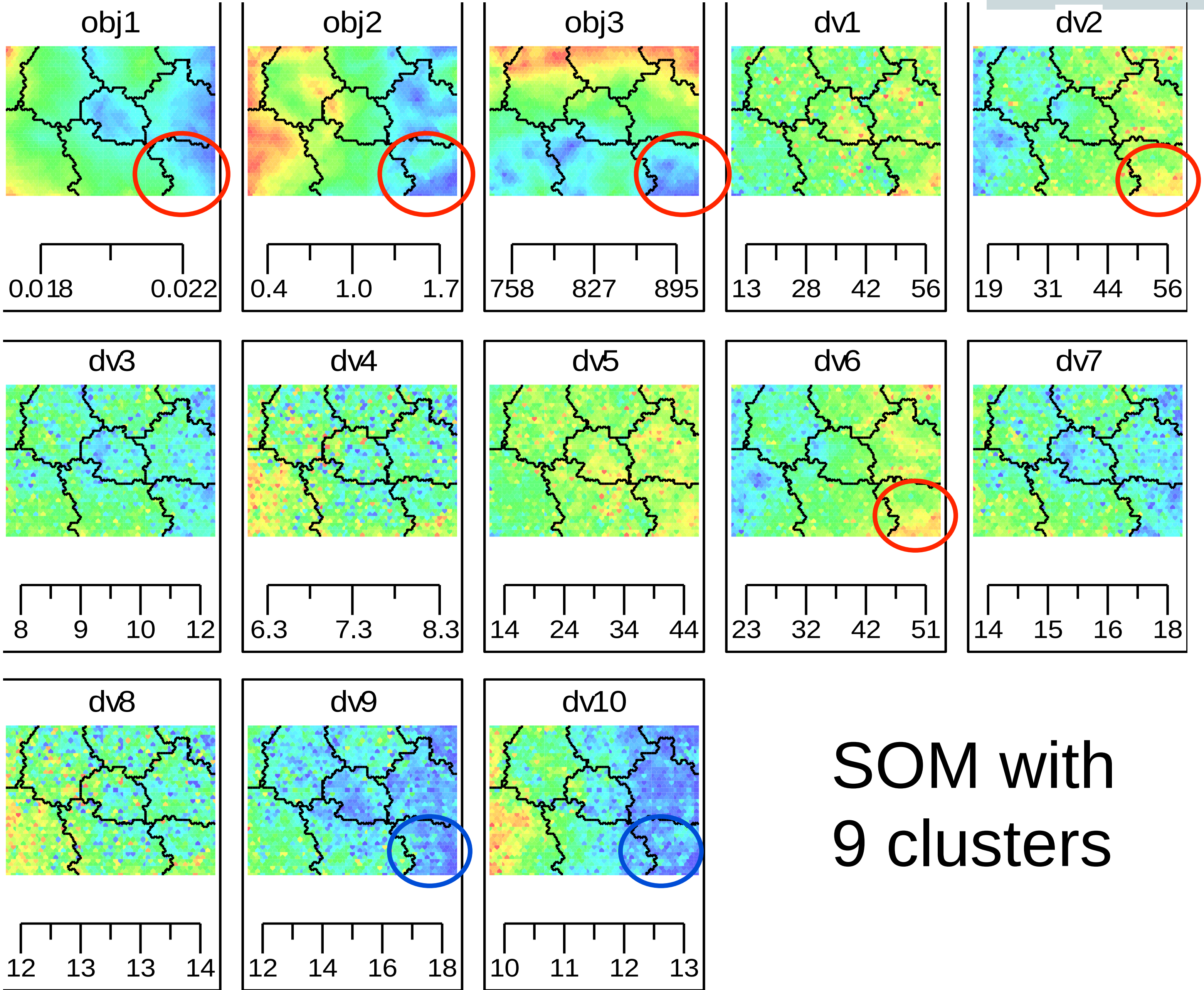
Definition of Design Parameters for Data Mining

- XmaxL
- maxL
- XmaxTC
- maxTC
- sparTC
  - At wing root and pylon locations
  - 10 variables



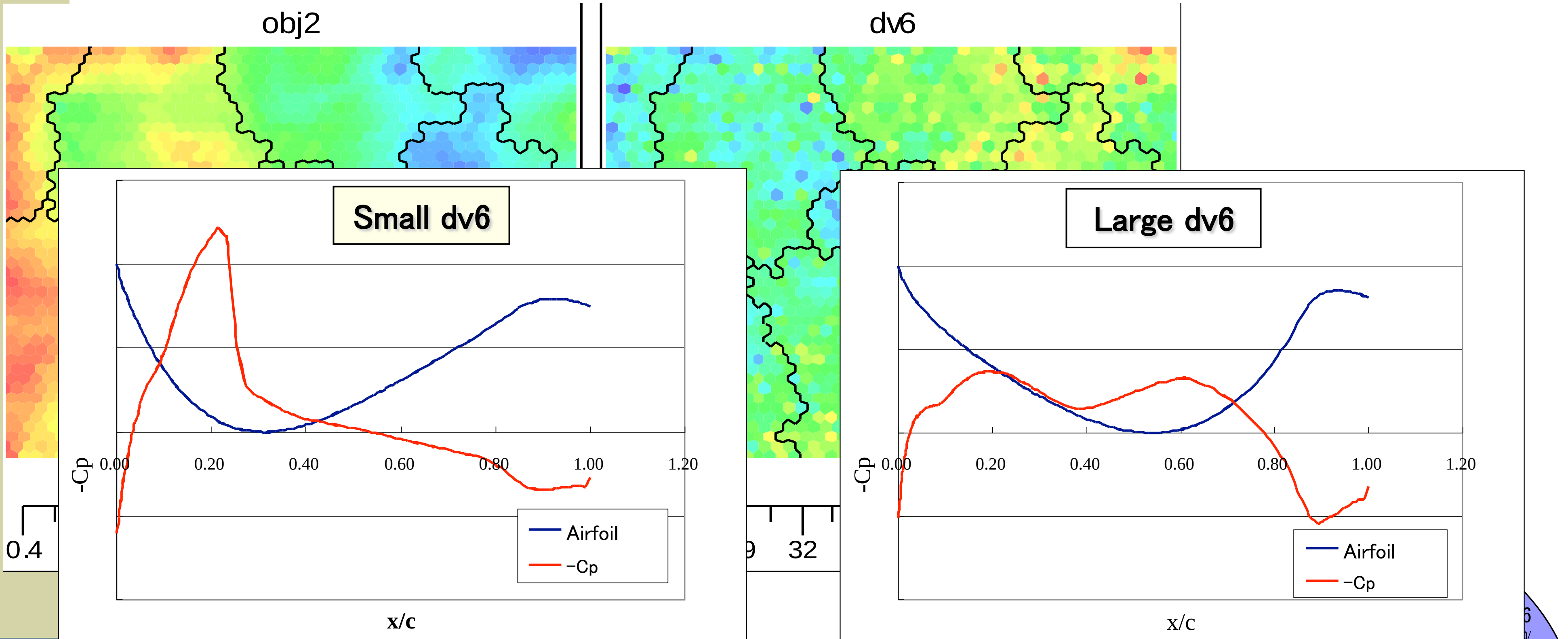


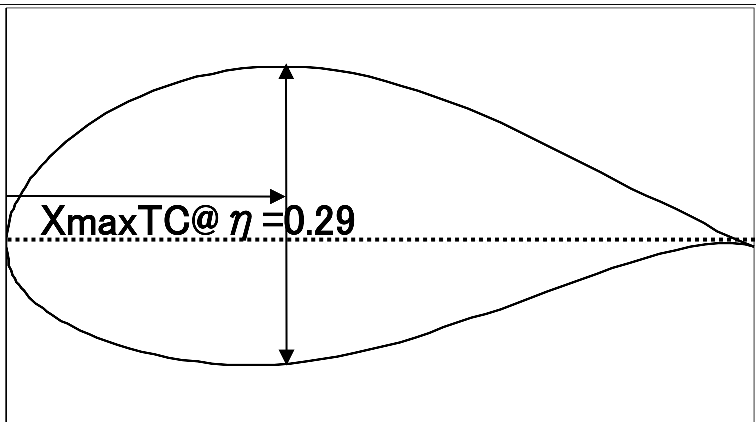
Visualization of Design Space

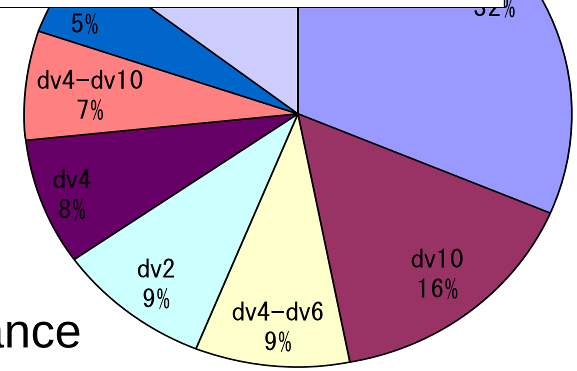


SOM with
9 clusters

-Cp,max and dv6 (XmaxTC at pylon)





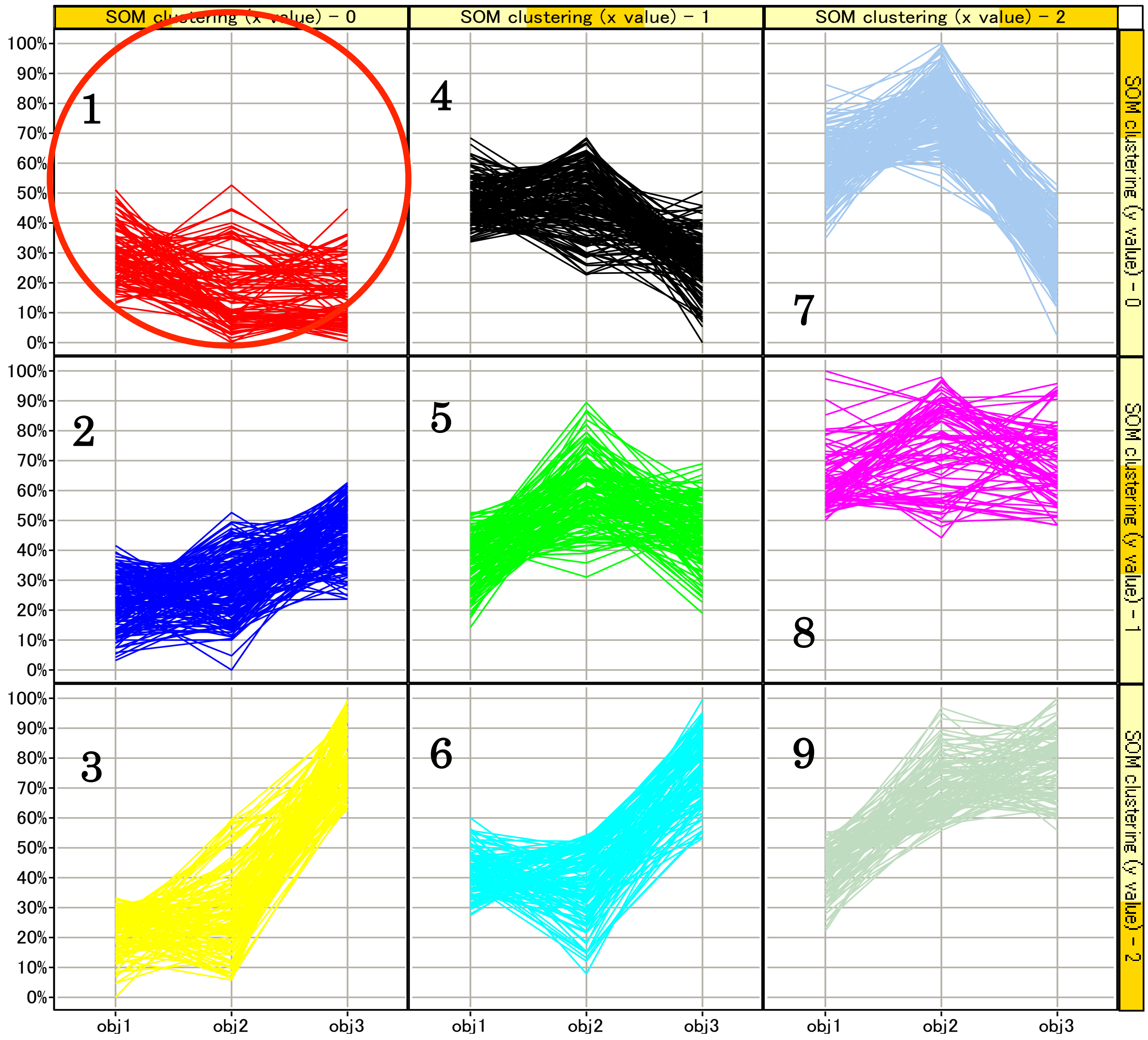


Analysis of Variance (ANOVA)

Analysis of Sweet–Spot Cluster

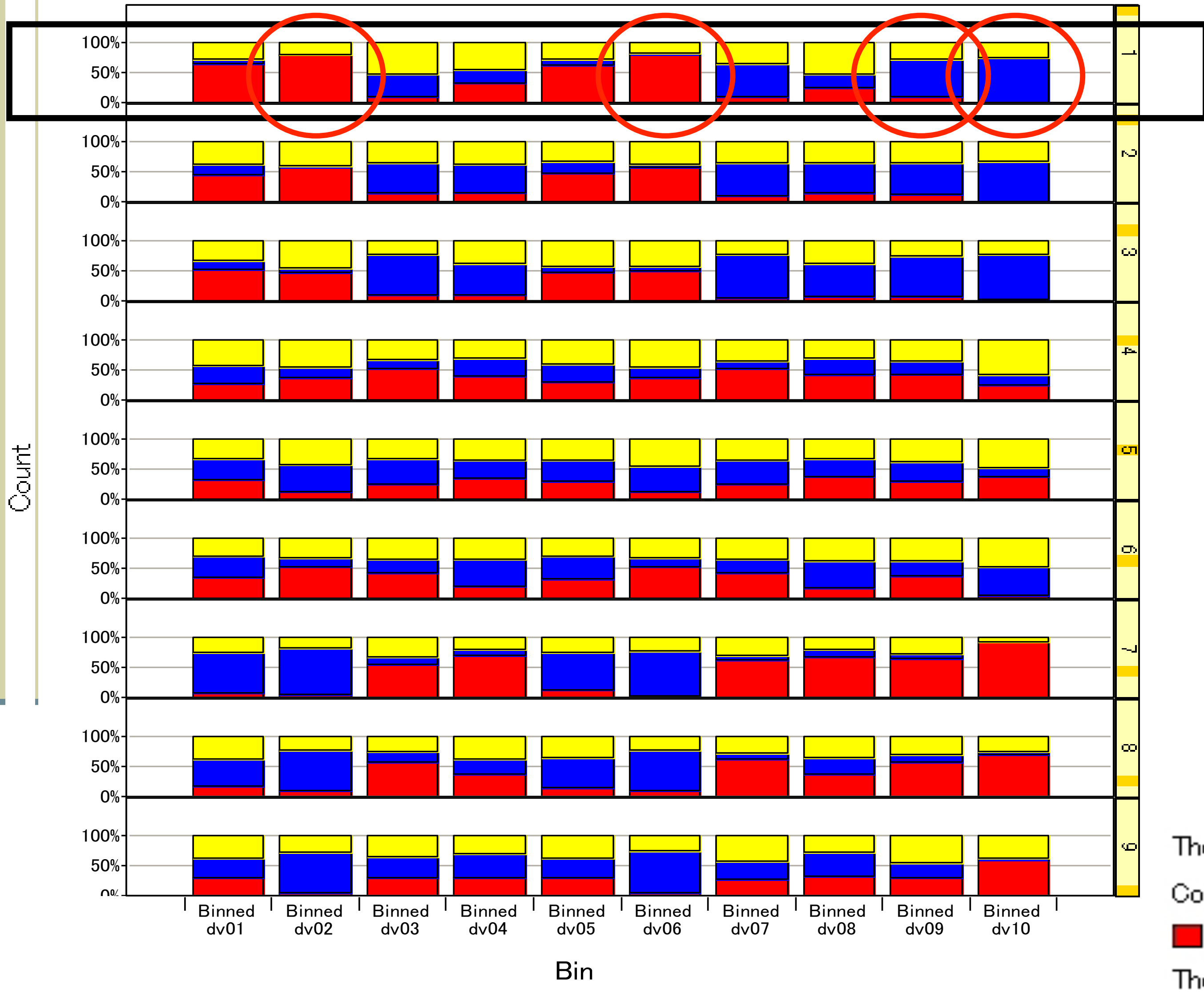
- Handpick
- Parallel coordinates
- Extraction of design rules by discretization of configuration variables
  - ✓ Visualization
  - ✓ Rough set

Visualization of SOM Clusters by Parallel Coordinates



Discretization of Configuration Variables by Equal Frequency Binning

Finding Design Rules by Visualization



Sweet-spot cluster

	Airfoil parameters
dv2	XmaxL @ η= 0.29
dv6	XmaxTC @ η= 0.29
dv9	sparTC @ η= 0.12
dv10	sparTC @ η= 0.29

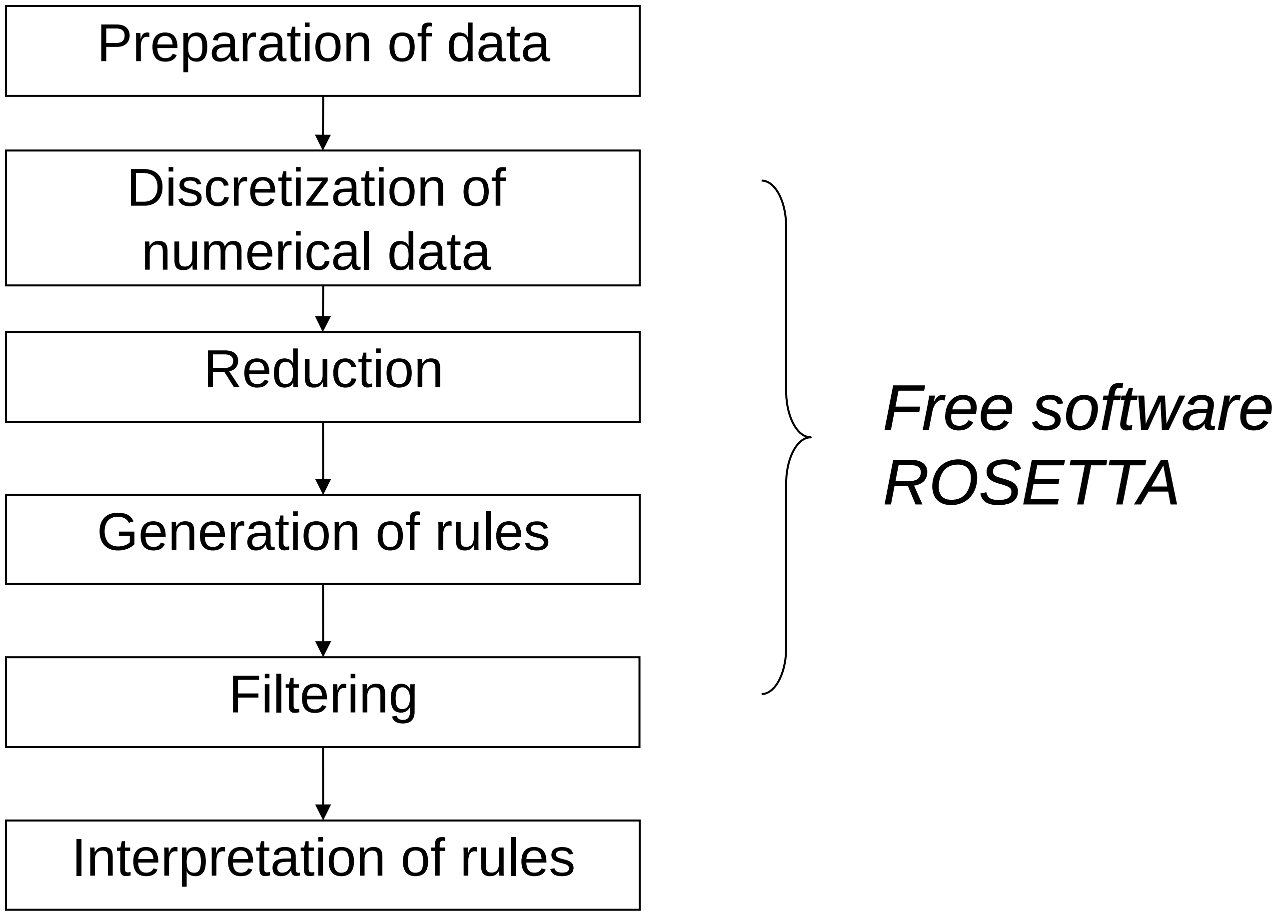
The height of a bar represents the number of records.

Color by Group:

High Low Middle

The labels show the height of each bar.

Flowchart of Data Mining Using Rough Set



Generated rules to belong to sweet spot cluster with support of more than eight occurrence

Rule	Count
dv1([33.08, 39.30)) AND dv2([40.69, *)) AND dv5([29.65, 33.61)) AND dv7([15.09, 15.83)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	10
dv1([33.08, 39.30)) AND dv2([40.69, *)) AND dv3([8.88, 9.57)) AND dv5([29.65, 33.61)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	10
dv1([33.08, 39.30)) AND dv3([8.88, 9.57)) AND dv5([29.65, 33.61)) AND dv6([39.25, *)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	10
dv1([33.08, 39.30)) AND dv5([29.65, 33.61)) AND dv6([39.25, *)) AND dv7([15.09, 15.83)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	10
dv1([33.08, 39.30)) AND dv2([40.69, *)) AND dv5([29.65, 33.61)) AND dv6([39.25, *)) AND dv7([15.09, 15.83)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	10
dv1([33.08, 39.30)) AND dv3([8.88, 9.57)) AND dv4([7.54, *)) AND dv6([39.25, *)) AND dv10([*, 10.58)) => Cluster(C6)	9
dv1([33.08, 39.30)) AND dv2([40.69, *)) AND dv3([8.88, 9.57)) AND dv4([7.54, *)) AND dv10([*, 10.58)) => Cluster(C6)	9
dv3([8.88, 9.57)) AND dv4([7.54, *)) AND dv5([29.65, 33.61)) AND dv6([39.25, *)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv2([40.69, *)) AND dv3([8.88, 9.57)) AND dv5([29.65, 33.61)) AND dv8([12.82, 13.32)) AND dv9([*, 12.62)) => Cluster(C6)	8
dv2([40.69, *)) AND dv5([29.65, 33.61)) AND dv7([15.09, 15.83)) AND dv8([12.82, 13.32)) AND dv9([*, 12.62)) => Cluster(C6)	8
dv1([33.08, 39.30)) AND dv4([7.54, *)) AND dv5([29.65, 33.61)) AND dv7([15.09, 15.83)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv1([33.08, 39.30)) AND dv3([8.88, 9.57)) AND dv4([7.54, *)) AND dv5([29.65, 33.61)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv1([33.08, 39.30)) AND dv4([7.54, *)) AND dv6([39.25, *)) AND dv7([15.09, 15.83)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv1([33.08, 39.30)) AND dv2([40.69, *)) AND dv4([7.54, *)) AND dv7([15.09, 15.83)) AND dv9([*, 12.62)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv2([40.69, *)) AND dv3([8.88, 9.57)) AND dv4([7.54, *)) AND dv5([29.65, 33.61)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv2([40.69, *)) AND dv4([7.54, *)) AND dv5([29.65, 33.61)) AND dv7([15.09, 15.83)) AND dv10([*, 10.58)) => Cluster(C6)	8
dv4([7.54, *)) AND dv5([29.65, 33.61)) AND dv6([39.25, *)) AND dv7([15.09, 15.83)) AND dv10([*, 10.58)) => Cluster(C6)	8

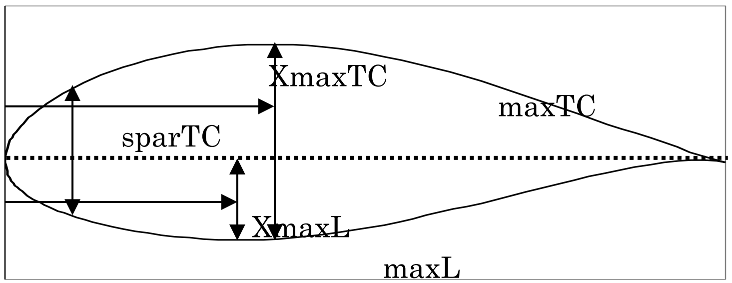
Statistics of rule conditions and comparison with previous results

	Sweet
dv1	11
dv2	9
dv3	8
dv4	10
dv5	13
dv6	7
dv7	9
dv8	2
dv9	9
dv10	14

large

small

Number	Airfoil parameters
dv1	XmaxL @ η= 0.12
dv2	XmaxL @ η= 0.29
dv3	maxL @ η= 0.12
dv4	maxL @ η= 0.29
dv5	XmaxTC @ η= 0.12
dv6	XmaxTC @ η= 0.29
dv7	maxTC @ η= 0.12
dv8	maxTC @ η= 0.29
dv9	sparTC @ η= 0.12
dv10	sparTC @ η= 0.29



Statistics of rule conditions for all objectives

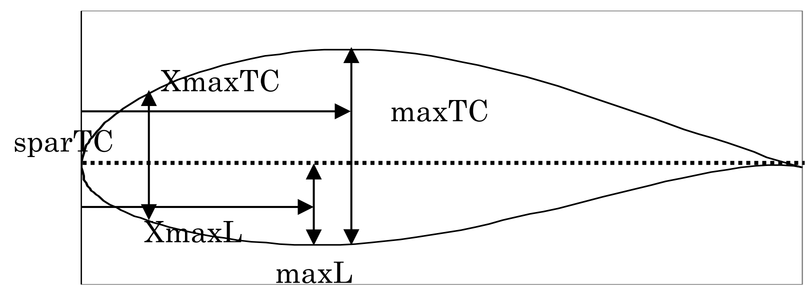
	Sweet	Cd	Cp	WW
dv1	11	1	1	5
dv2	9	2	6	3
dv3	8	5	6	4
dv4	10	3	5	11
dv5	13	8	1	7
dv6	7	6	3	3
dv7	9	5	6	5
dv8	2	4	3	2
dv9	9	2	2	3
dv10	14	9	8	8

Number	Airfoil parameters
dv1	XmaxL @ η= 0.12
dv2	XmaxL @ η= 0.29
dv3	maxL @ η= 0.12
dv4	maxL @ η= 0.29
dv5	XmaxTC @ η= 0.12
dv6	XmaxTC @ η= 0.29
dv7	maxTC @ η= 0.12
dv8	maxTC @ η= 0.29
dv9	sparTC @ η= 0.12
dv10	sparTC @ η= 0.29

large

small

No large dv10



Lessons Learned

Designers do not like optimizer decides their design

- Optimal solutions are often unrealistic
  - Optimization problem is a model of actual design
- Optimization algorithms are continuously developed
  - A better solution will be obtained tomorrow

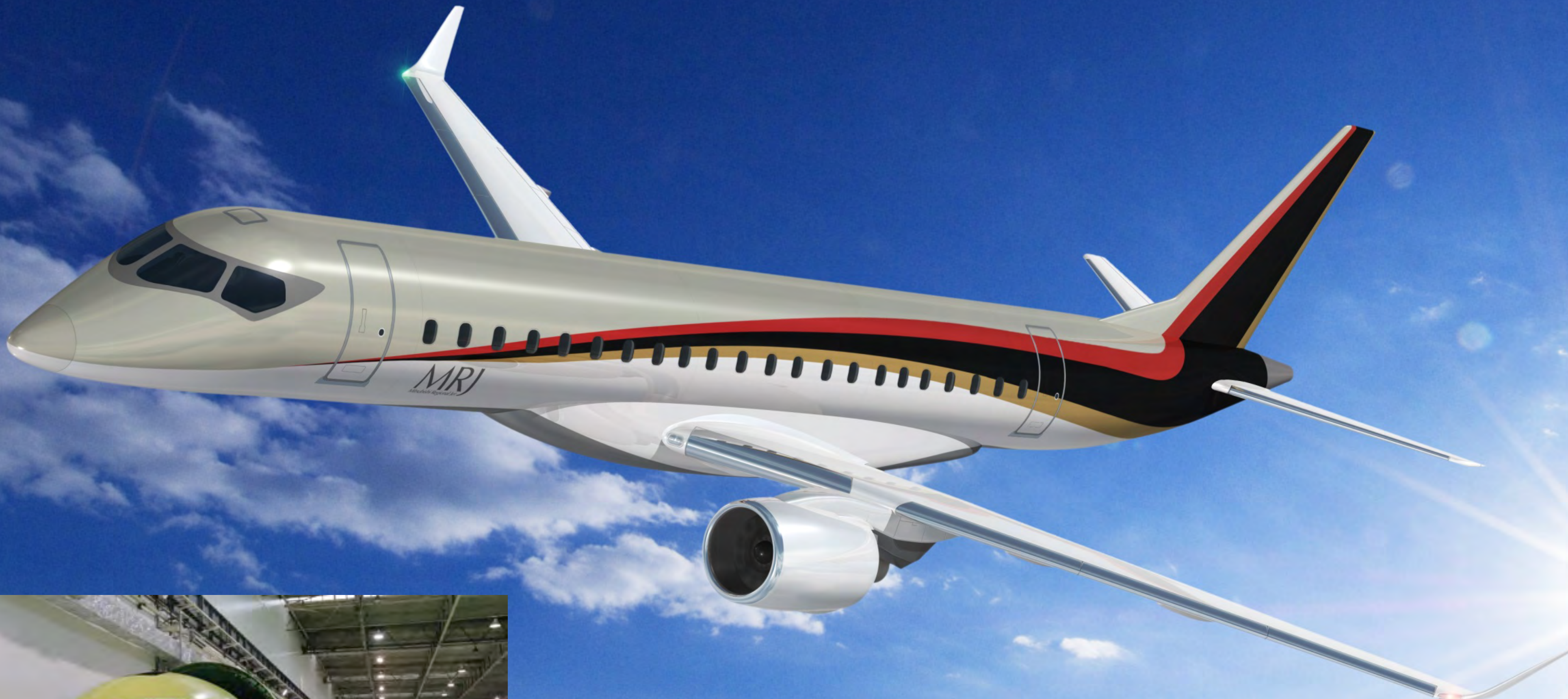
Designers need supports for their decisions

- Information about design space is desired
  - MODE has been proposed
- Visualization and data mining extract design knowledge
  - SOM has become an essential design tool

Acknowledgements

- Mitsubishi Aircraft Corporation
- Mitsubishi Heavy Industries
- Supercomputer NEC SX-9 and SGI Altix-UV at Institute of Fluid Science
- Prof. Yasushi Ito, University of Alabama at Birmingham, for MEGG3D (mesh generator)
- Prof. Kazuhiro Nakahashi, Tohoku University, for TAS (unstructured-mesh flow solver)

Stay tuned for the first flight in 2015!




MRJ in production

謝謝