TOHOKU UNIVERSITY

Data Mining for Aircraft Design Space

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V-I-S-I-O-N 2030

2018 Institute of Fluid Science, Tohoku University 75th

1943

Institute of High-Speed Mechanics Established.

1959


国産発電機にがい歌
東北電力 東北大苦心の研究
軽く外国製しのぐ
カプラン水車採用 震動等悪条件も克服
優秀な国産技術立証

Delivery of Kaplan turbines, the world's largest size at the time, to an electric power company through industry-academia collaborative research with Hitachi.

1969

Prof. Numachi gave a lecture in the Emperor's presence.

1989

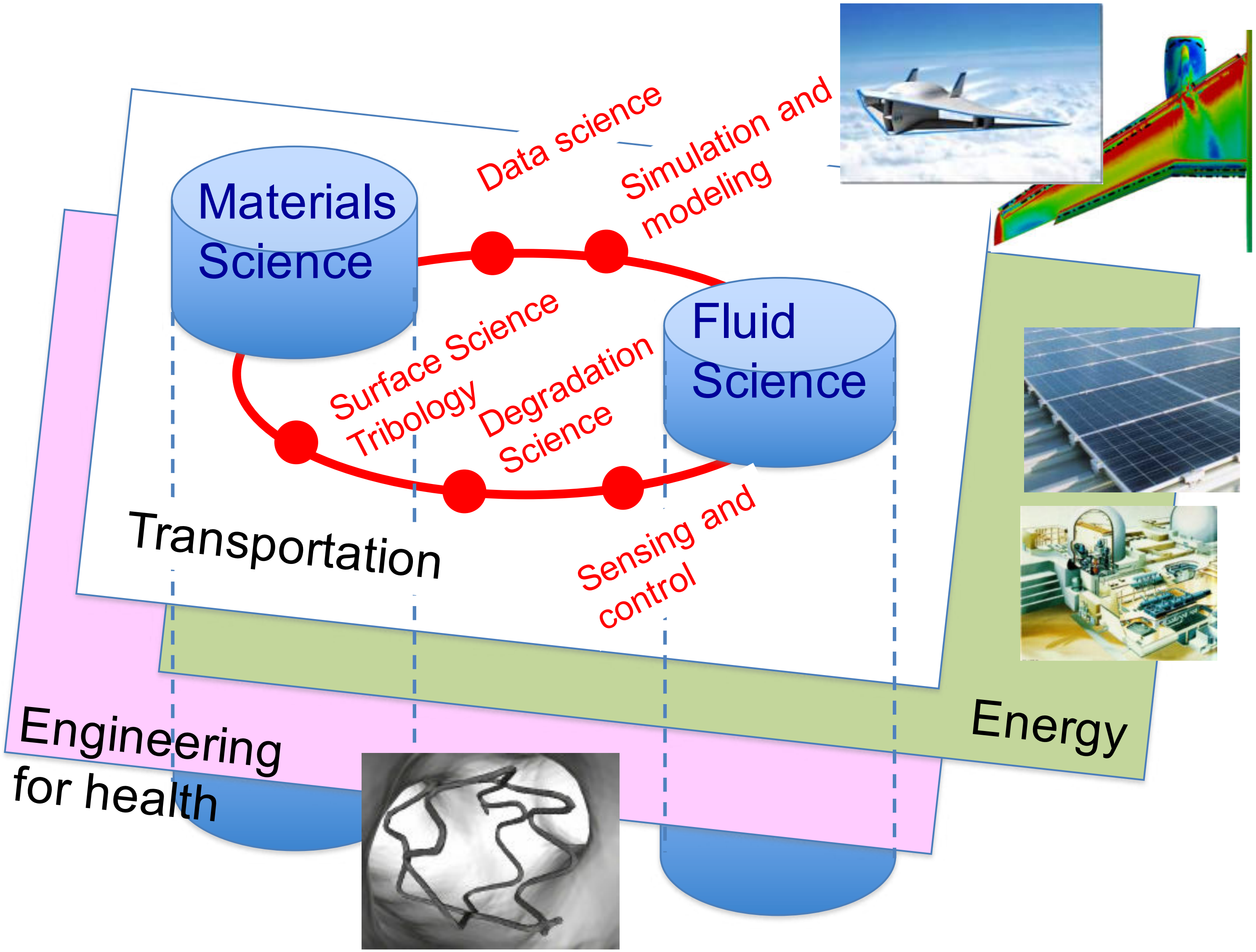
Reorganization and conversion to the Institute of Fluid Science.
(12 Research Division and 1 Research Center)

2018

Lyon Center(LyC) -Integration Research Center for Materials and Fluid Sciences- was established at the Université de Lyon.

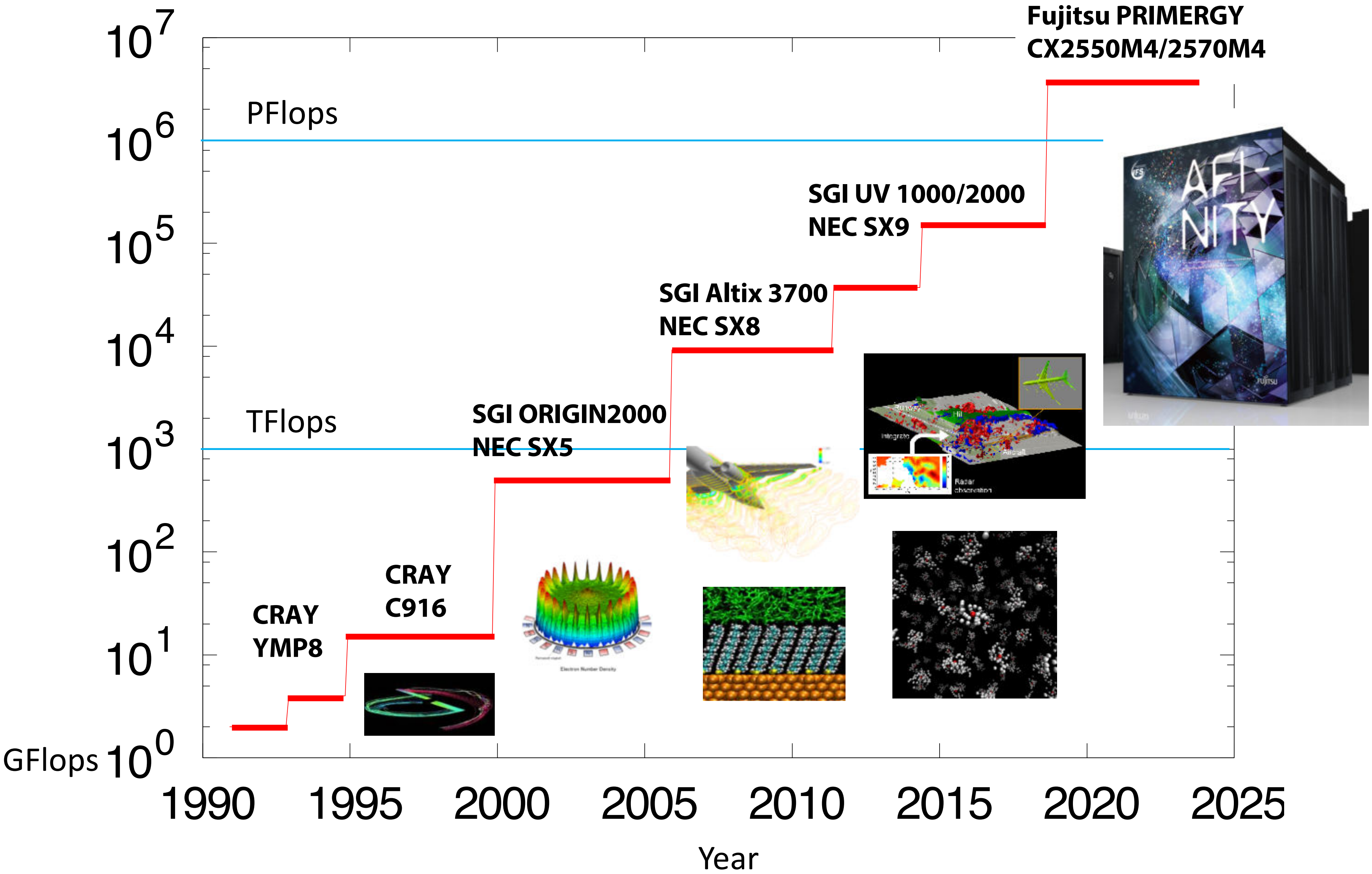
Issues that IFS Lyon Center Tackles

Lyon center explores interdisciplinary science based on fluid science and materials science to answer current societal stakes in the fields of transportation, energy and engineering for health.



IFS Supercomputers

Peak Performance 3.7 PFlops
= 24 times faster than previous



Outline

- Introduction
  - MRJ Project
  - Multi-Objective Design Exploration (MODE)
- Recent Application of MODE
  - Finding Design Rules for Vortex Generators
- How can Optimization Help Design?

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Introduction

MRJ MDO Problems (2003-2013)

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

MRJ Program Status

- ✓ 2007.10 Authorization To Offer (ATO)
- ✓ 2008.3 Launch (25 Orders from ANA)
- ✓ 2008.4 Mitsubishi Aircraft Corporation commences operation
- ✓ 2009.4 PDR (Preliminary Design Review)
- ✓ 2009.10 Announcement of 100 Orders from TSH TRANS STATES HOLDINGS
- ✓ 2010.9 CDR (Critical Design Review)
- ✓ 2012.12 Announcement of 200 Orders from SKYWEST, INC.
- ✓ 2014.7 More orders from Eastern Air Lines Group, Inc. and Air Mandalay Limited
- ✓ 2015.11 First Flight
- ✓ 2019.6 Renamed to Mitsubishi SpaceJet
- 2020 First Delivery

Mitsubishi Heavy Industries, Ltd.

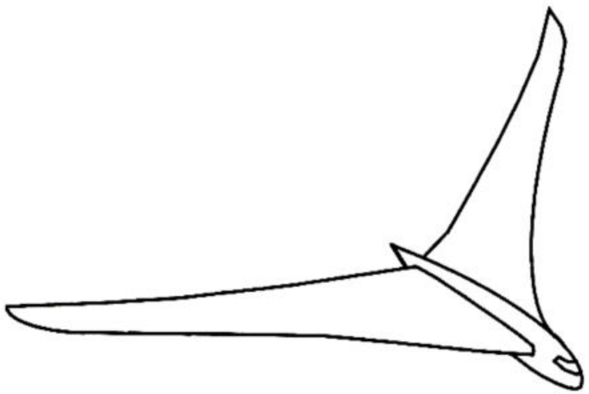
Mitsubishi Aircraft Corporation

ANA order for 25 MRJ (15 firm, 10 option)

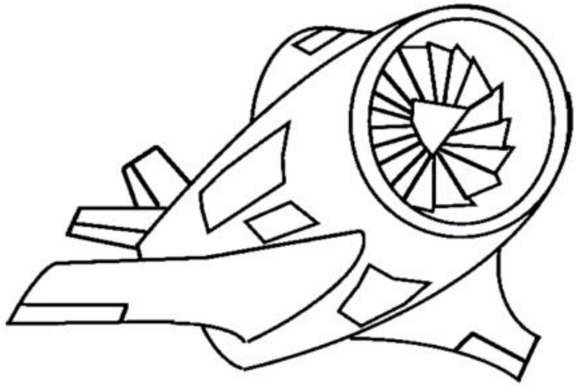
TSH order for 100 MRJ (50 firm, 50 option)

Mitsubishi SpaceJet

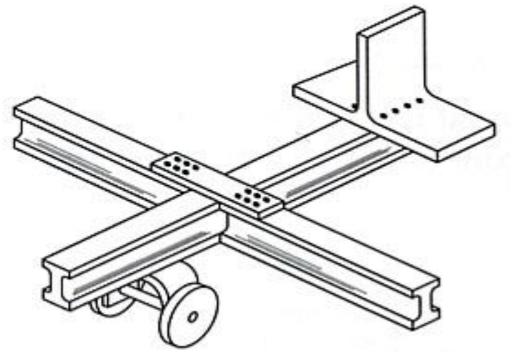
Aircraft Design



Aerodynamics



Propulsion

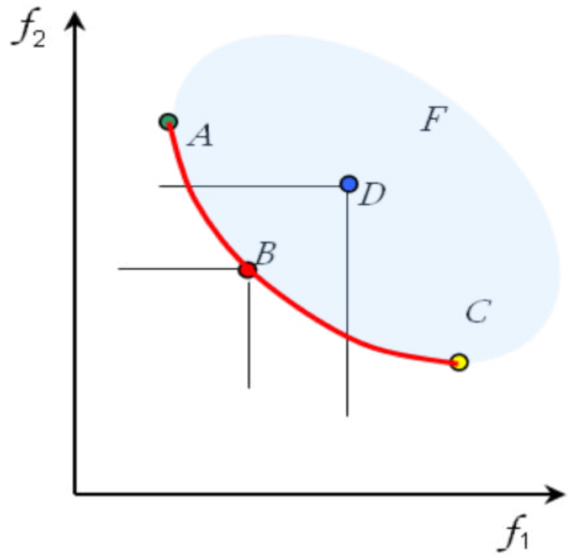


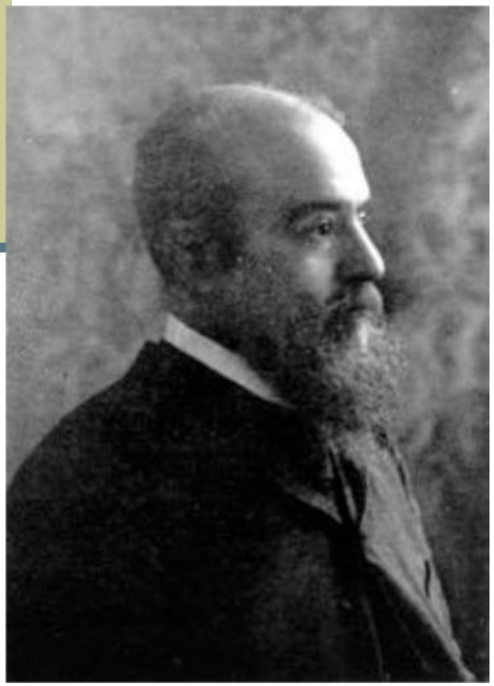
Structure

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

Multi-Objective Optimization and Pareto Solution

- Comparison of solutions for multiple objectives
  - Total order for a single index
  - Partial order for multiple indices
- Non-dominated solutions
  - Pareto front
  - Representation of trade-offs

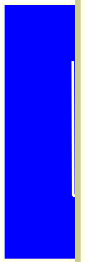




Vilfredo Pareto (1848–1923)
An Italian economist who used this concept in his studies of economic efficiency and income distribution [Wikipedia]

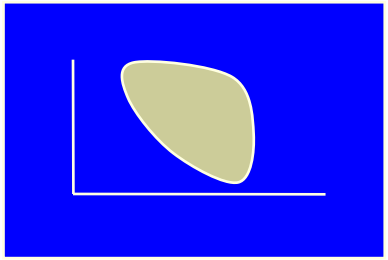
Visualization of Tradeoffs

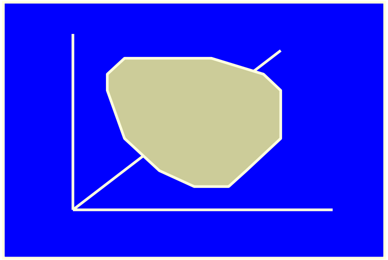
2 o

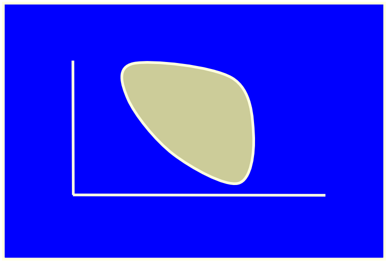


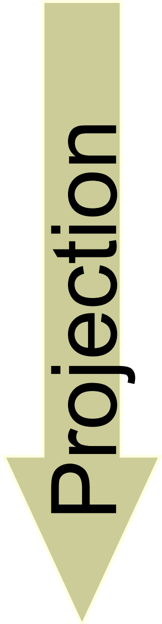
- Global optimization is needed
- Visualization is essential!
- Data mining is required for higher dimensions
- Design optimization → Design exploration

Minimization problems





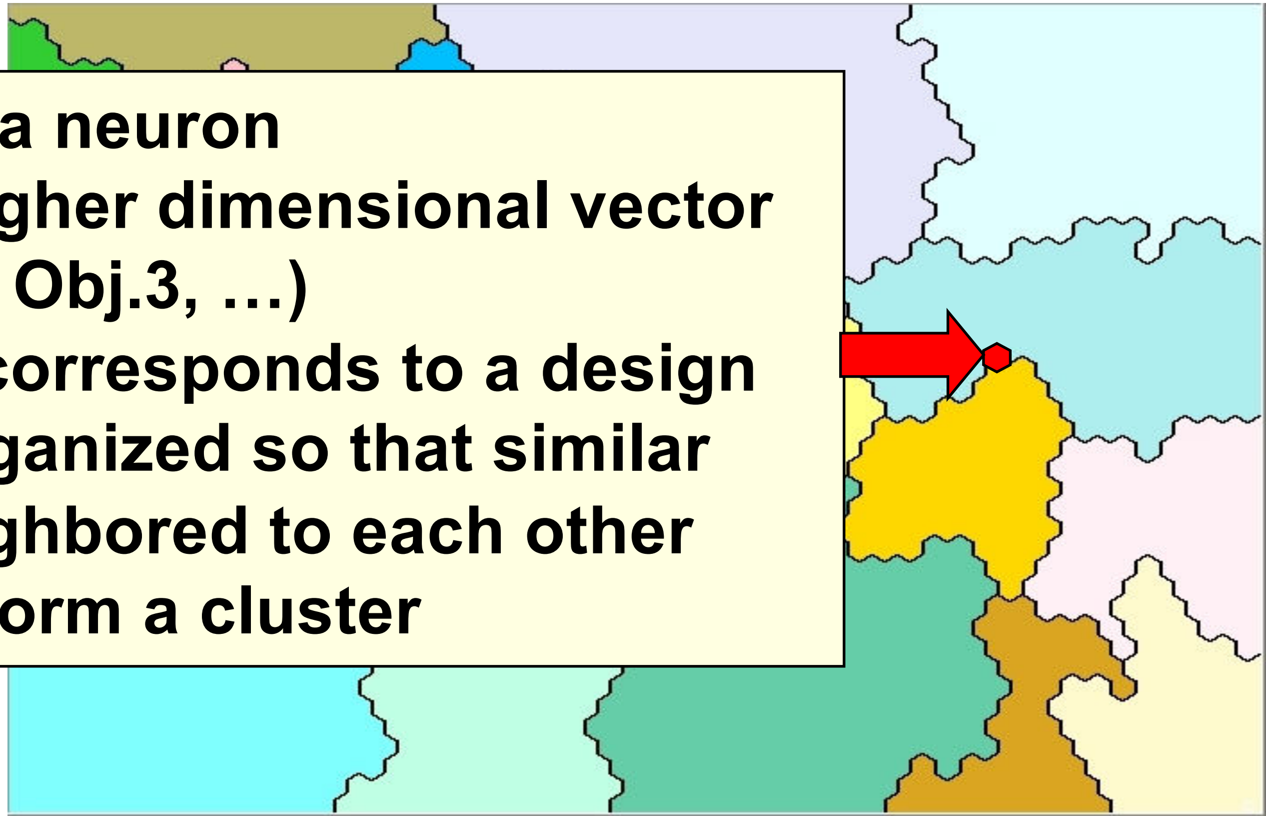




Self-Organizing Map (SOM)

- Neural network model proposed by Kohonen
  - Unsupervised, competitive learning
- High-dimensional data → 2D map
- Qualitative description of data

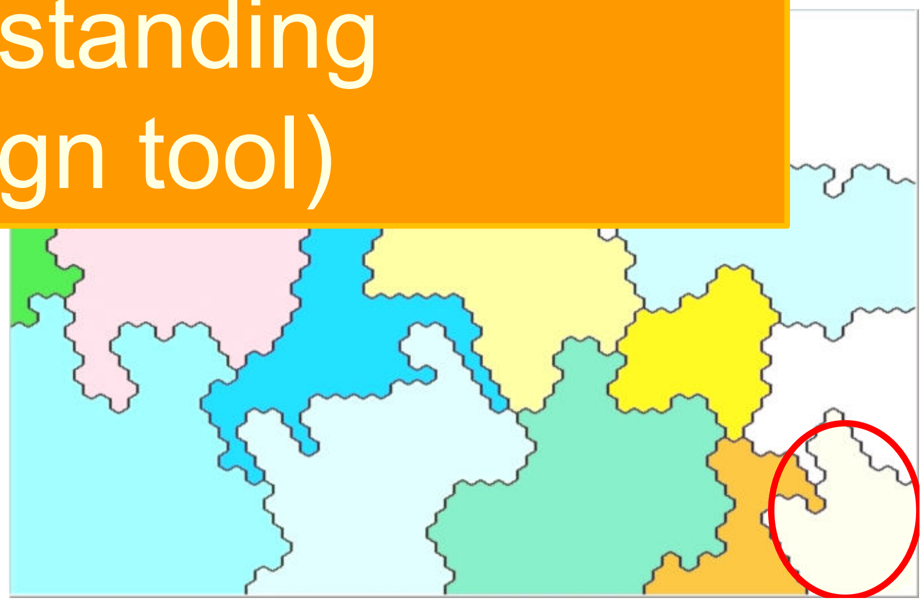
•Node represents a neuron
-Neuron is a higher dimensional vector (Obj.1, Obj.2, Obj.3, …)
-Each neuron corresponds to a design
•Neuron is self-organized so that similar neurons are neighbored to each other
•Similar neurons form a cluster



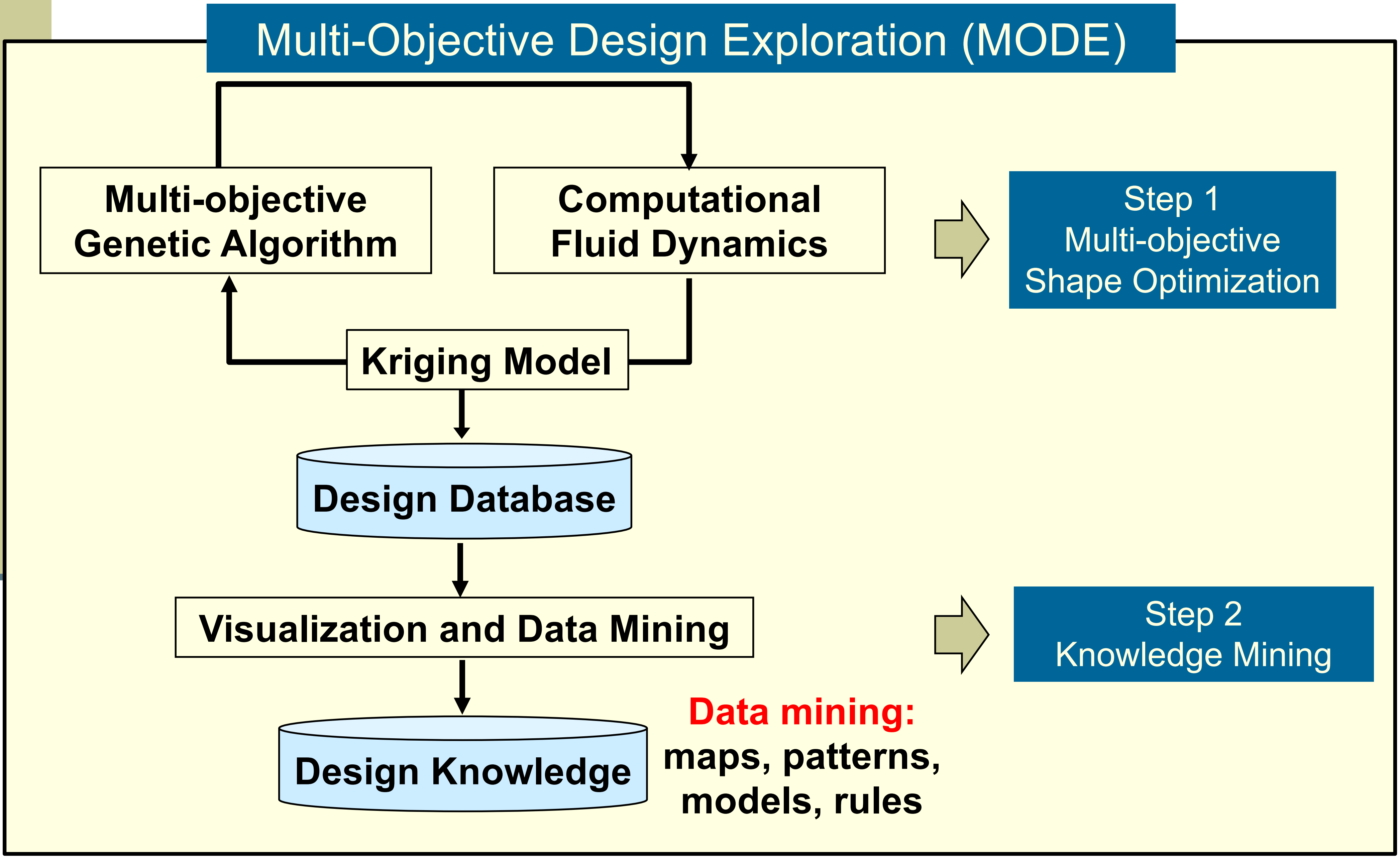
How to Understand SOM Better?

- Colored SOMs identify the global structure of the design space
- Resulting clusters classify possible designs
  - If a cluster has all objectives near optimal, it is called as sweet-spot cluster
  - If the sweet-spot cluster exists, it should be analyzed in

SOM provides design visualization:
Seeing is understanding
(Essential design tool)



MODE to Solve MDO Problems



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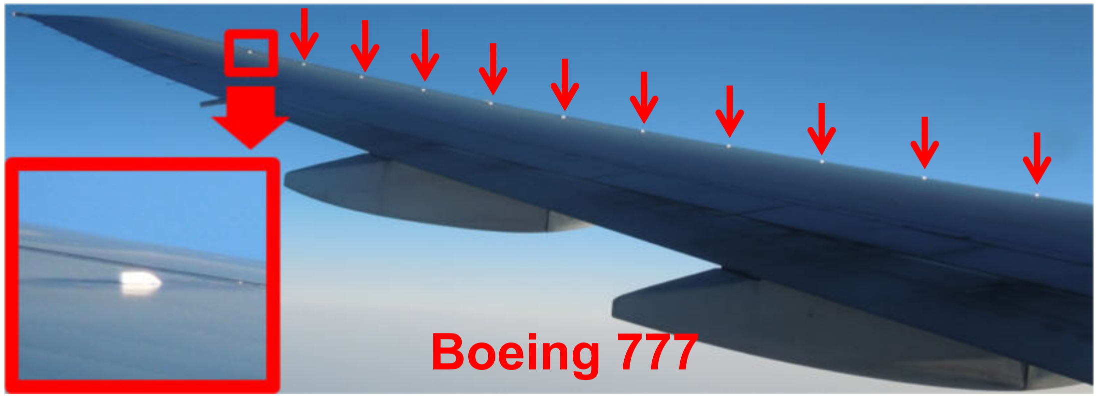
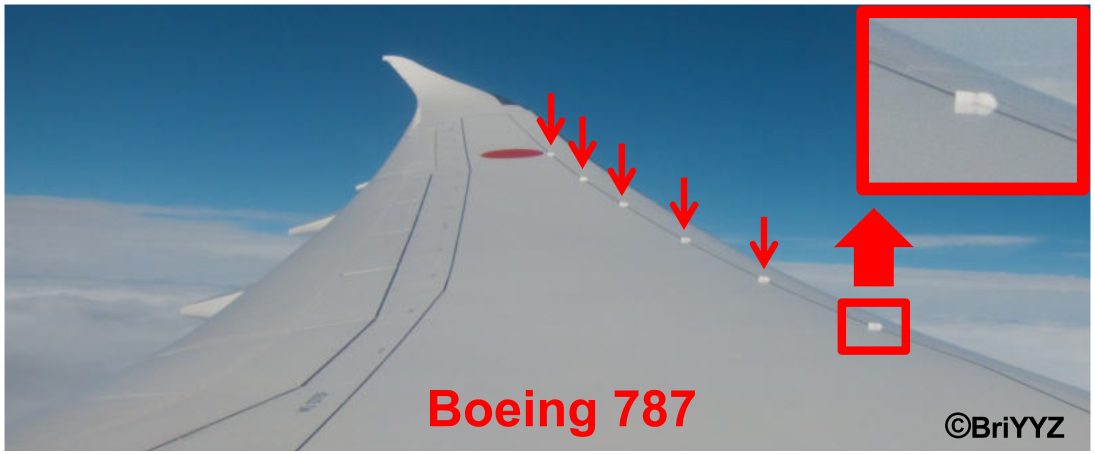
Finding Design Rules for Vortex Generators





Surrogate-Based Multi-Objective Optimization and Data Mining of Vortex Generators on a Transonic Infinite-Wing

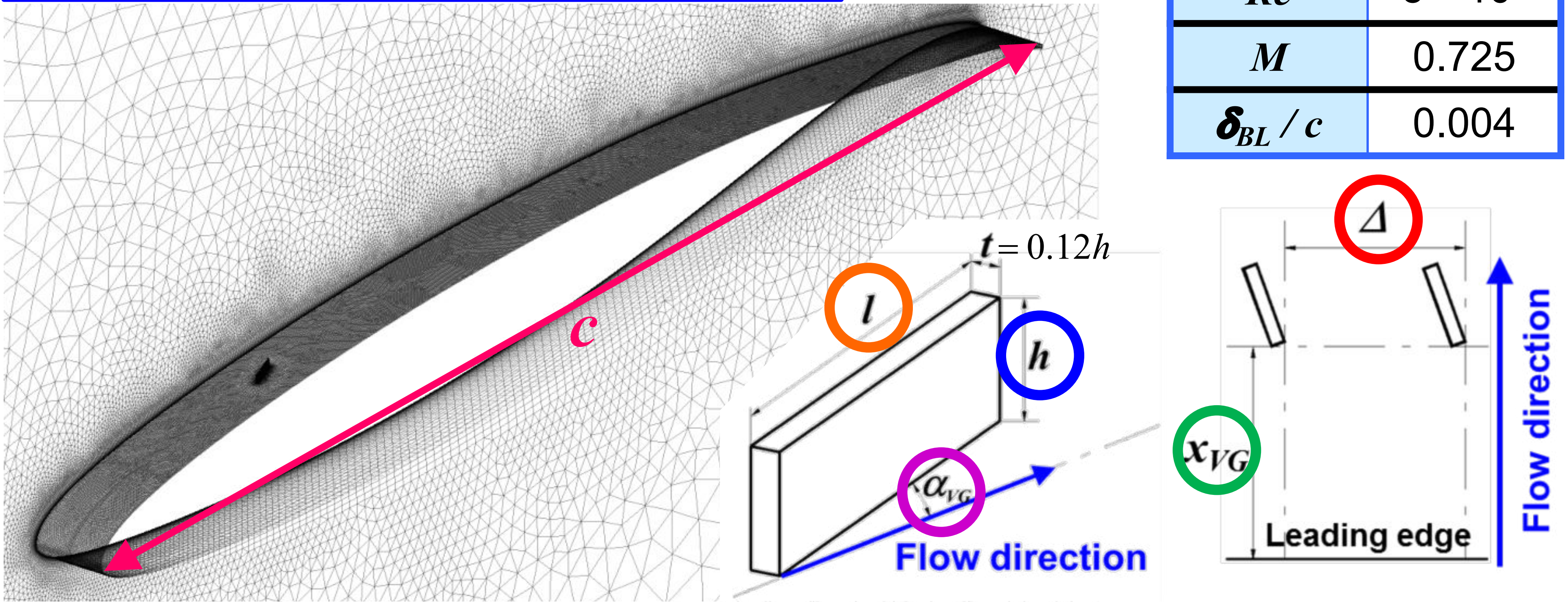
N. Namura, S. Obayashi and S. Jeong

2013 IEEE Congress on Evolutionary Computation

Design Variables and Constraints

- Rectangular wing with super critical airfoil
- Periodic boundary condition in span direction

Re	5×10^6
M	0.725
δ_{BL} / c	0.004



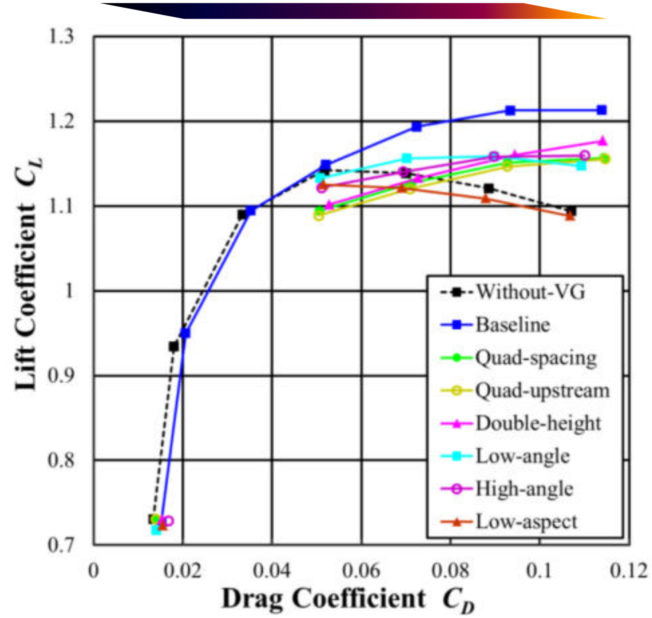
Design Variables

1. Height $0.004 \le h/c \le 0.012$
2. Length $0.004 \le l/c \le 0.072$
3. Angle $10° \le \alpha_{VG} \le 30°$
4. Location $0.15 \le x_{VG}/c \le 0.30$
5. Spacing $0.02 \le \Delta/c \le 0.36$

Constraints

1. Aspect ratio $1 \le l/h \le 8$
2. Spacing ratio $5 \le \Delta/h \le 50$

Objective Functions



1. Lift-drag ratio

Maximize L/D at $\alpha = 1$ [deg]

To improve the fuel consumption under cruise conditions

2. Lift coefficient

Maximize C_L at $\alpha = 7$ [deg]

To alleviate the two-dimensional shock-induced separation

3. Chordwise separation location

Maximize $X_{sep} = [x_{max}/c]_{C_{fx} > 0}$ at $\alpha = 7$ [deg]

To alleviate the three-dimensional shock-induced separation

Evaluation

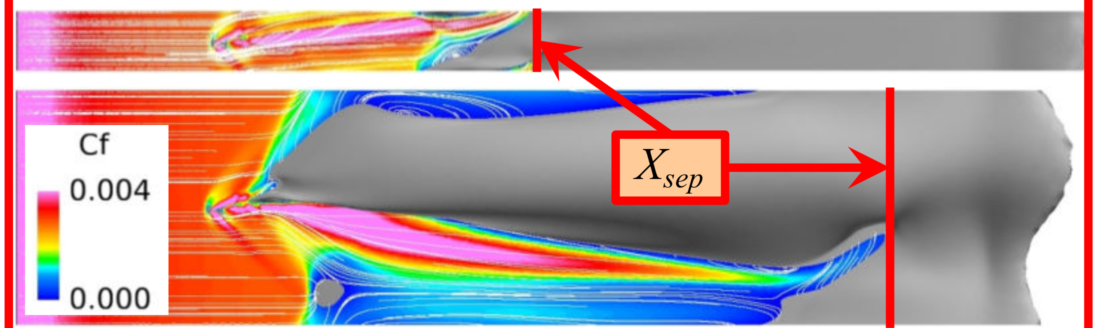
CFD solver

- Compressive Navier-Stokes equations
- **Two weeks** of computational time with a large-scale parallel computation for one design

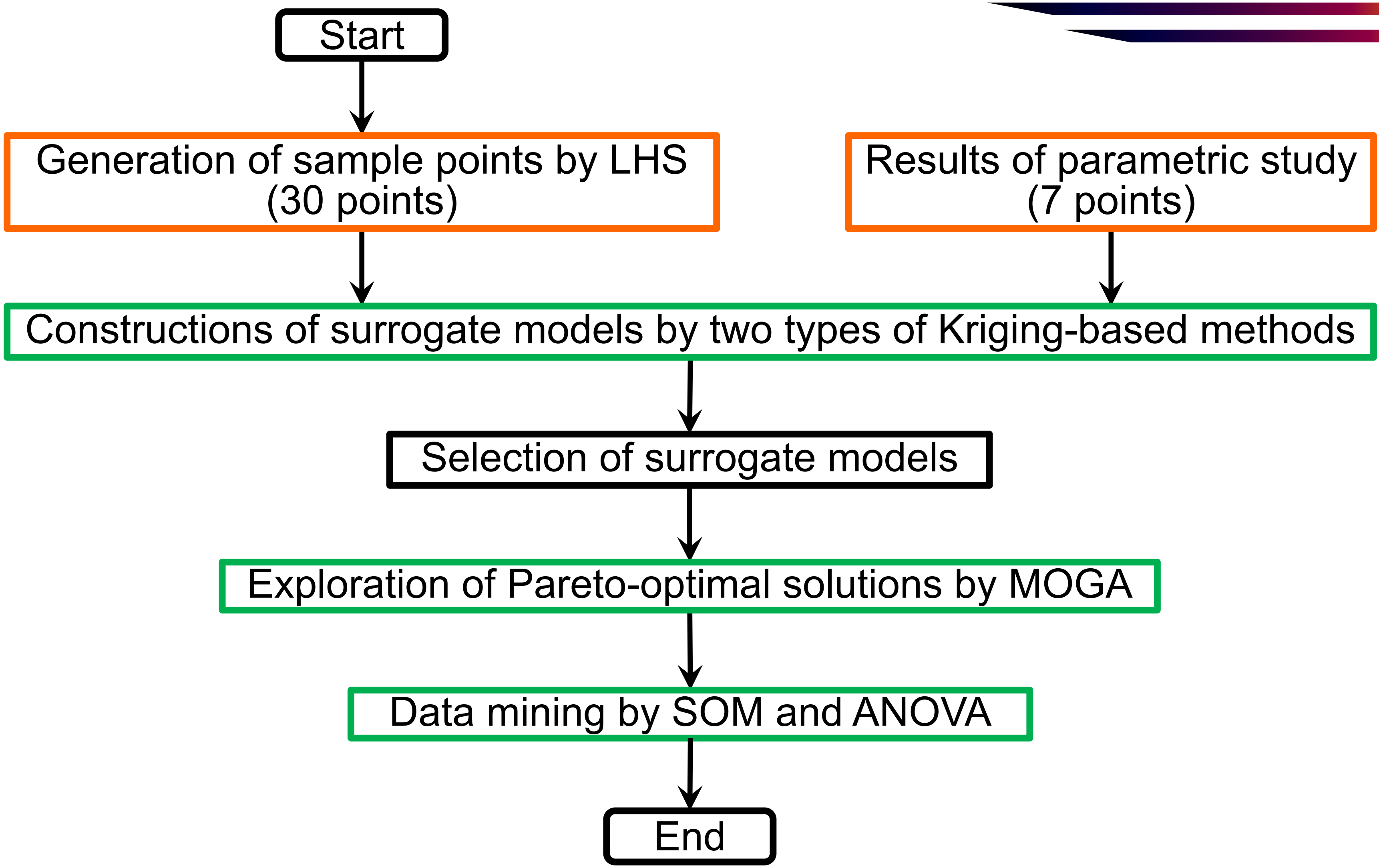
Surrogate-based optimization

Three-dimensional shock-induced separation (related to sweepback and wing-tip stall)

VG wake with thin boundary layer acts as a barrier against spanwise flow from wing-root to wing-tip



Optimization and Data Mining Procedures



LHS: Latin hypercube sampling

MOGA: multi-objective genetic algorithm

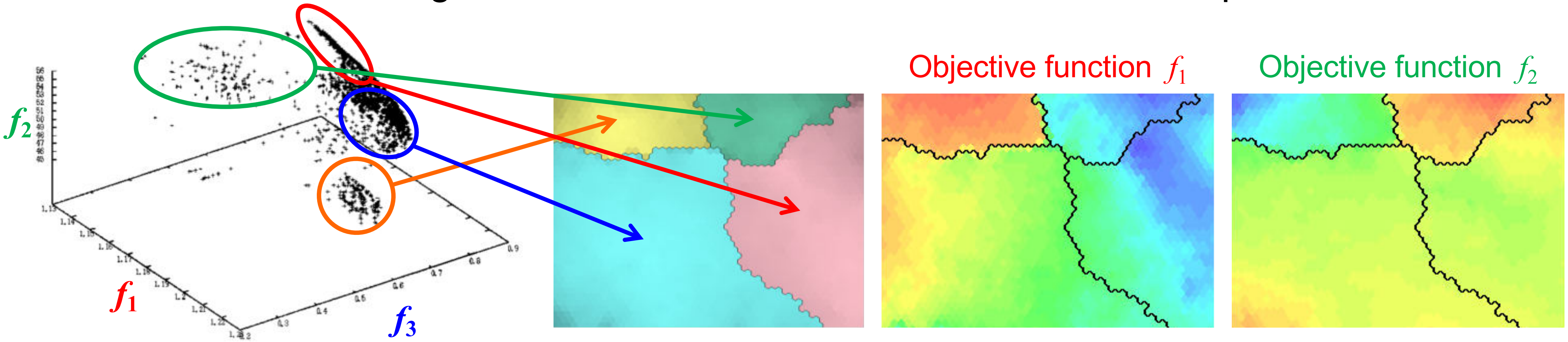
Real value evaluated by CFD analysis

Estimated value by surrogate model

Data Mining Methods

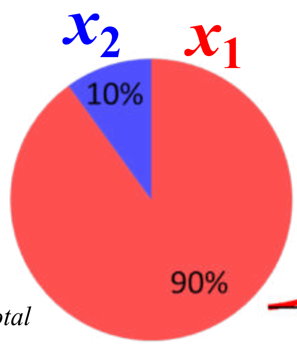
Self-organizing map (SOM)

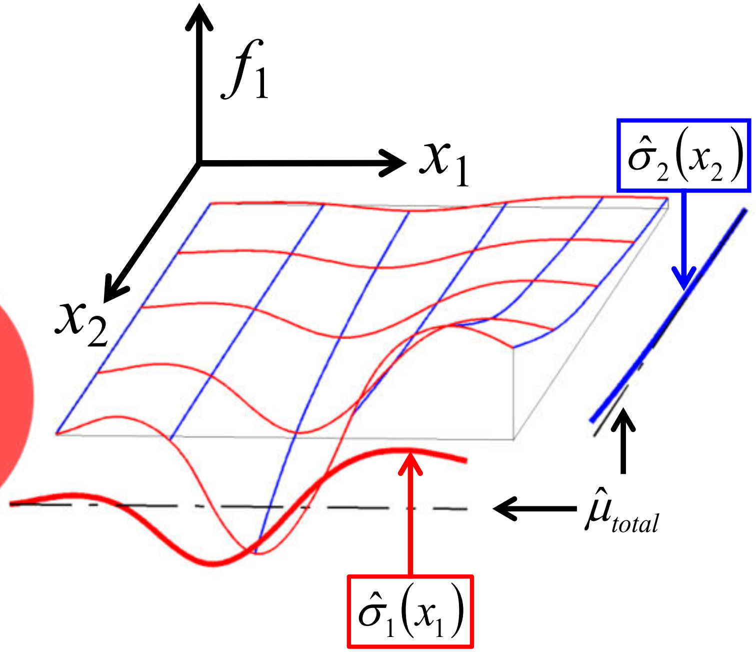
- Evaluate the correlation among design variables and objective functions
- Break down the high-dimensional data into two-dimensional maps



Analysis of variance (ANOVA)

- Evaluate the effect of each design variable on the objective function in a quantitative way
- Described by means of a pie chart





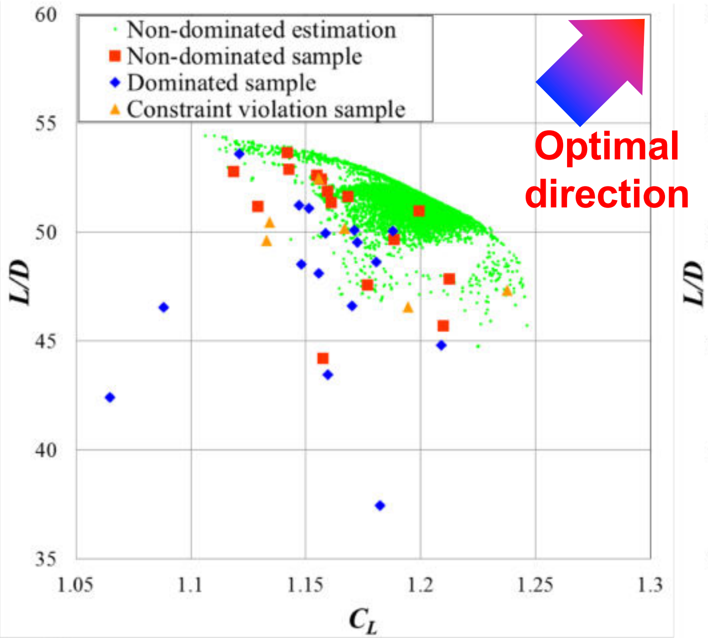
Main effect:

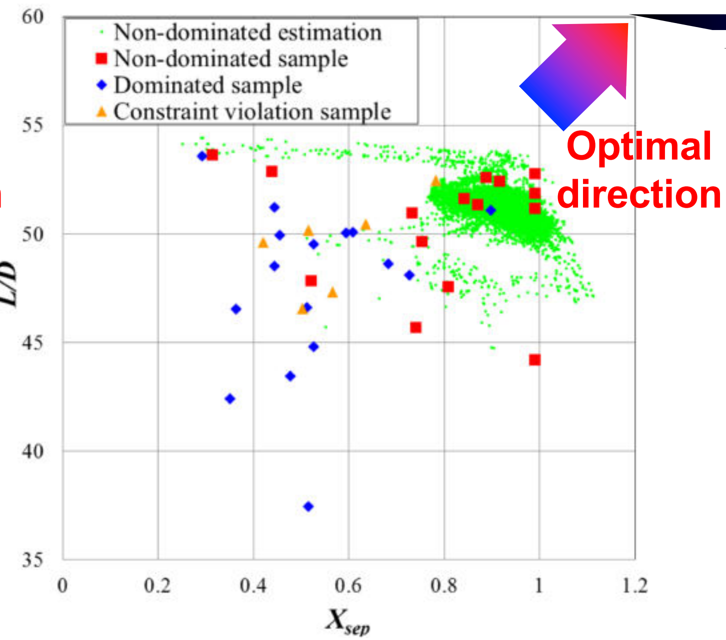
$$S_i = \int [\sigma_i(x_i)]^2 dx_i$$

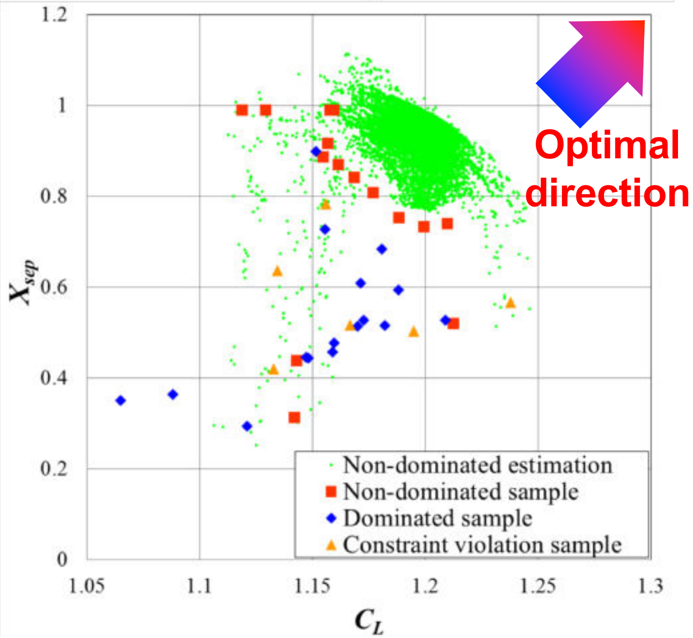
$$\hat{\sigma}_i(x_i) = \int \cdots \int \hat{y}(x_1, \cdots, x_m) dx_1 \cdots dx_{i-1} dx_{i+1} \cdots dx_m - \hat{\mu}_{total}$$

* interaction effect among some variables is ignored in this study

Optimization Results







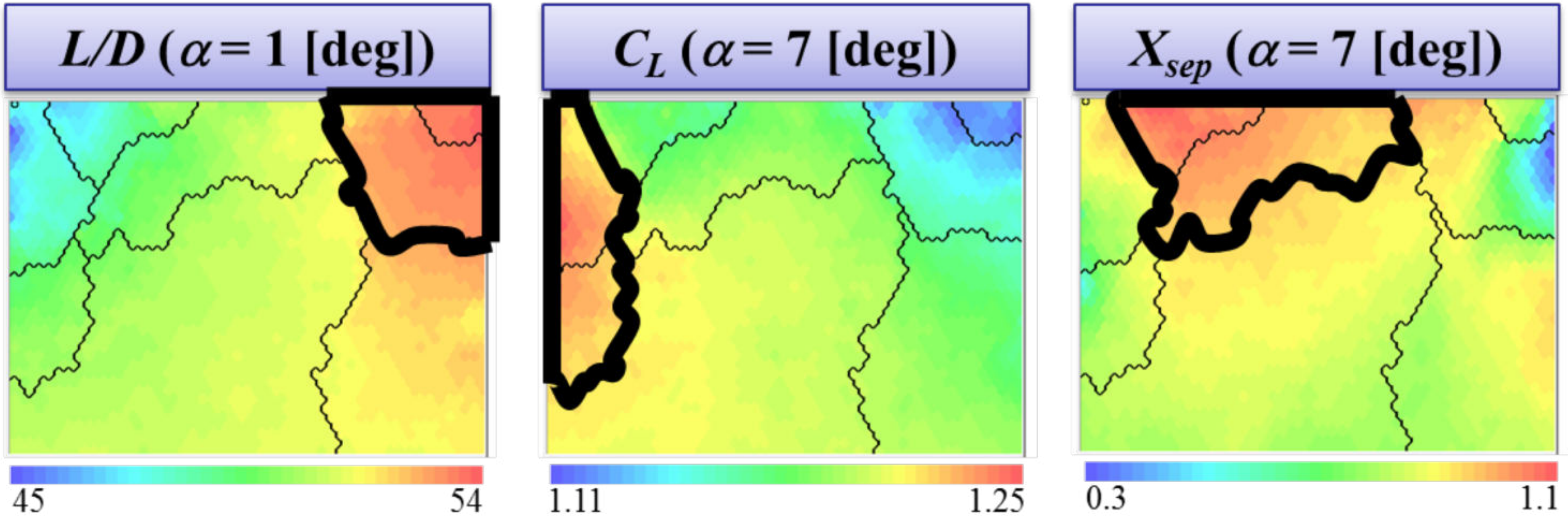
Non-dominated estimated solutions

- Explored by MOGA (population: 200, generation: 200)
- **Quantitative errors** in objective function values
- **Maintained qualitative relation** among objective functions and design variables

Data mining

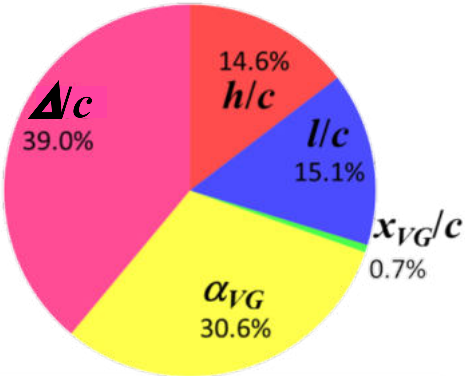
- SOM: Classify solutions into some clusters
- ANOVA: Identify effective design variables

SOMs among Three Objective Functions



- Non-dominated solutions are classified into four types (eight clusters).
- Design trade-offs exist among three objective functions.
  (especially strong between L/D and C_L)
- The other clusters represent balanced solutions.

Solutions with High *L/D*

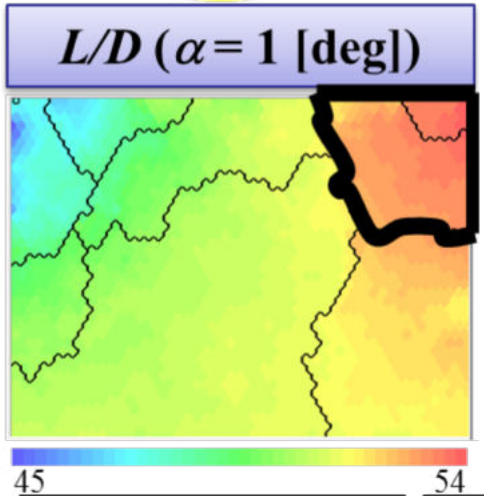


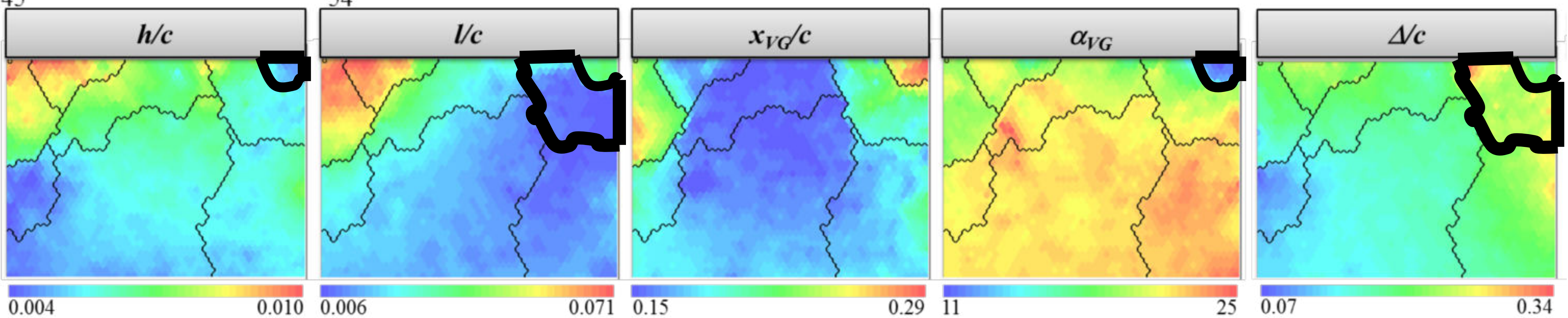
- Lower h/c and α_{VG}
- Lower l/c and higher Δ/c

➢ ***L/D* is improved by reducing VG effects in both clusters.**

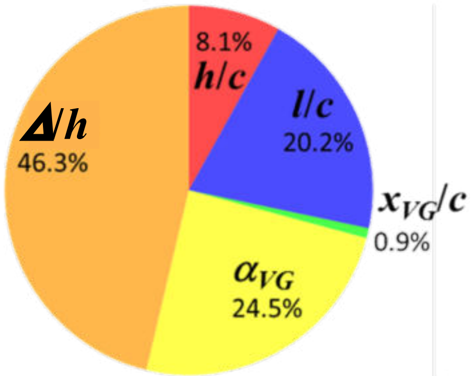
➢ **C_L and X_{sep} in these clusters are too low to alleviate the shock-induced separation.**

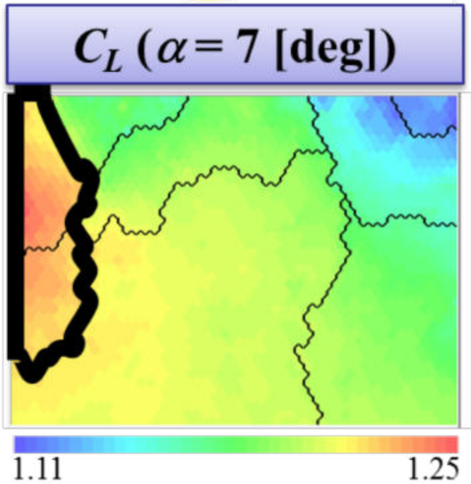
➢ Solutions in these clusters are not useful.





Solutions with High C_L





Appropriate values of design variables

- **Δ/h with the strong effect in ANOVA have lower values between 15 and 28** (not the lower limit $\Delta/h = 5$).
- α_{VG} for generating the vortex most efficiently is from 19 to 23 [deg].

Interaction among design variables

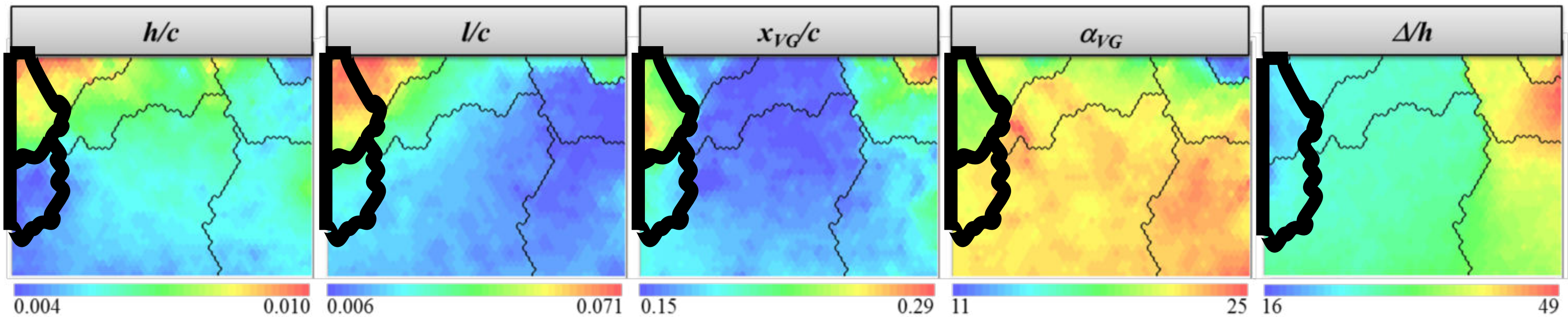
- **SOM divides these solutions into two clusters.**

Maximize C_L: Higher h/c, l/c, x_{VG}/c and lower α_{VG}

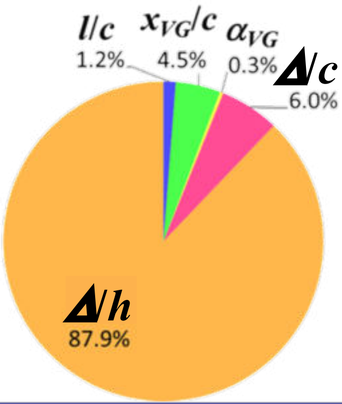
(move shock wave farther downstream)

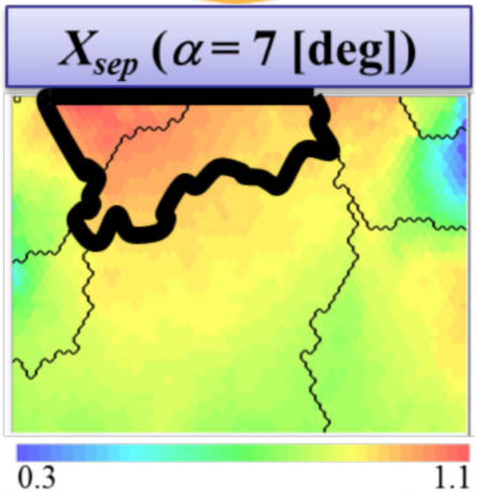
Sustain L/D: Lower h/c, l/c, x_{VG}/c and higher α_{VG}

→ **Small VG with high angle (α_{VG} = 23 [deg]) is preferable**



Solutions with High X_{sep}





Appropriate values of design variables

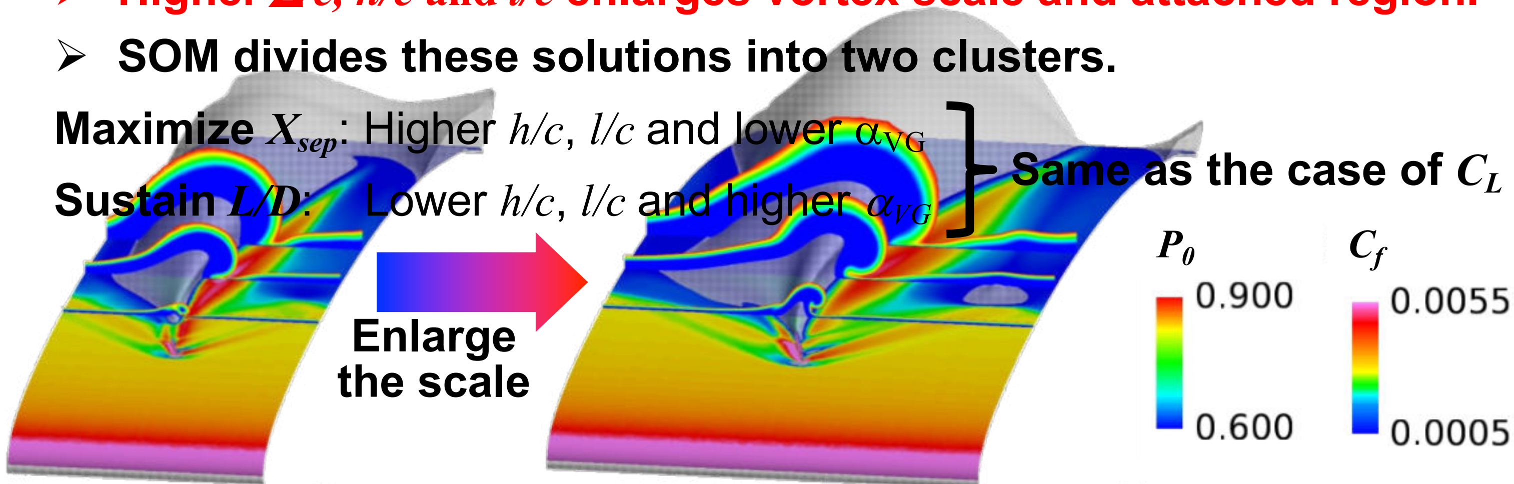
- **VG effect is dominated by Δ/h = 24 - 30.**

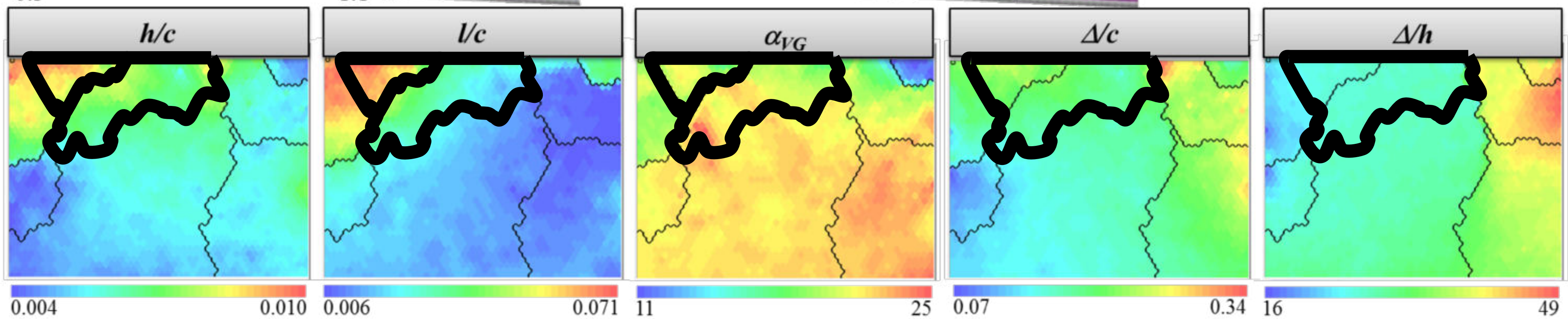
Interaction among design variables

- **Higher Δ/c, h/c and l/c enlarges vortex scale and attached region.**
- **SOM divides these solutions into two clusters.**

Maximize X_{sep}: Higher h/c, l/c and lower α_{VG}
Sustain L/D: Lower h/c, l/c and higher α_{VG}

Same as the case of C_L





Findings

Multi-objective optimization and data mining of vortex generators (VGs) on the transonic infinite-wing were performed to identify the design rules of VG arrangement.

- The appropriate VG spacing to height ratio and incidence angle were revealed by the surrogate-based optimization.
- ANOVA suggested that the VG spacing to height ratio is most important parameter to determine the VG effects.
- SOM discovered the interaction among design variables related to the trade-offs and the vortex scale.

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How can Optimization Help Design?

Design is an inverse problem to find a shape that satisfies design requirements (Tomiyama, 2003)

- Design in a narrow sense is the abduction (Yoshikawa, 1989)
- Three patterns for inference (Peirce, 1903)
  - Deduction obtains theorems from axioms and facts
  - Induction obtains axioms from facts and theorems
  - Abduction obtains facts from axioms and theorems
- Abduction: hypothesis to the best design, which includes not only the discovery but also a preliminary evaluation of design candidates

How to Aid Designer's Abduction?

Aid to design means aid to designer's abduction

- "Gadget" for designers to think of various proposals and hypotheses
  - Hypothesis is to find a pattern from various observations

- "Gadget for abduction" to structurize and visualize of design space

Providing an optimal solution may not be aid to a designer

Data mining for design space is necessary

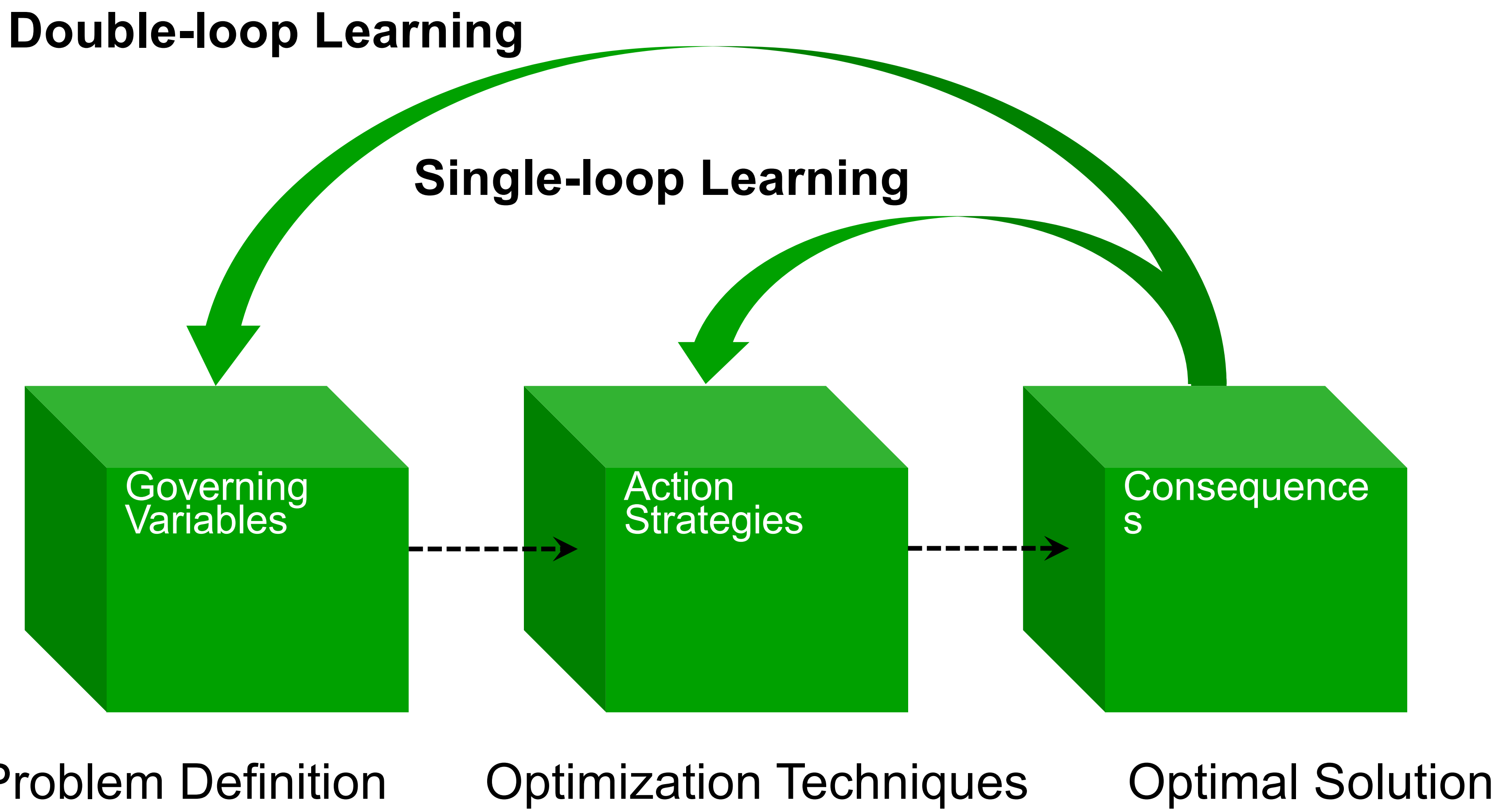
MODE - Structurization and Visualization of Design Space

- Structurization
  - Identify trade-offs among multiple design objectives
- Visualization
  - Provide a Bird's-eye view of the design space (objective function space)
- Data mining for design space
  - Identify region of interest in design space and corresponding design variable distributions

➢ Lead to a better understanding and a new design

Double-Loop Learning for Design

Argyris & Schon (Harvard Business Review, 1974)



Data Mining is Essential for Double-Loop Learning