

foam-Extend와 AADO 기술을 이용한 축류 송풍기 최적설계

2024. 09. 27

(주)피도텍

이형진, 최병열, 최동훈

본 연구는 2024년도 산업통상자원부(MOTIE)의 재원으로 한국에너지기술평가원(KETEP)의 지원을 받아 수행한 연구과제임.
(20211202080026D, AI/ICT 기반 가변형 유체기기 설계·상태진단을 위한 기반·플랫폼 기술 및 운영관리 시스템 개발)

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CONTENTS

- 1. AI-Aided Design Optimization**
- 2. CFD analysis**
- 3. Optimization**
- 4. Validation**

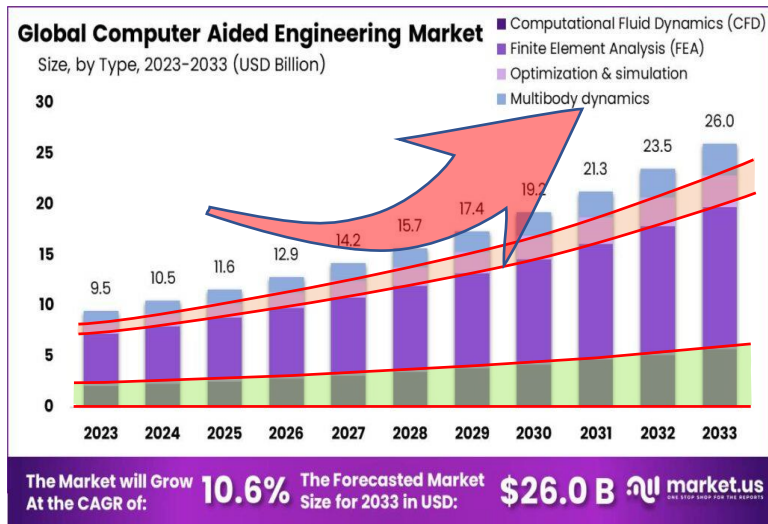
A background image showing two business people shaking hands. The person on the left is wearing a light blue suit, and the person on the right is wearing a dark suit. They are standing on a rooftop or balcony overlooking a city skyline at night, with lights from buildings and a bridge visible. The image has a dark, blue-tinted overlay.

01

AI-Aided Design Optimization

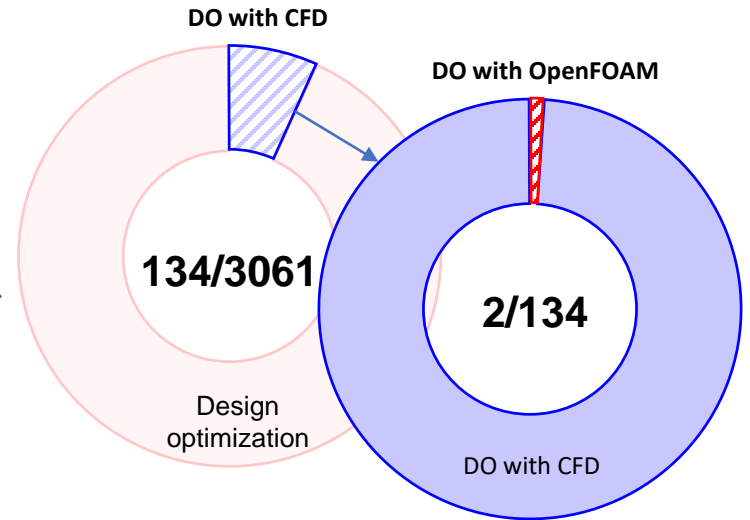
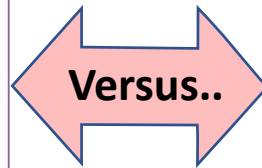
Design Optimization: Necessity

- Demands & Markets of Design optimization increases gradually
- In the other hands, DO based on CFD analysis cannot follow the trends



<https://market.us/report/computer-aided-engineering-market/>

Trends: CAE and Design optimization markets



(Result of dbpia paper search)
Filters: Design optimization / Design optimization CFD / Design optimization openfoam

Domestic papers related to design optimization on Recent 5 yrs*

Design Optimization: prerequisites

- Base knowledge of CAE process & Design optimization theories
- Difficult to catch both items..

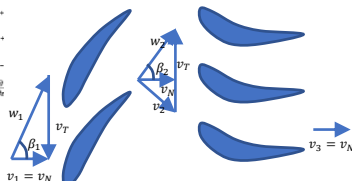
Computational Fluid Dynamics

Navier-Stokes Equations 3-dimensional - unsteady

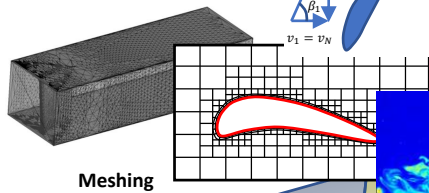
Coordinate (x,y,z) **Time: t** **Pressure: p** **Heat Flux: q**
Velocity Components (u,v,w) **Density: ρ** **Stress: τ** **Reynolds Number: Re**
Total Energy: E **Prandtl Number: Pr**

Continuity: $\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$
X-Momentum: $\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}$
Y-Momentum: $\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho v^2)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}$
Z-Momentum: $\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}$
Energy: $\frac{\partial (\rho E)}{\partial t} + \frac{\partial (\rho u E)}{\partial x} + \frac{\partial (\rho v E)}{\partial y} + \frac{\partial (\rho w E)}{\partial z} = \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} + \dot{q}$

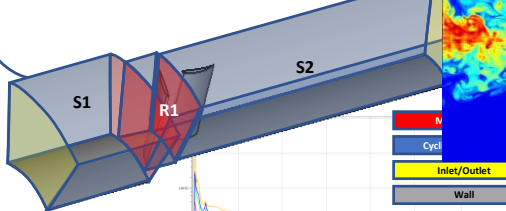
Theoretical basis



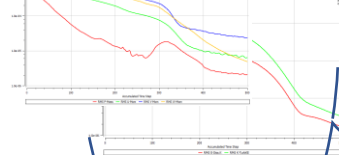
Physics



Meshing

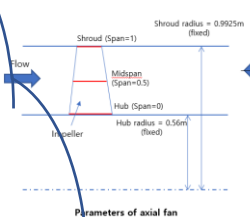
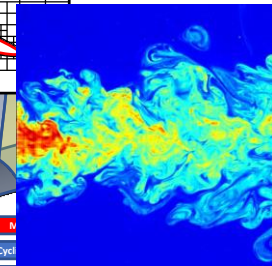


Boundary conditions

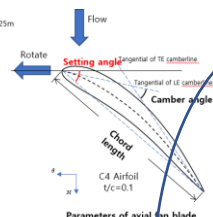


Convergence criteria

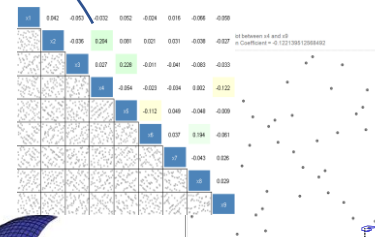
Turbulences



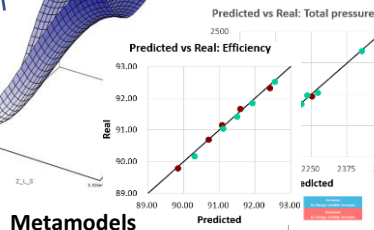
Parametrization



Design optimization

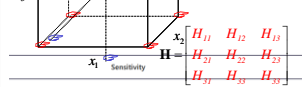


Design of Experiments



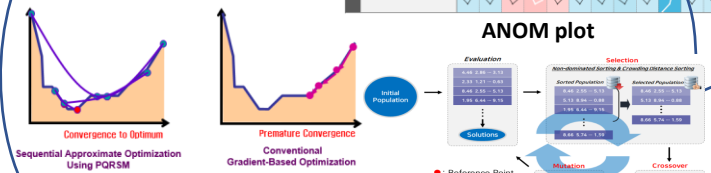
Metamodels

Quadratic modeling

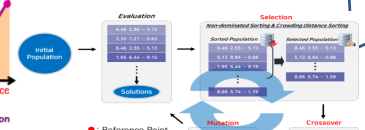


Design number	x1	x2	x3	H11	H12	H13	H21	H22	H23	H31	H32	H33
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
28	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
29	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

ANOM plot



Gradient based optimization



MOGA

AI-Aided Design Optimization

- AI covers the region of design optimization
- Can focus on computational fluid dynamic regions

Computational Fluid Dynamics

Navier-Stokes Equations
3-dimensional - unsteady

Glenn Research Center

Coordinate: (x, y, z)
Velocity Components: (u, v, w)
Total Energy: E

Time: t Pressure: p Heat Flux: q
Density: ρ Stress: τ Reynolds Number: Re
Total Energy: E Prandtl Number: Pr

Continuity: $\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0$

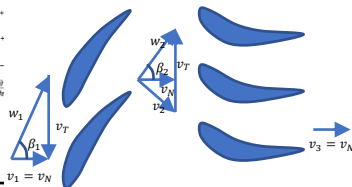
X-Momentum: $\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}$

Y-Momentum: $\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho v^2)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}$

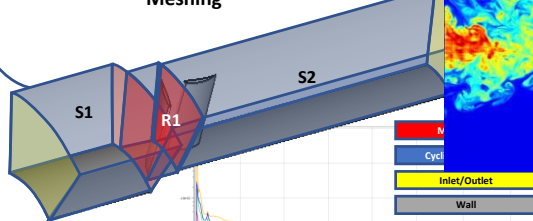
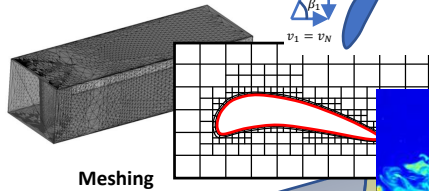
Z-Momentum: $\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}$

Energy: $\frac{\partial (\rho E)}{\partial t} + \frac{\partial (\rho u E)}{\partial x} + \frac{\partial (\rho v E)}{\partial y} + \frac{\partial (\rho w E)}{\partial z} = -\frac{\partial (p u)}{\partial x} - \frac{\partial (p v)}{\partial y} - \frac{\partial (p w)}{\partial z} + \frac{\partial (q_x)}{\partial x} + \frac{\partial (q_y)}{\partial y} + \frac{\partial (q_z)}{\partial z}$

Theoretical basis



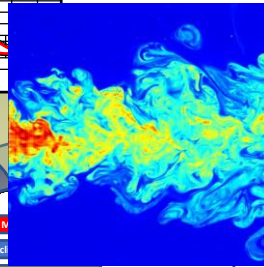
Physics



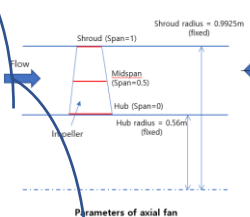
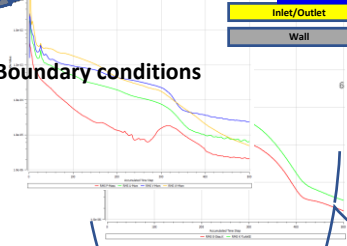
Boundary conditions



Turbulences

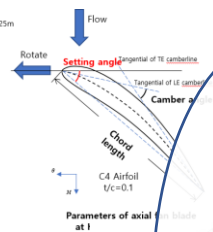


Convergence criteria



Parametrization

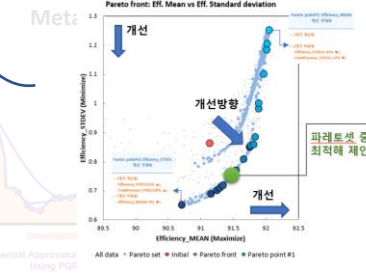
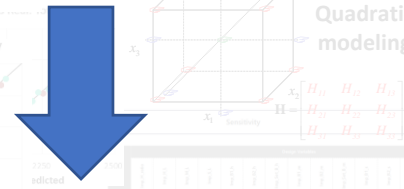
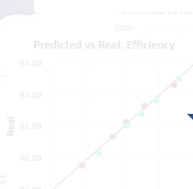
Design optimization



AI proceeds it automatically

Design of Experiments

Quadratic modeling



Pareto point#1) 모든 목적함수가 요구값범위내 개선

3/3

목적함수	개최값	최대값	최소값	초기값
efficiency_MEAN	0.926	0.926	0.926	0.926
efficiency_STDEV	0.000	0.000	0.000	0.000
TotalPressure_STDEV	15.841	15.841	15.841	15.841
TotalPressure_MEAN	2099.915	2099.915	2099.915	2099.915

Optimal for Multi-objective optimization

Can analysis results w/o background knowledge

Gradient based optimization

MOGA

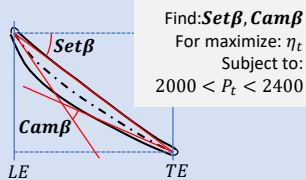
AI-Aided Design Optimization: Process

- AI covers the region of design optimization
- Can focus computational fluid dynamic regions

Pre-requisites

Formulation

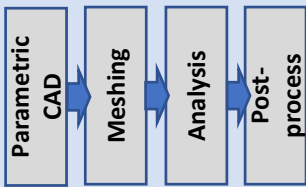
Determine what to improve
Set the rule of shape changing



Process integration(PI)

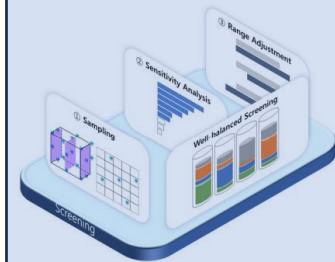
Integrate whole process of CAE analysis
Get simulation results with unified rules

Process integration



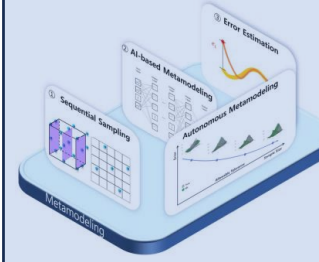
AI- Aided design optimization

Well balanced Screening



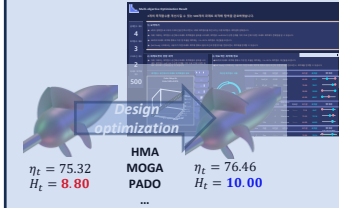
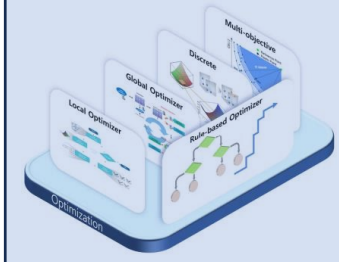
Filters less important parameters
Suggests the parameter ranges

Autonomous Metamodeling



Sequential sampling by AI
Competitive modeling

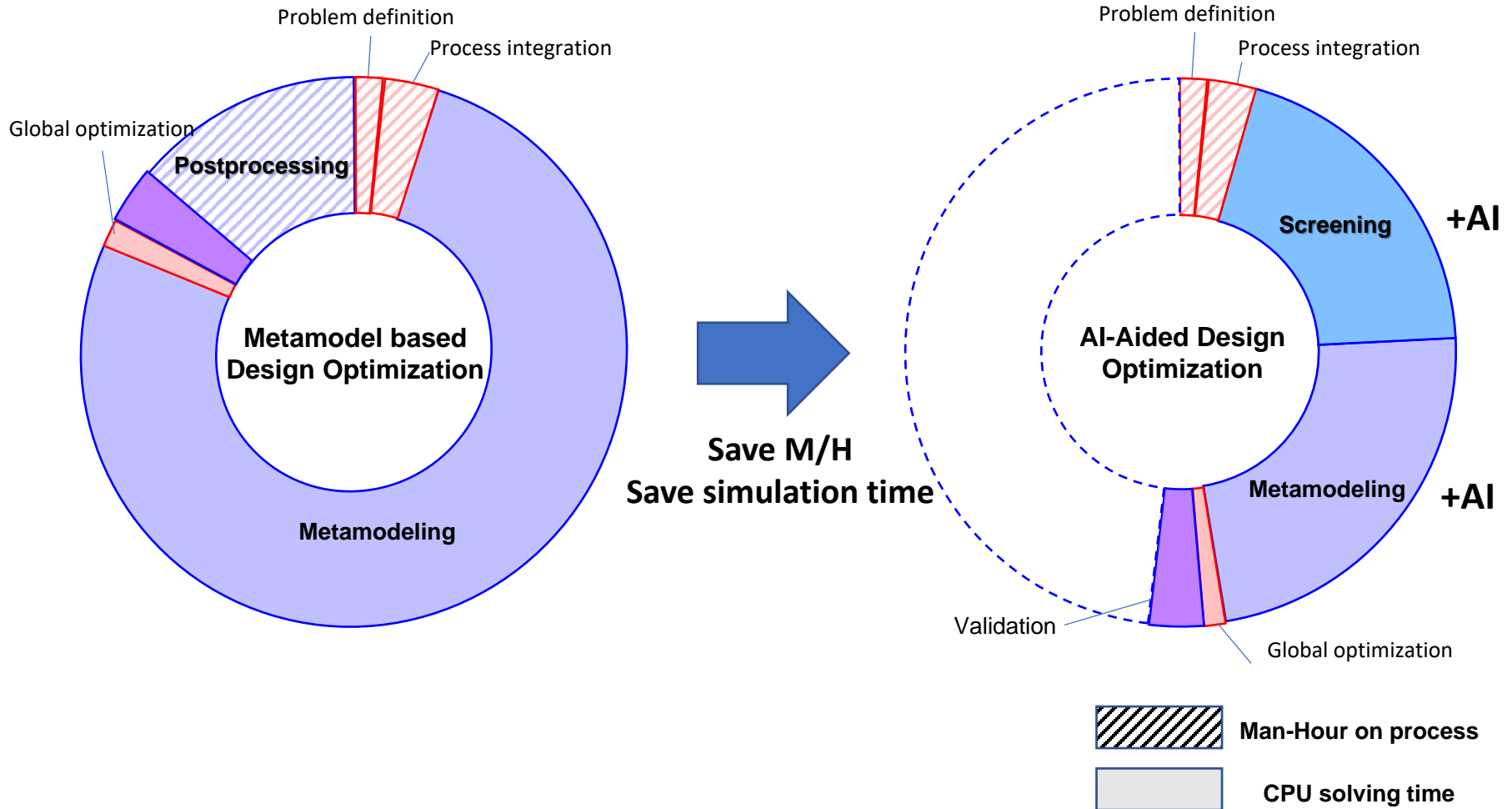
Rule-based Optimizer



Select optimizer by determined optimization problem

AI-Aided design optimization: Pros

- Screening & metamodeling saves the time for CAE analysis on complicated design optimization problems
- AI model supports to reduce CAE simulation time for proper data selection



A background image showing two business people shaking hands in a dark suit. The scene is set against a blurred city skyline at night, with lights from buildings and a bright light source creating a lens flare effect. The overall tone is professional and collaborative.

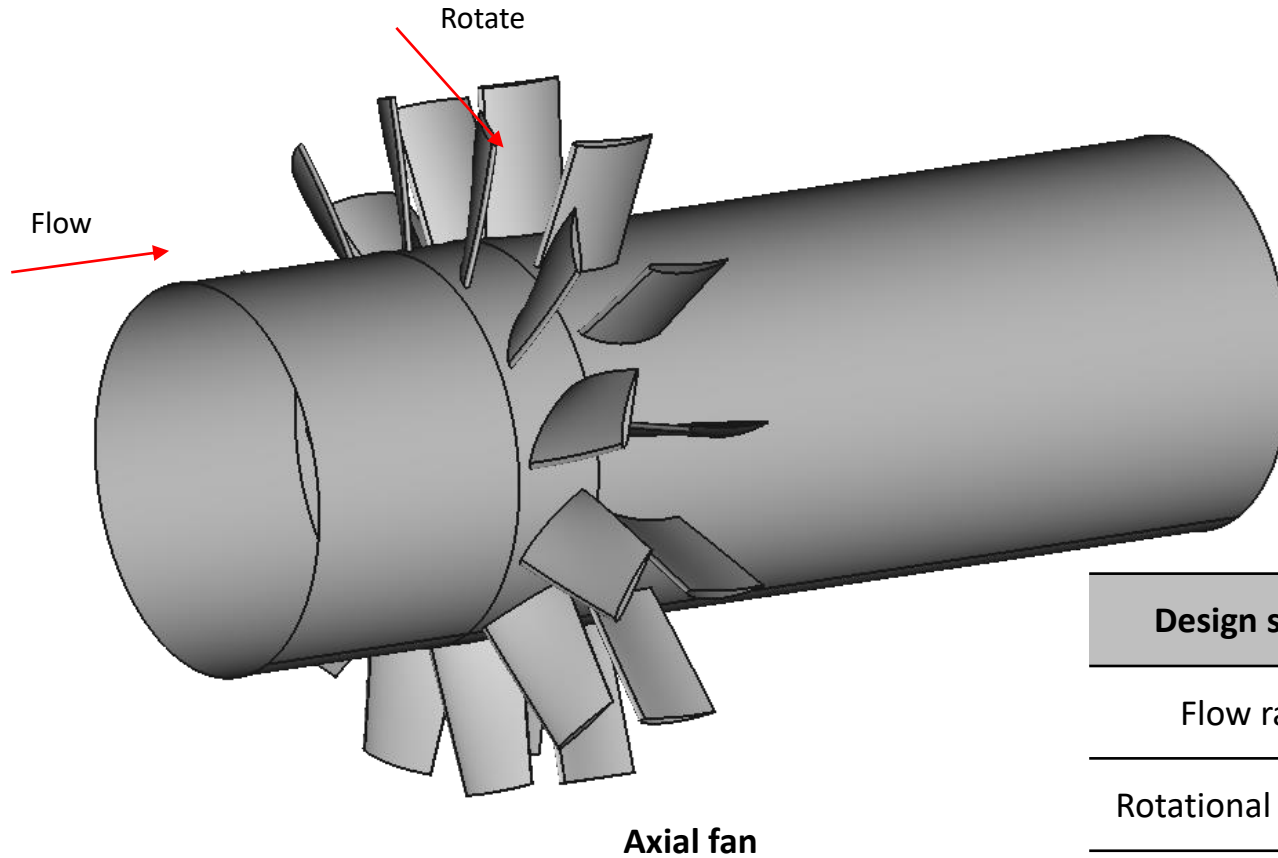
02

CFD analysis

Analysis domain

Large axial fan

- Large axial fan with high flow rate(5400RPM) and low pressure rise(2000Pa)
- Simplified inlet shape applied(bellmouth not applied)



Design specification	Values
Flow rate (CMM)	5400
Rotational velocity (RPM)	1200
Target pressure rise(Pa)	2000

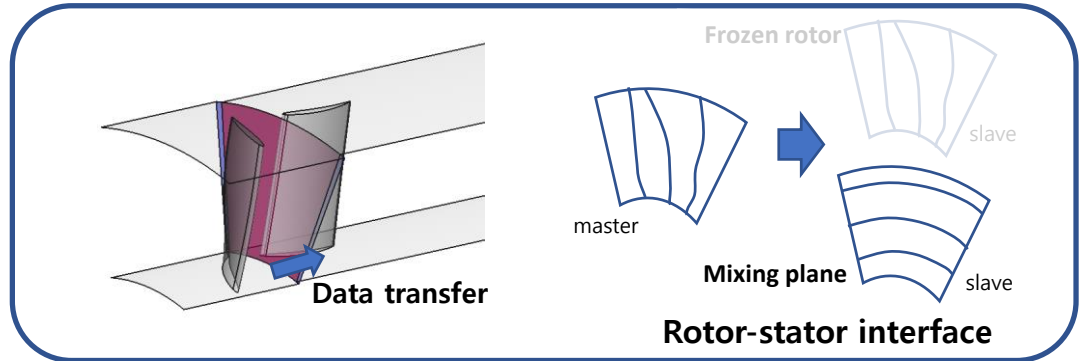
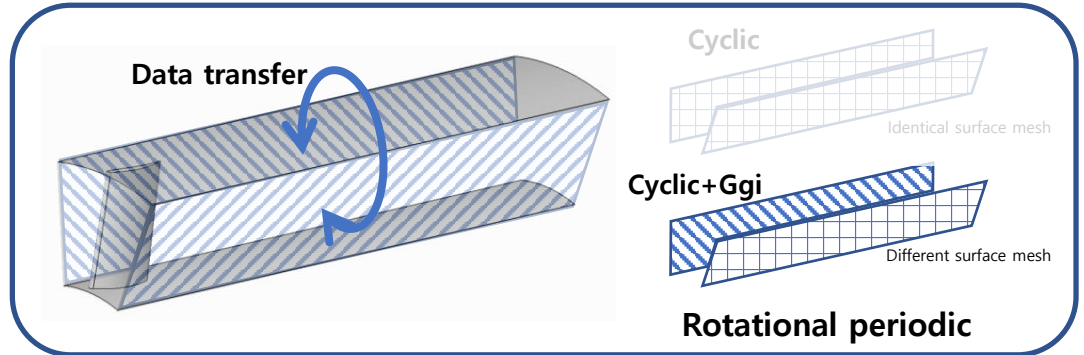
Design specification of axial fan

Solution info.

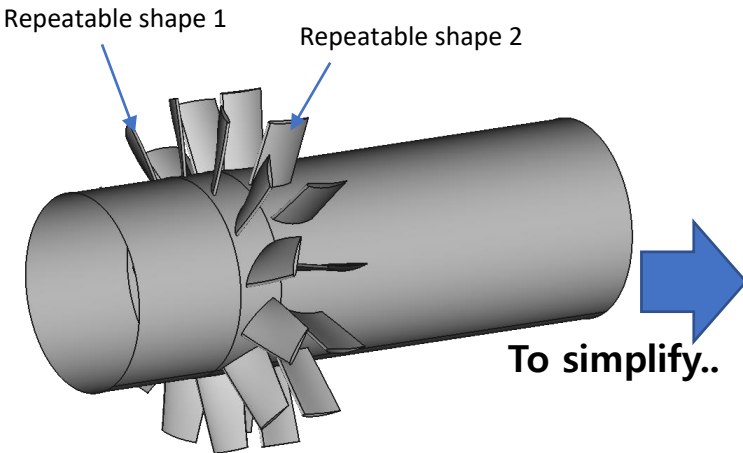
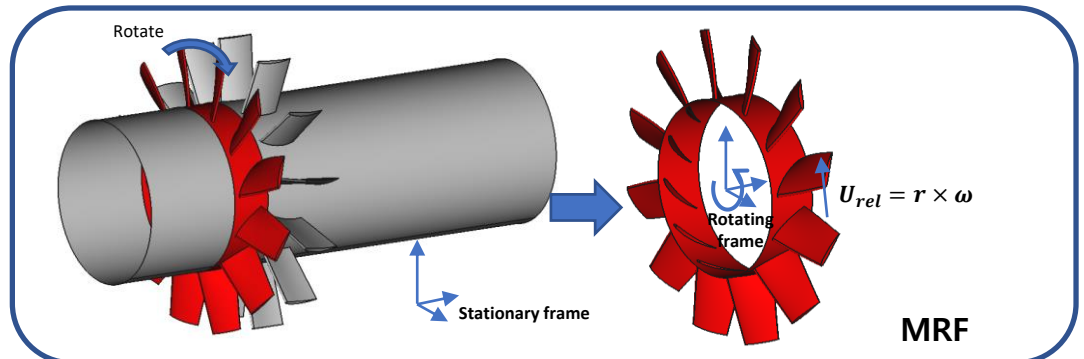
Simplification on turbomachinery

- Periodic and rotor-stator interface for domain
- MRF for timescale

Domain simplification



Timescale simplification

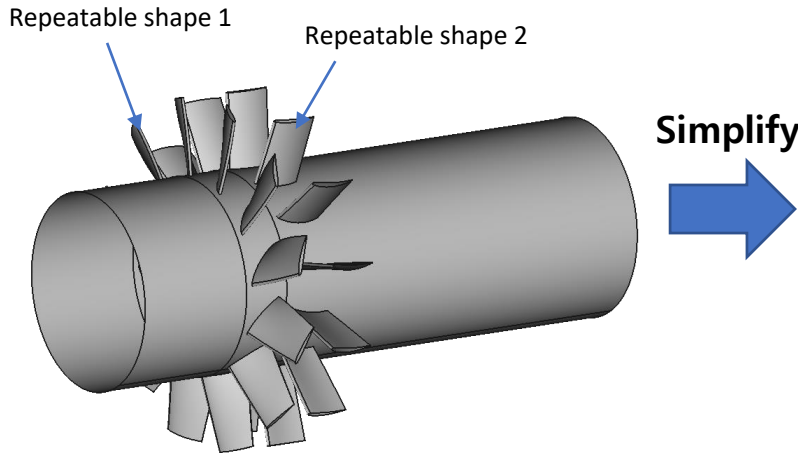


Full component

Solution info.

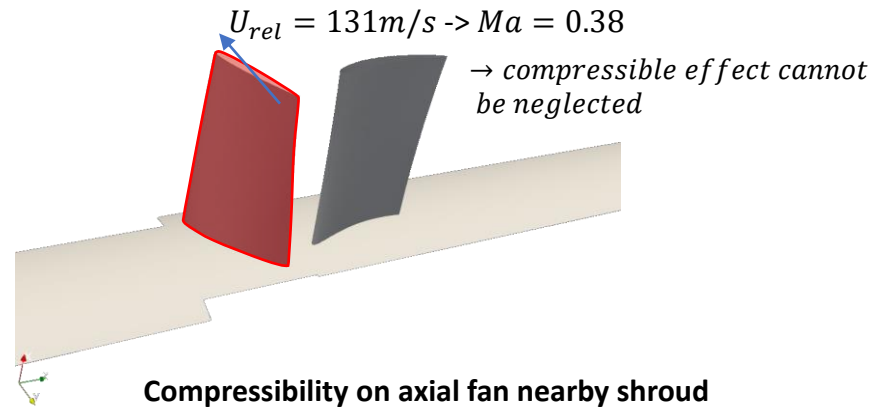
Version : foam-extend

- Mixing plane applicable



Solver : steadyCompressibleMRFFoam

- Steady state compressible solver with MRF
- Thermal issues are resolved on foam-extend 5.0



	Foundation	ESI	foam-Extend
Periodic	O (cyclicAMI)	O (cyclicAMI)	O (cyclicGgi)
Frozen rotor	O (cyclicAMI)	O (cyclicAMI)	O (overlapGgi)
Mixing plane	X	X	△ (mixingPlane)
Compressible-MRF	O (rhoSimple)	O (rhoSimple)	△ (steadyCompressibleMRF/steadyUniversalMRF)

```

BiCGStab: Solving for Ux, Initial residual = 0.0011952, Final residual = 1.82995e-12, No Iterations 5
BiCGStab: Solving for Uy, Initial residual = 0.000412004, Final residual = 4.61959e-14, No Iterations 5
BiCGStab: Solving for Uz, Initial residual = 0.00108151, Final residual = 1.75056e-13, No Iterations 5
smoothSolver: Solving for p, Initial residual = 0.0363556, Final residual = 0.000853289, No Iterations 300
smoothSolver: Solving for p, Initial residual = 0.00486205, Final residual = 0.000769511, No Iterations 300
time step continuity errors : sum local = 0.000252726, global = 5.99796e-06, cumulative = 5.99796e-06
    
```

```

From function void gradientEnthalpyFvPatchScalarField::updateCoeffs(const vectorField& Up)
in file derivedFvPatchFields/fixedEnthalpy/gradientEnthalpyFvPatchScalarField.C at line 135
Velocity fields U or URot or UTheta not found. Performing enthalpy value update for field i and patch 0

From function void gradientEnthalpyFvPatchScalarField::updateCoeffs(const vectorField& Up)
in file derivedFvPatchFields/gradientEnthalpy/gradientEnthalpyFvPatchScalarField.C at line 141
Velocity fields U or URot or UTheta not found. Performing enthalpy value update for field i and patch 1
objects
47
(
  interpolate(alphaEff)*magSF)
-(devRhoEff&&grad(Urel))
    
```

foam – extend 4.1

```

BiCGStab: Solving for Ux, Initial residual = 0.000942993, Final residual = 2.31181e-14, No Iterations 5
BiCGStab: Solving for Uy, Initial residual = 6.17652e-05, Final residual = 2.1769e-15, No Iterations 5
BiCGStab: Solving for Uz, Initial residual = 3.59515e-05, Final residual = 1.28638e-15, No Iterations 5
smoothSolver: Solving for p, Initial residual = 0.0200537, Final residual = 0.000190137, No Iterations 26
smoothSolver: Solving for p, Initial residual = 0.00114382, Final residual = 6.6237e-05, No Iterations 300
time step continuity errors : sum local = 0.000236179, global = 1.06495e-06, cumulative = 1.06495e-06
BiCGStab: Solving for i, Initial residual = 0.00021772, Final residual = 2.69592e-10, No Iterations 5
BiCGStab: Solving for omega, Initial residual = 9.98276e-07, Final residual = 9.57384e-14, No Iterations 5
BiCGStab: Solving for k, Initial residual = 4.58434e-06, Final residual = 1.82101e-12, No Iterations 5
bounding k, min: -0.54508 max: 2112.74 average: 11.2549
ExecutionTime = 3.43 s ClockTime = 3 s
    
```

foam – extend 5.0

Rothalpy issues on foam-extend 4.1 and 5.0

Solution info.

Schemes & Solutions:

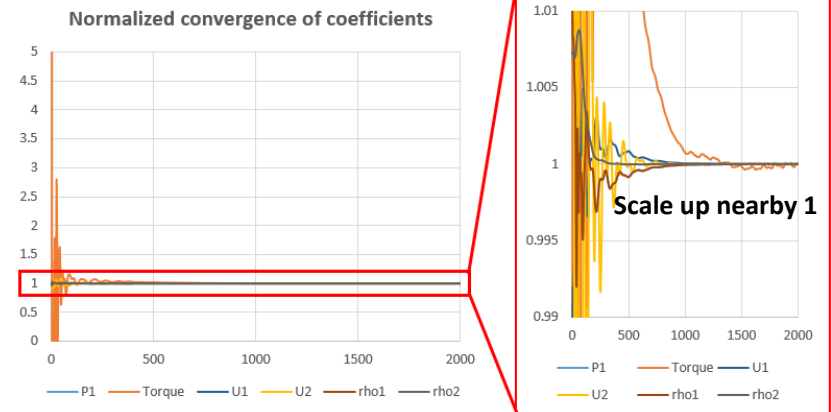
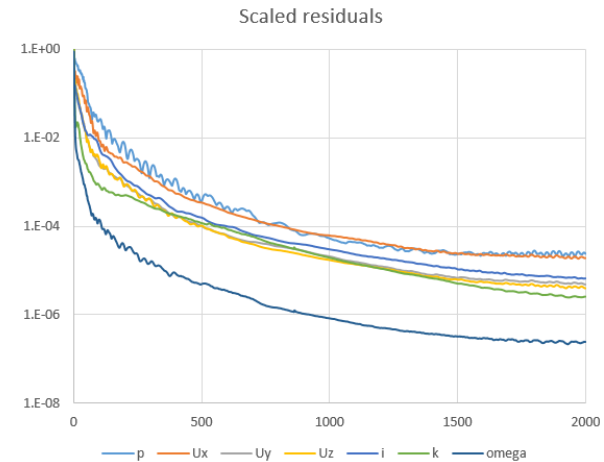
- Second order upwind for P, U, and T
- First order upwind for k and omega

	Scheme
div(phi, U)	linearUpwindV
div(phi, p) div(phi, i)	linearUpwind
div(phi, k) div(phi, ω)	Upwind
div(phi, i) div(phi, T)	linearUpwind

	Solver	Relaxation factor
p	smoothSolver	0.7
U	BiCGStab	0.4
i, k, ω		0.7

Convergence

- Residuals: Below 10^{-4} scale on Pressure and velocity x
- Coefficients: 0.1% scale on Torque (Basis: final value)



Solution info.

◆ Analysis condition:

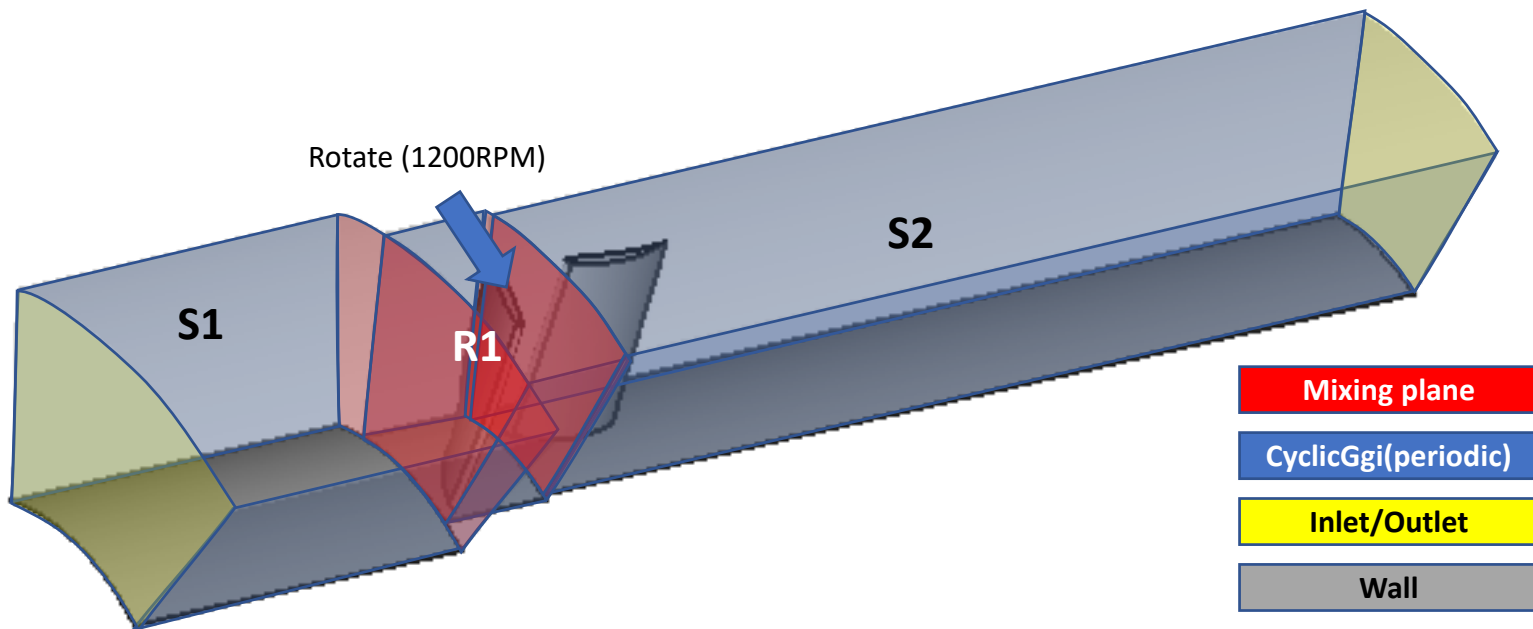
- Turbulence modeling: $k - \omega SST$
- Steady state analysis with MRF on Impeller

◆ Initial & Boundary condition:

- Fixed velocity inlet & static pressure outlet
- Stage(Mixing plane) for rotor-stator interface

Initial conditions

		Type	Value
Inlet	P	zeroGradient	-
	V	flowRateInletVelocity	12.92
	T	fixedValue	300
Outlet	P	fixedValue	101325
	V	inletOutlet	-
	T	zeroGradient	-

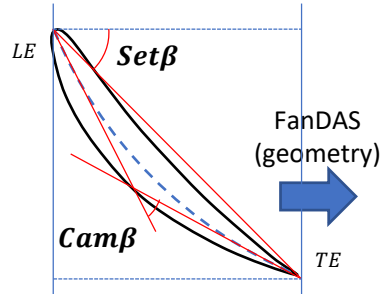


Boundary conditions

Surface meshing automation

I. Update parameters: FanDAS

```
ANALYSIS
SETAG1 = 37.26
SETAG2 = 36.61390625
SETAG3 = 35.953125
SETAG4 = 35.27765625
SETAG5 = 34.5875
SETAG6 = 33.88265625
SETAG7 = 33.163125
SETAG8 = 32.42890625
SETAG9 = 31.68
SETAG10 = 30.91640625
SETAG11 = 30.138125
SETAG12 = 29.34515625
SETAG13 = 28.5375
SETAG14 = 27.71515625
SETAG15 = 26.878125
SETAG16 = 26.02640625
SETAG17 = 25.16
```



ROTOR BLADE ELEMENT COORDINATES [mm] ****

RADIAL LOCATION INDEX(J)= 1
CENTER OF GRAVITY[Xc,Yc,Zc] = 58.4941 103.0213
SECTION AREA= 8421.8508 mm²

CAMBER LINE	XCB	YCB	ZC	LOWER SURFACE XLOWER	YLOWER	ZL
8.2578	-123.9791	543.8167	-68.2578	-123.9791	543.8167	
-7.7386	-102.6150	544.1259	-65.0766	-123.6324	543.8956	
-67.2161	-121.2535	544.4309	-63.5066	-122.6928	544.1106	
-66.6903	-119.8944	544.7318	-62.2018	-121.6380	544.3451	
-66.1612	-118.5379	545.0286	-61.0342	-120.5457	544.5890	
-65.6289	-117.1838	545.3213	-59.9540	-119.4242	544.8391	
-65.0931	-115.8323	545.6100	-58.9357	-118.2927	545.0940	
-64.5541	-114.4833	545.8947	-57.9642	-117.1269	545.3336	
-64.0119	-113.1368	546.1753	-57.0296	-115.9601	545.5828	
-63.4663	-111.7920	546.4520	-56.1249	-114.7949	545.8313	
-62.9173	-110.4514	546.7247	-55.2451	-113.6030	546.0785	
-62.3654	-109.1152	546.9934	-54.3894	-112.3822	546.3244	

II. Get points of shape data: in-house code

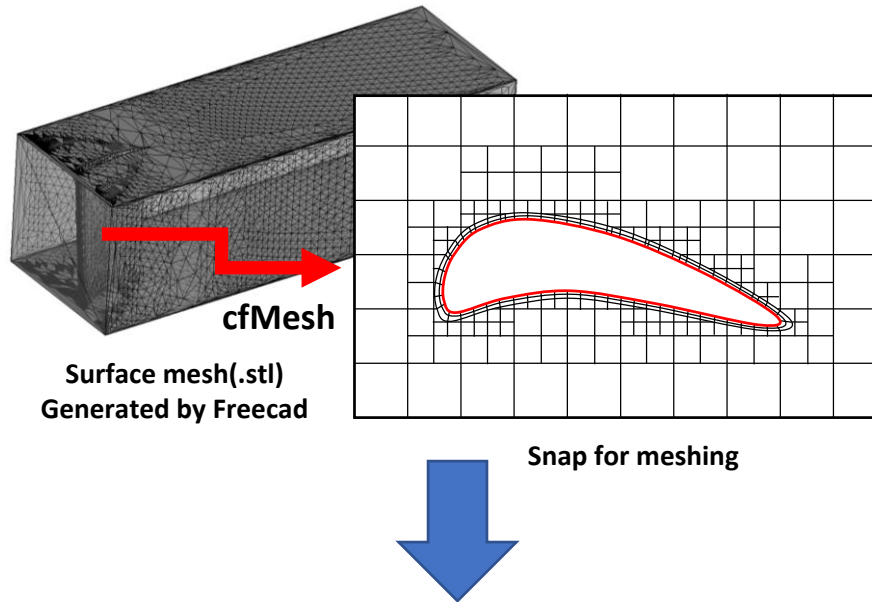
137개 항목

III. Generate analysis domain: FreeCAD macro

IV. Surface meshing: FreeCAD macro

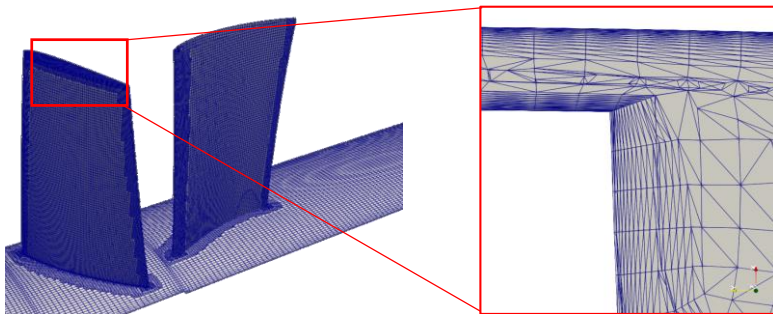
Unstructured mesh automation

Volume meshing: cfMesh

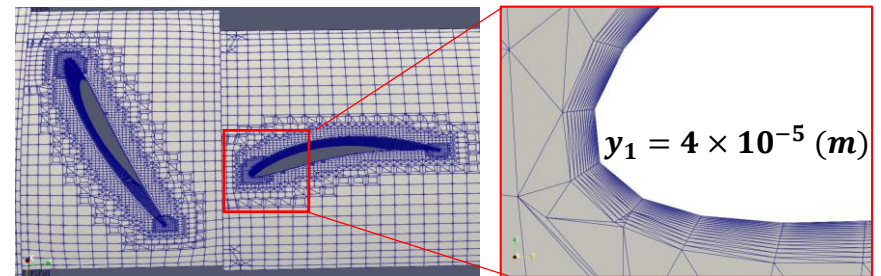


Mesh information

		Baseline	Range
Sizing	#Cells: S1	0.34 M	
	#Cells: R1	0.39M	0.36M-0.4M
	#Cells: S2	0.50M	0.49M-0.50M
	First layer thickness	4e-5 (m)	
Quality	Max. non-orthogonality	78.05	75-80
	Skewness	2.97	2.7-3.5



Mesh of impeller and diffuser

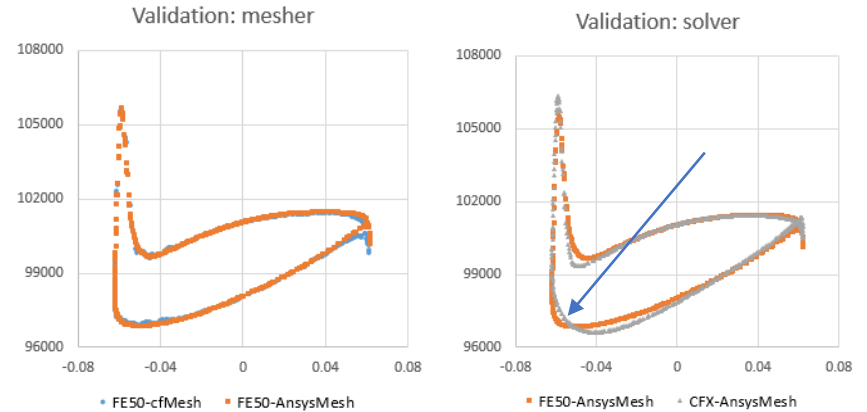
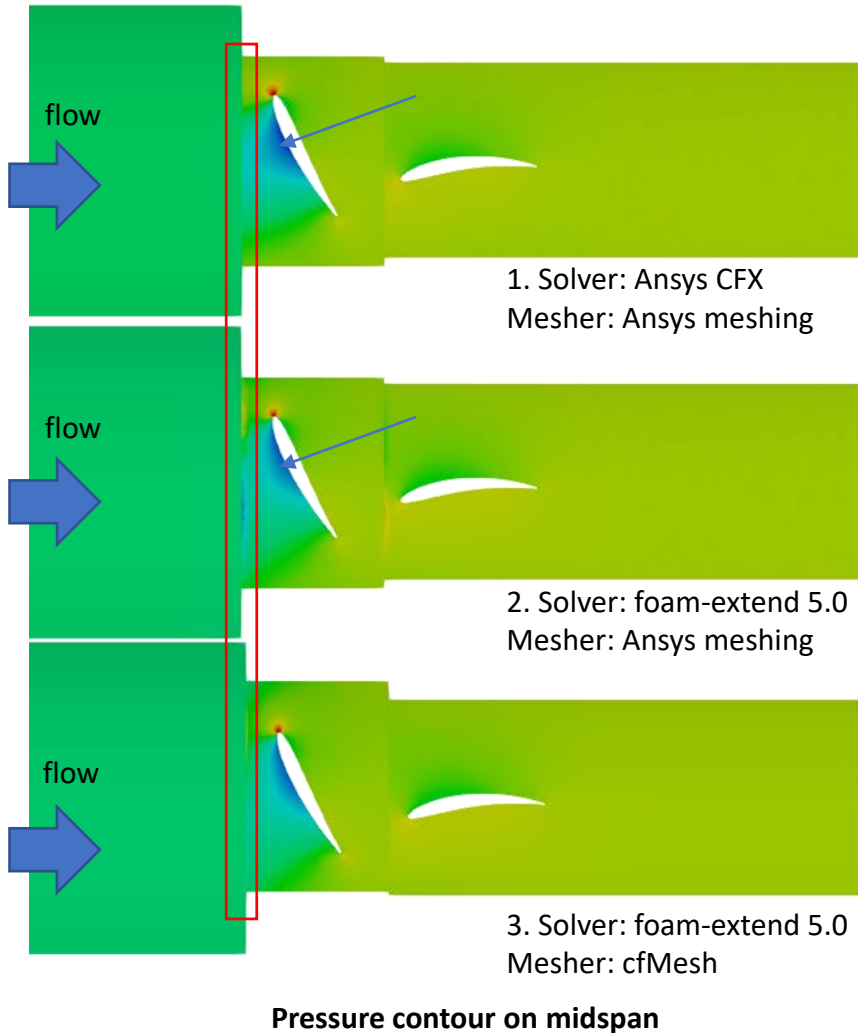


Cross section on midspan

Validation

Solver and Mesher validation

- Solver: Has similar pressure distribution but not identical
- Mesher: Same blade loading except trailing edge



Blade loading by flow direction on midspan

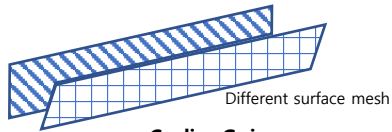
Performances comparison

Mesher	Solver	Total pressure (Pa)	Power (W)	Efficiency (%)
Ansys meshing	Ansys CFX	1802.8	15.96	84.72
	foam-Extend 5.0	1785.2	15.26	87.73
cfMesh	foam-Extend 5.0	1804.1	15.61	86.68

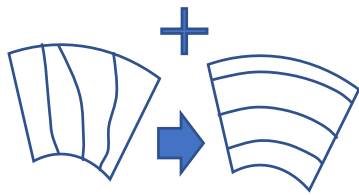
Summary: CFD analysis

Solver selection

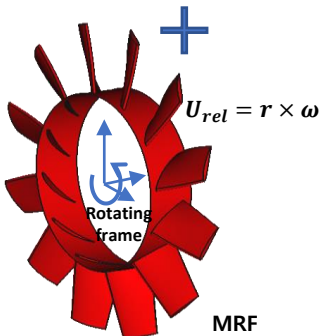
- Selected solver with satisfying all simplification conditions



Cyclic+Ggi



Mixing plane

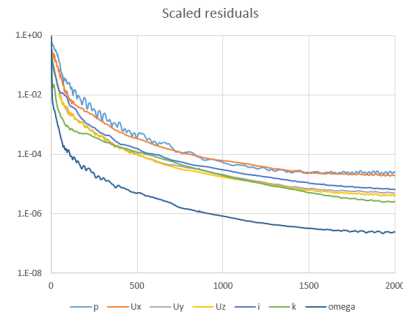


MRF

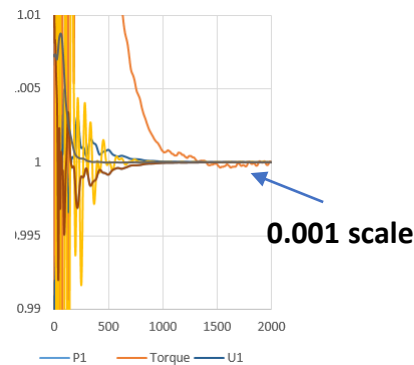
Compressible..
steadyCompressibleMRFfoam
on foam-extend

Convergence evaluation

- Scaled residual dropped under $1e-4$ scale
- Coefficients are well convergent



Scaled residuals

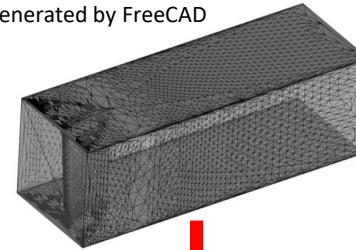


Coefficients convergence

Meshing

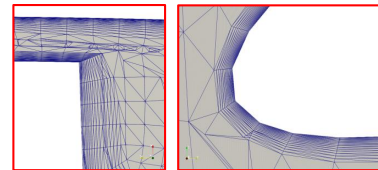
- Mesh constructed by cfMesh
- Boundary layer generated, acceptable quality acquired

Surface mesh(.stl)
Generated by FreeCAD



cfMesh

Volume mesh: nearwall



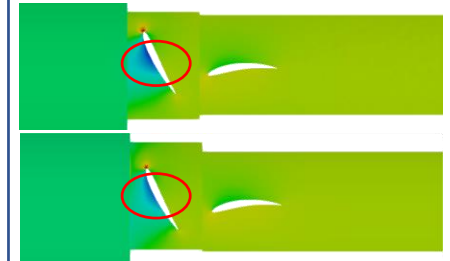
$$y_1 = 4 \times 10^{-5} (m)$$

Volume mesh: quality

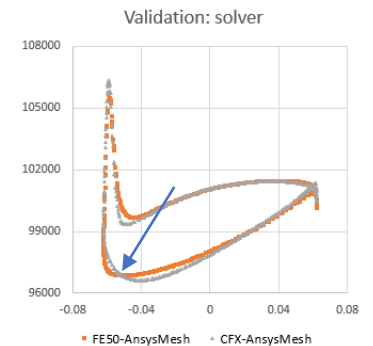
	Baseline	Range
nonOrtho.	78.05	75-80
Skew	2.97	2.7-3.5

Validation

- Pressure distribution slightly differs -> performance differs each other



Pressure contour on midspan



Blade loading by flow direction
on midspan

A background image showing two business people shaking hands in a firm grip. The scene is set against a dark, blue-tinted city skyline at night, with numerous lights from buildings and streets visible. The overall mood is professional and collaborative.

03

Optimization

AADO tool: AIDesigner sim



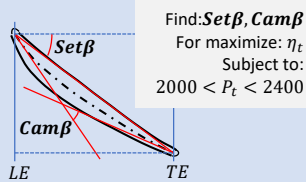
AIDesigner sim

Powered by PIDOTECH

Pre-requisites

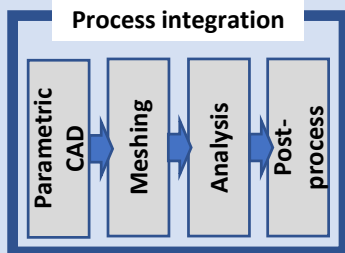
Formulation

Determine what to improve
Set the rule of shape changing



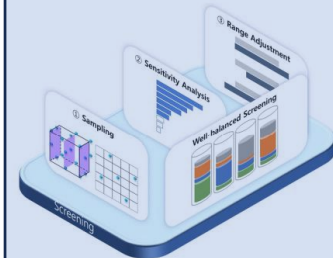
Process integration(PI)

Integrate whole process of CAE analysis
Get simulation results with unified rules



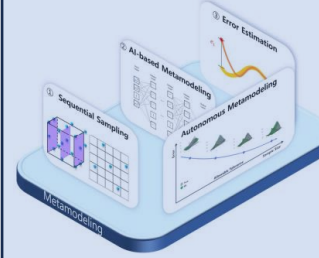
AI- Aided design optimization

Well balanced Screening



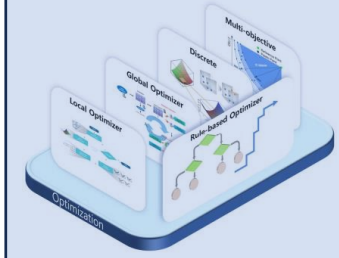
Filters less important parameters
Suggests the parameter ranges

Autonomous Metamodeling



Sequential sampling by AI
Competitive modeling

Rule-based Optimizer

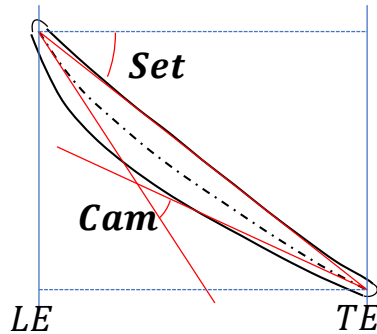


Select optimizer by determined optimization problem

Problem definition

Parametrization

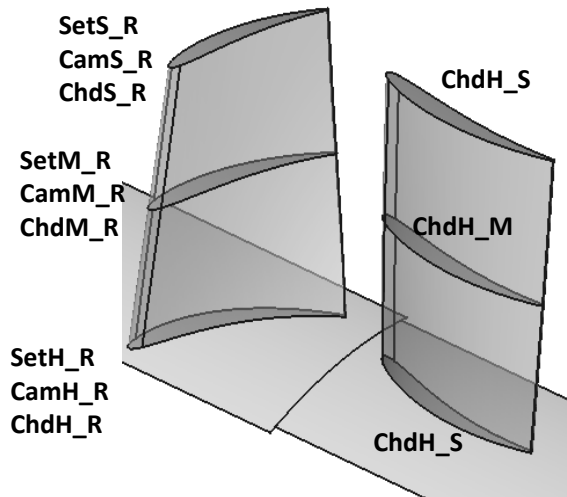
- For design optimization, the shape of impeller is parametrized, 12 design variables acquired by parametrized CAD
- To get global optima with less execution of CAE, global optimizer using metamodel is selected



Find: *Set, Cam, Chd*
 on impeller & DV
 For maximize: η_t, P_t
 For minimize: *Pwr*
 Subject to:
 $2000 < P_t < 2400$

No. of design variables: 12
 No. of objectives: 3
 No. of constraints: 1

Problem definition



Design variables on blade

Variables	Minimum	Nominal	Maximum
SetH_R	38.26	41.26	44.26
SetM_R	24.68	27.68	30.68
SetS_R	20.16	23.16	26.16
CamH_R	28.00	31.00	34.00
CamM_R	12.09	15.09	18.09
CamS_R	16.61	19.61	22.61
ChdH_R	270.00	290.00	310.00
ChdM_R*	0	0.5	1
ChdS_R	219.50	239.50	259.50
ChdH_S	255.00	270.00	285.00
ChdM_S	255.00	270.00	285.00
ChdS_S	255.00	270.00	285.00

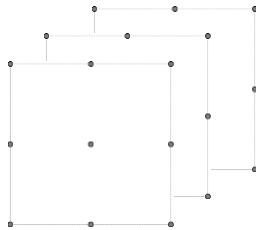
Range of design variables

$$* ChdM_{R_{real}} = ChdH_R * (1 - ChdM_R) + ChdS_R * ChdM_R$$

Result: Screening

Summary

- DOE data which is acquired by OA with $L_{36}(3^{13})$, 5 design variables selected by screening process
- Design variables(DVs) of rotor midspan are all selected, DVs on diffuser vane are all screened



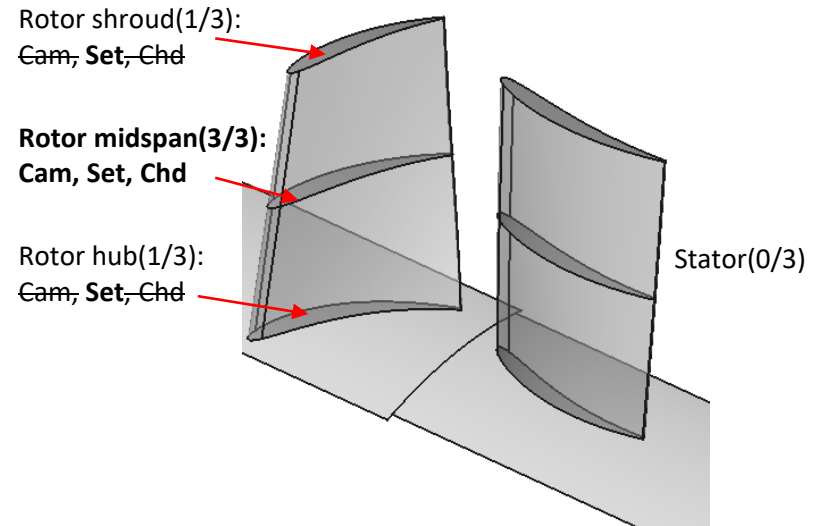
DOE: 3Lv Orthogonal array $L_{36}(3^{13})$



스크리닝 요약

설계변수 중요도 순위	변수명	선택 이유	설계자유도 누적합			설계자유도 누적합의 평균값	
			Pwr	Pt	Efft		
1	SetM_R	for Pwr	SetM_R	SetM_R	SetM_R	SetM_R	78.6%
2	SetS_R	for Pwr	+ SetS_R	+ SetS_R	+ SetS_R	+ SetS_R	91.2%
3	SetH_R	for Efft	+ SetH_R	+ SetH_R	+ SetH_R	+ SetH_R	93.2%
4	CamM_R	for Efft	+ CamM_R	+ CamM_R	+ CamM_R	+ CamM_R	96.3%
5	ChdM_R	for Efft	+ ChdM_R	+ ChdM_R	+ ChdM_R	+ ChdM_R	97.2%
6	ChdM_S	for Efft	+ ChdM_S	+ ChdM_S	+ ChdM_S	+ ChdM_S	97.7%
7	CamH_R	for Efft	+ CamH_R	+ CamH_R	+ CamH_R	+ CamH_R	98.1%
8	ChdH_S	for Efft	+ ChdH_S	+ ChdH_S	+ ChdH_S	+ ChdH_S	98.3%
9	ChdS_R	for Efft	+ ChdS_R	+ ChdS_R	+ ChdS_R	+ ChdS_R	99.1%
10	ChdS_S	for Efft	+ ChdS_S	+ ChdS_S	+ ChdS_S	+ ChdS_S	99.3%
11	CamS_R	for Efft	+ CamS_R	+ CamS_R	+ CamS_R	+ CamS_R	99.8%
12	ChdH_R	for Efft	+ ChdH_R	+ ChdH_R	+ ChdH_R	+ ChdH_R	100.0%

Selected design variables



Selected design variables

Result: Screening

Nominal value selection by sensitivity analysis

- Confliction between objective functions: Pwr(minimize) vs Efft(maximize)
- Nominal values cannot be changed by conflicted objective functions

Direction of improvement direction: Pwr(Minimize) <-> Efft (Maximize)
 (Pt: constraint)

민감도 매트릭스 (평균분석)		설계변수											
		SetH_R	SetM_R	SetS_R	CamH_R	CamM_R	CamM_S	ChdH_R	ChdM_R	ChdS_R	ChdH_S	ChdM_S	ChdS_S
설계변수가 커질수록 성능값 증가	최대값	44.26	30.68	26.16	34.00	18.09	22.61	310.00	1.00	259.50	285.00	285.00	285.00
	평균값	41.26	27.68	23.16	31.00	15.09	19.61	290.00	0.50	239.50	270.00	270.00	270.00
	최소값	38.26	24.68	20.16	28.00	12.09	16.61	270.00	0.00	219.50	255.00	255.00	255.00
	선택	V	V	V		V		V					
↓ Pwr	Pwr	12.9%	100.0%	37.0%	-3.7%	19.7%	-8.6%	-2.4%	-9.9%	11.5%	-2.4%	-1.5%	-2.7%
	Pt	12.2%	100.0%	37.0%	-3.4%	19.3%	-8.2%	-1.6%	-8.9%	10.6%	-2.4%	-2.4%	-3.4%
	Efft	21.6%	100.0%	45.2%	-11.1%	21.0%	7.7%	-7.4%	13.5%	8.3%	-8.9%	-13.5%	-7.9%

Sensitivity analysis result on screening process

Variables	Nominal
CamH_R	31.00
CamM_S	19.61
ChdH_R	290.00
ChdS_R	239.50
ChdH_S	270.00
ChdM_S	270.00
ChdS_S	270.00

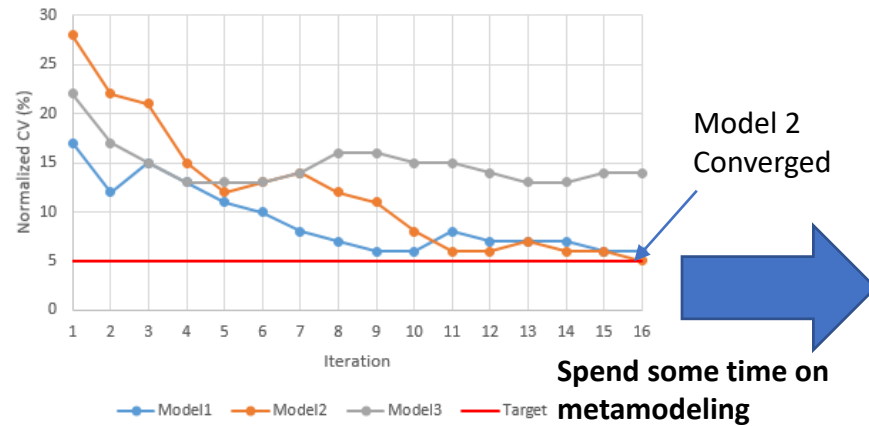
Nominal values of screened DVs

Metamodeling

Competitive metamodeling

- Generate various metamodels using acquired data by sequential sampling
- The models which have least error are selected when any model reached target error.
- It can save the time of CAE analysis using small amount of time with constructing metamodels

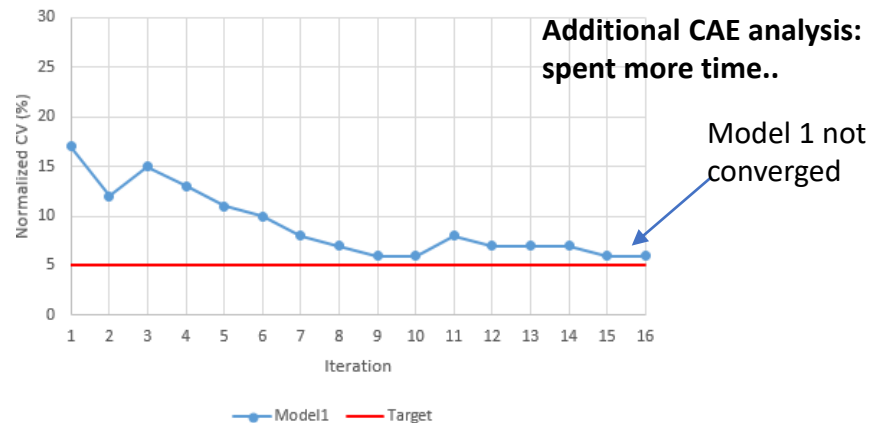
Competitive metamodeling: P1



To get metamodel of..

$P1=f(x1,x2)$
f is unknown

Metamodeling: model1 only

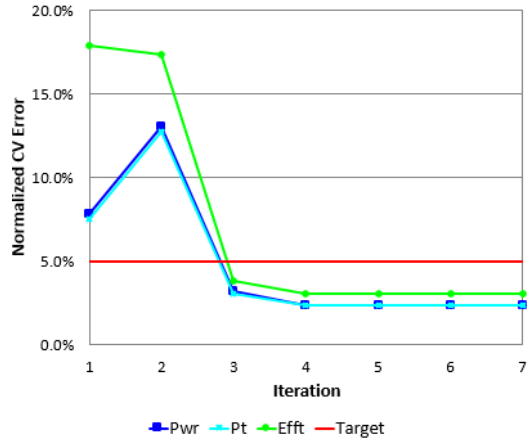


Metamodeling

Result

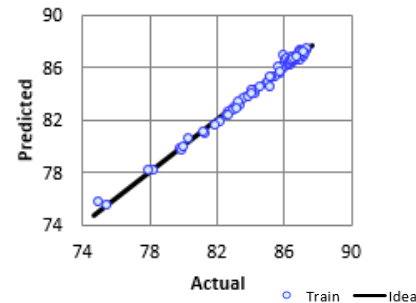
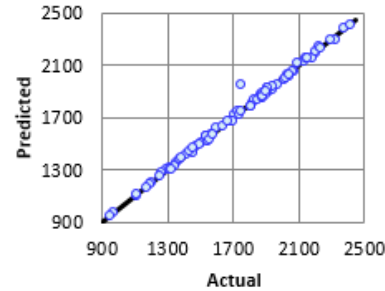
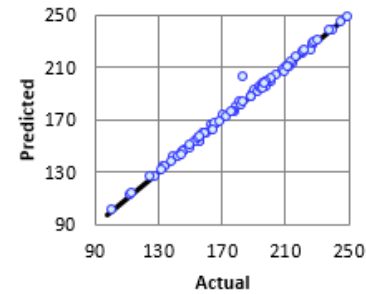
- Normalized CV error converged normally on 7th iterations, **Polynomial regression** is selected for all performances
- Metamodels can predict the tendencies with predicted vs actual chart

Normalized CVe of best metamodel

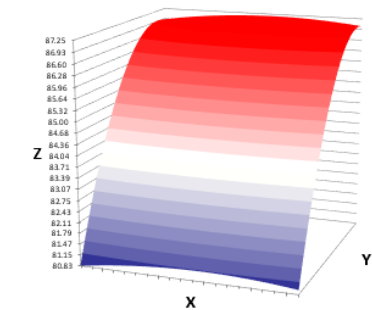
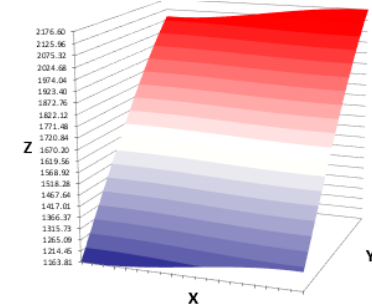
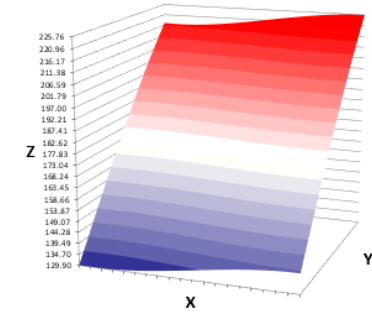


Normalized CVe on final iteration (unit: %)

	Pwr	Pt	Efft
Kriging	5.19	5.07	4.61
RBFi	4.04	4.08	4.56
RBFr	3.99	3.94	4.01
PR	2.40	2.37	3.04
MLP	3.26	3.87	6.84
EDT	6.39	6.10	5.62
Target	5.00	5.00	5.00



Predicted vs Actual chart

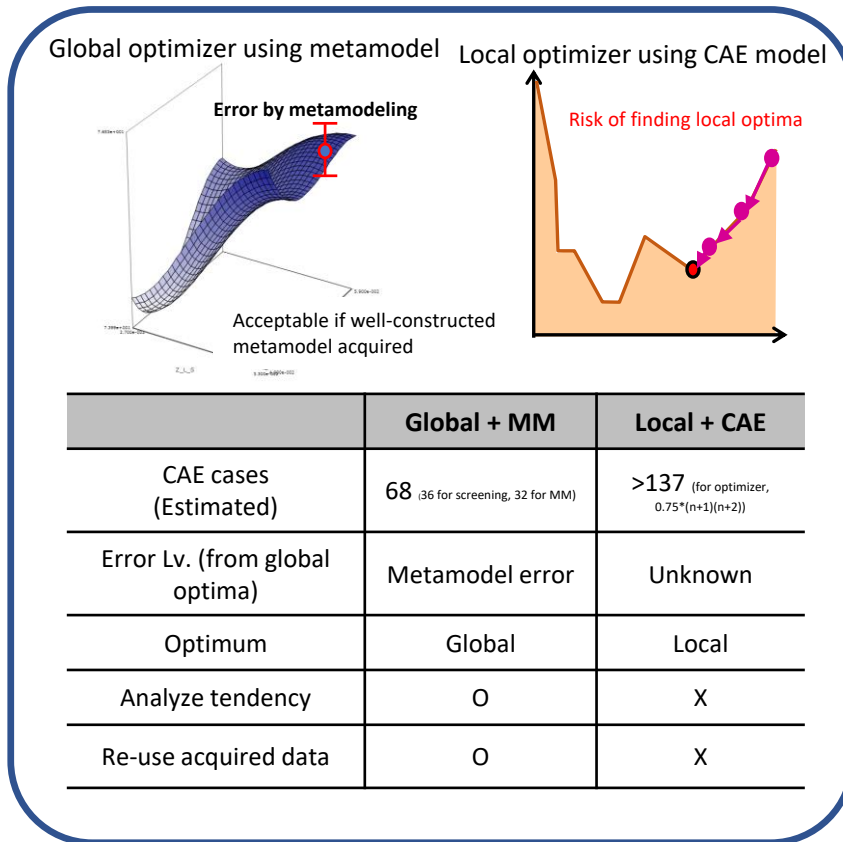


Response surfaces of generated metamodels

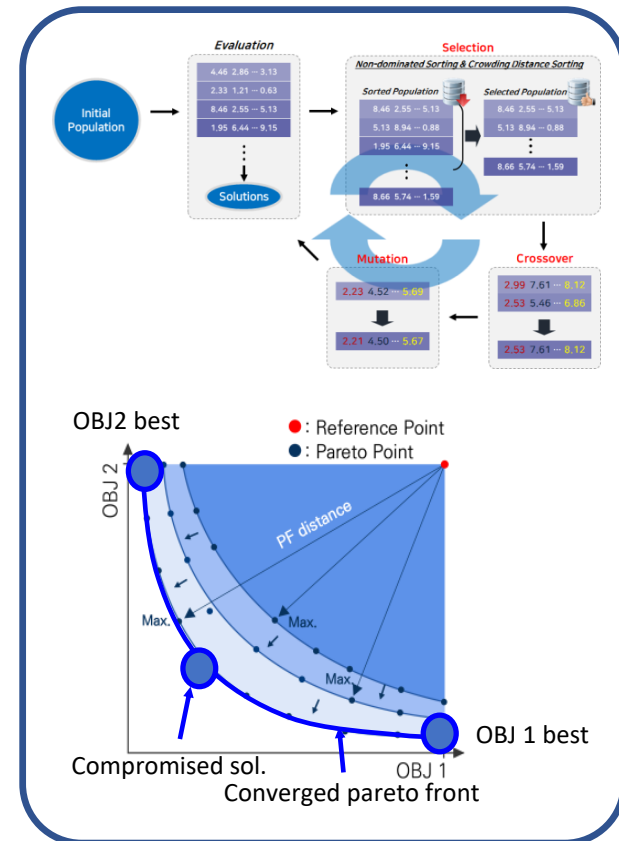
Design optimization

Pareto optimization: NSGA-II

- Metamodel based design optimization spends less time -> Global design optimizer & Multi-objective optimizer available
- Can analyse the relation of objectives or objectives vs design variables by pareto sets



Analysis time: metamodel based vs CFD based



Process: multi-objective design optimization, NSGA-II

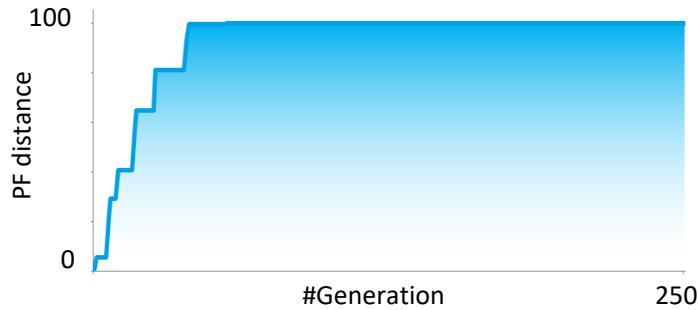
Design optimization

Overall results

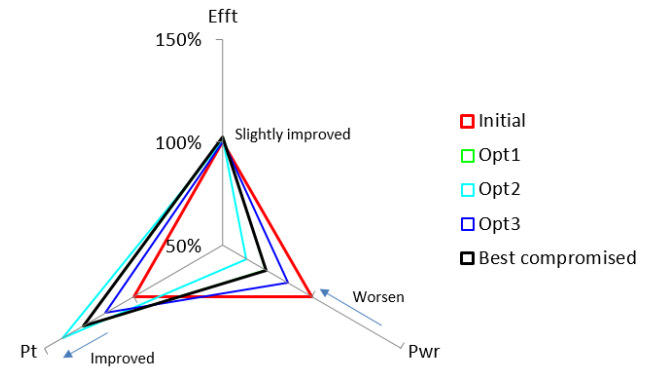
- Design optimization is successfully finished, **Pwr is worsened** on whole pareto sets **for satisfy constraints**
- Compromised solution has similar tendencies to the ideal solution of Efft

* Ideal solution: the pareto point which provides the best improvement of specific objective

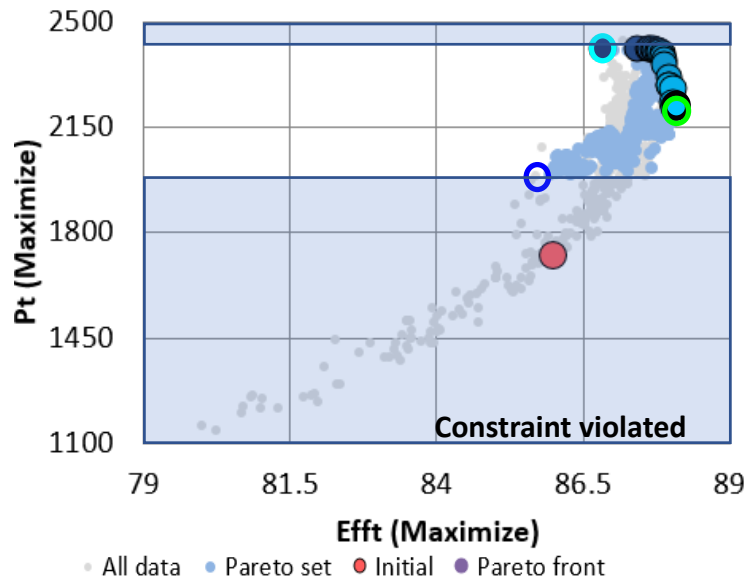
Convergence of MOGA



Improvement of objectives (larger: improved)



Pareto front: Efft vs Pt



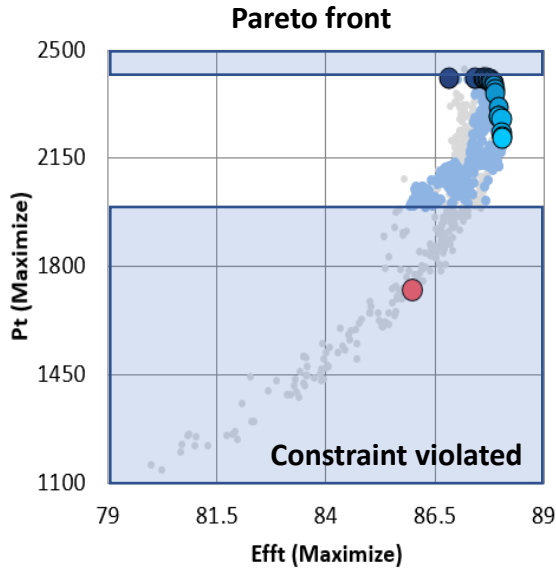
Design variables and performances: Initial-optimum

	Initial	Eff (Opt1)	Pt (Opt2)	Pwr (Opt3)	Compromised
SetH_R	41.26	42.92	44.09	38.50	42.89
SetM_R	27.68	29.08	30.35	30.32	29.09
SetS_R	23.16	26.16	25.73	20.25	26.16
CamM_R	15.09	14.24	18.05	18.05	14.20
ChdM_R	0.50	1.00	0.77	0.60	1.00
Eff	86.00	88.05	86.85	86.27	88.05
Pwr	180.94	227.61	247.41	205.41	227.58
Pt	1,722.55	2,213.03	2,407.20	1,994.01	2,212.58
Pt const.	violated	Satisfied	Satisfied in tolerance		Satisfied

Design optimization

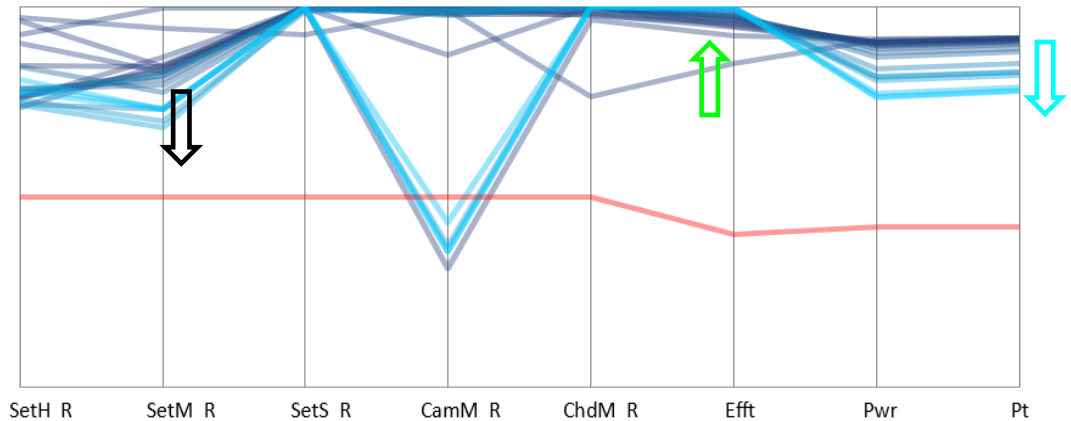
Pareto fronts: Efft vs Pt

- Efft decreases and Pt increases when SetM_R increases by parallel plot
- The conflict between Efft and Pt is mainly dependent on SetM_R by contribution analysis



• All data • Pareto set • Initial • Pareto front

Parallel plot

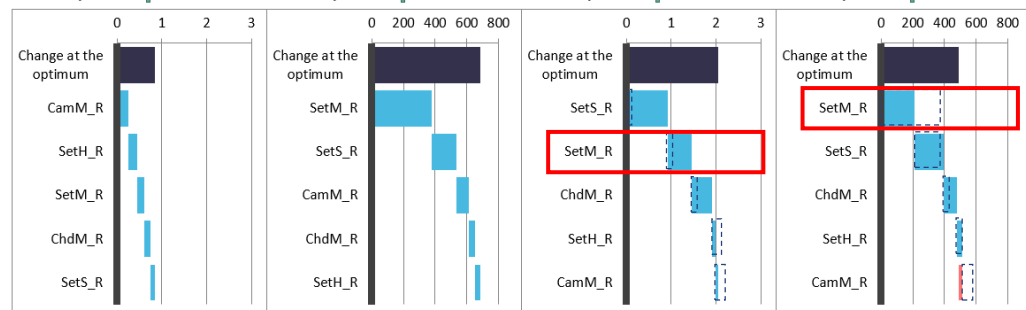


Contribution analysis

Opt2

Opt1

Efft		Pt		Efft		Pt	
Improved (Maximize)		Improved (Maximize)		Improved (Maximize)		Improved (Maximize)	
초기값	86.003	초기값	1722.554	초기값	86.003	초기값	1722.554
최적값	86.85	최적값	2407.2	최적값	88.049	최적값	2213.025
변화량	↑ 0.847	변화량	↑ 684.646	변화량	↑ 2.046	변화량	↑ 490.471

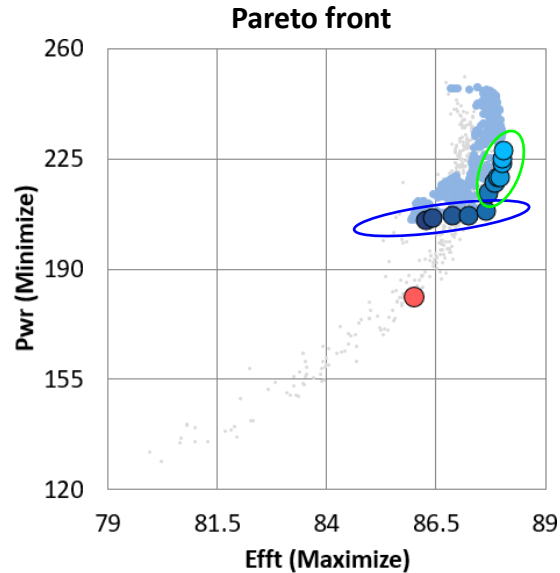


Dotted: OPT#1 data

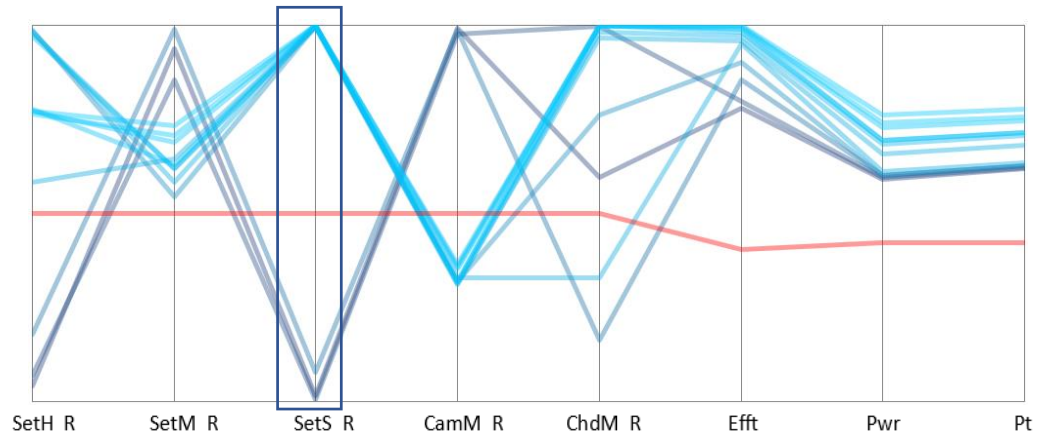
Design optimization

Pareto fronts: Efft vs Pwr

- Pareto front has two regions: less worsen Pwr(blue, max SetS_R) and improve Efft(green, min. SetS_R)
- The contribution of SetS_R has completely opposite between two optimum



Parallel plot

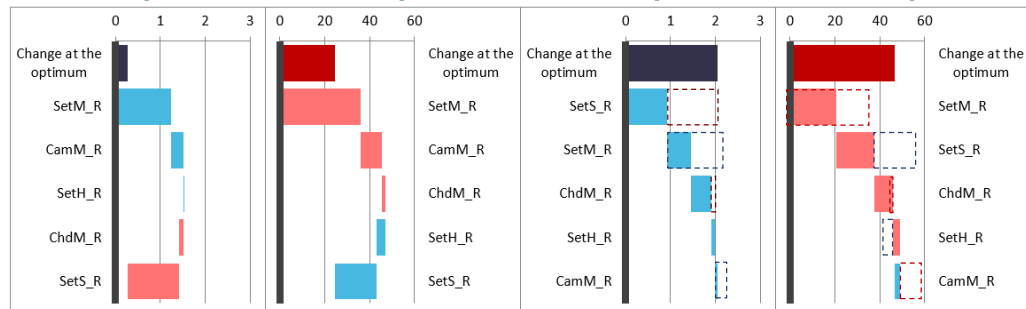


Contribution analysis

Opt3

Opt1

Efft Improved (Maximize)		Pwr Worsen (Minimize)		Efft Improved (Maximize)		Pwr Worsen (Minimize)	
초기값	86.003	초기값	180.937	초기값	86.003	초기값	180.937
최적값	86.274	최적값	205.414	최적값	88.049	최적값	227.579
변화량	↑ 0.271	변화량	↑ 24.477	변화량	↑ 2.046	변화량	↑ 46.642



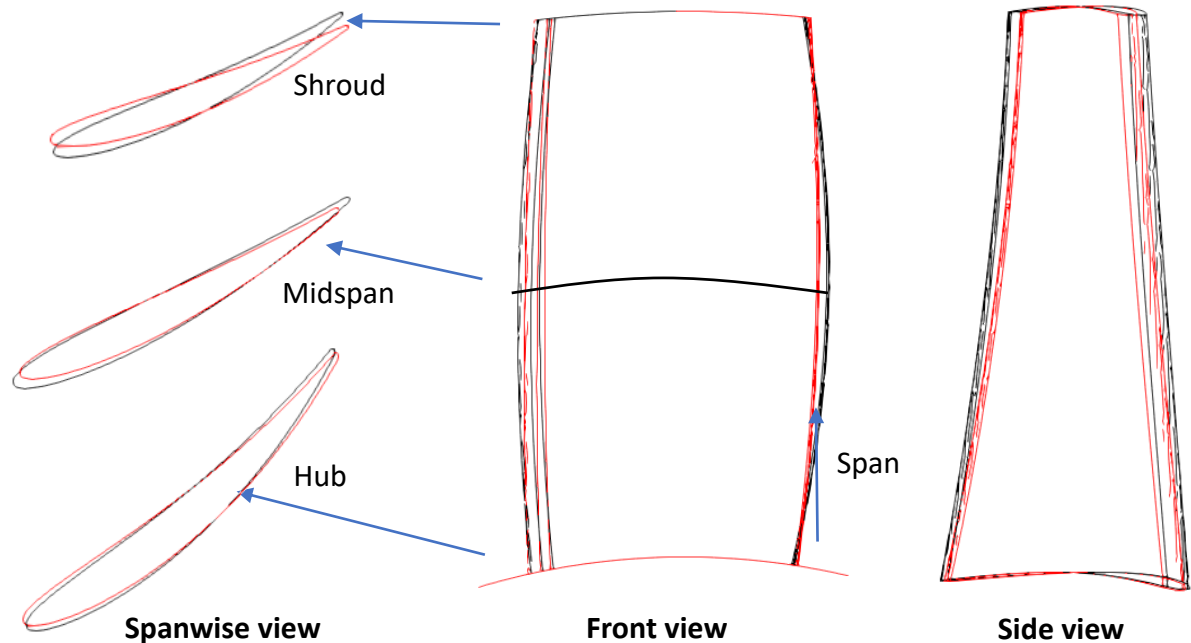
All data • Pareto set ● Initial ● Pareto front

Shape & Performance comparison: Initial vs Optimal

Comparing shape between initial vs Optimal

- Setting angle(Set*) changes are significant by span increases
- Midspan chord length increased

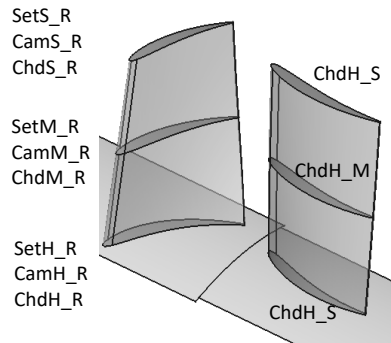
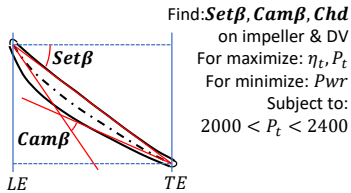
	Initial	Compro-mised
SetH_R	41.26	42.89
SetM_R	27.68	29.09
SetS_R	23.16	26.16
CamM_R	15.09	14.20
ChdM_R	0.50	1.00
Eff	86.00	88.05
Pwr	180.94	227.58
Pt	1,722.55	2,212.58



Summary: Optimization

Problem definition

- 3 DVs on each span
- 1 DV on each span of DV
- MOGA is selected as optimizer

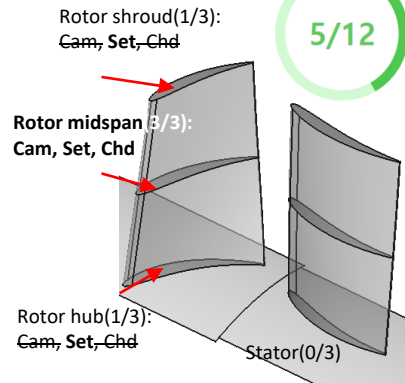
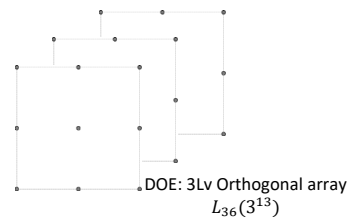


No. of design variables: 12
No. of objectives: 3
No. of constraints: 1

➔ **Multiobjective optimization**
MOGA

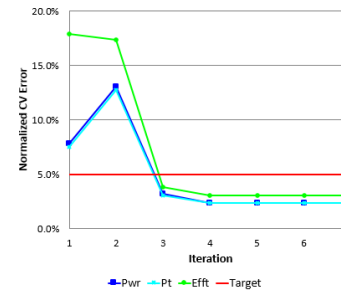
Well balanced screening

- 5 DVs are selected by DOE & sensitivity analysis
- Nominal values are not changed

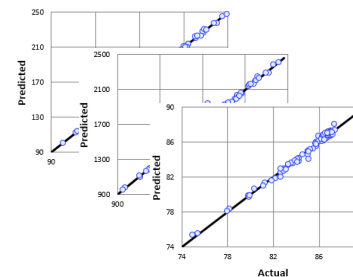


Metamodeling

- 7 iteration to converge
- Predict the tendencies (predicted vs actual chart)



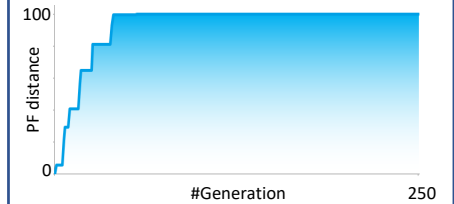
Normalized CVE on final iteration (unit: %)



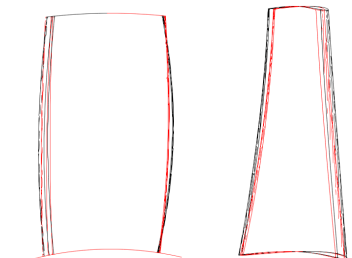
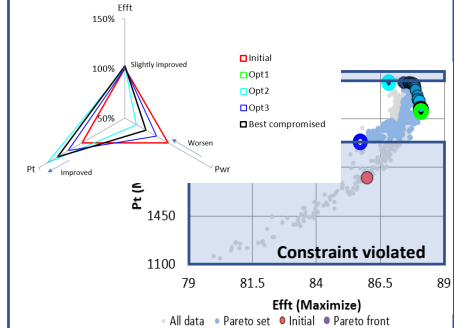
Predicted by actual

Pareto optimization

- Design optimization is successfully finished
- Pwr is worsened for satisfy constraints



Improvement of objectives (larger: improved)



A photograph of two business people shaking hands, overlaid on a dark, blue-tinted image of a city skyline at night. The handshake is the central focus, with the hands clasped together. The city lights are visible in the background, creating a bokeh effect. The overall mood is professional and successful.

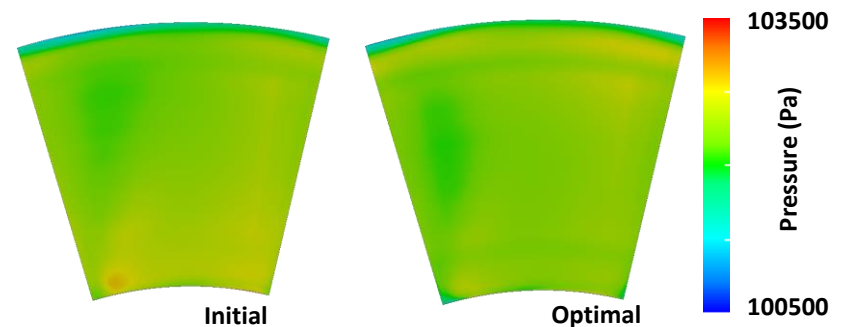
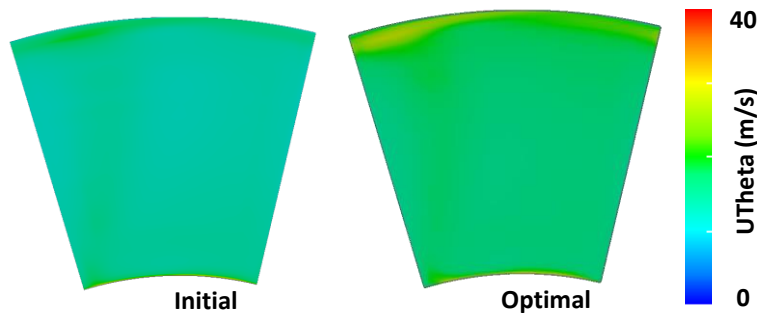
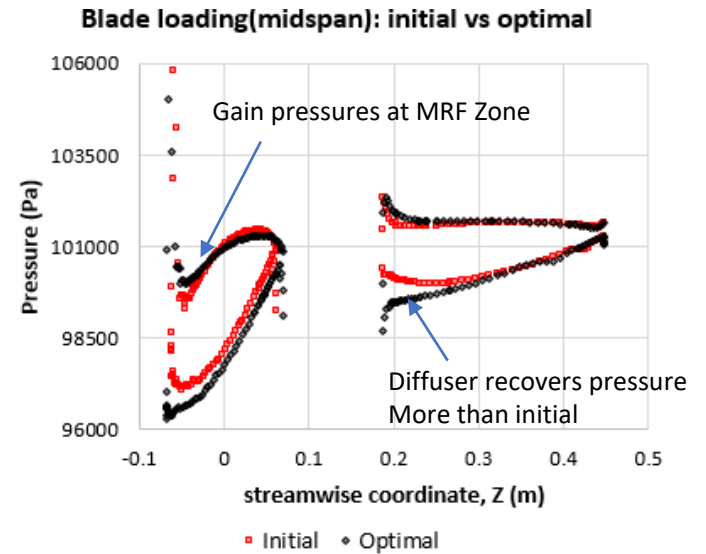
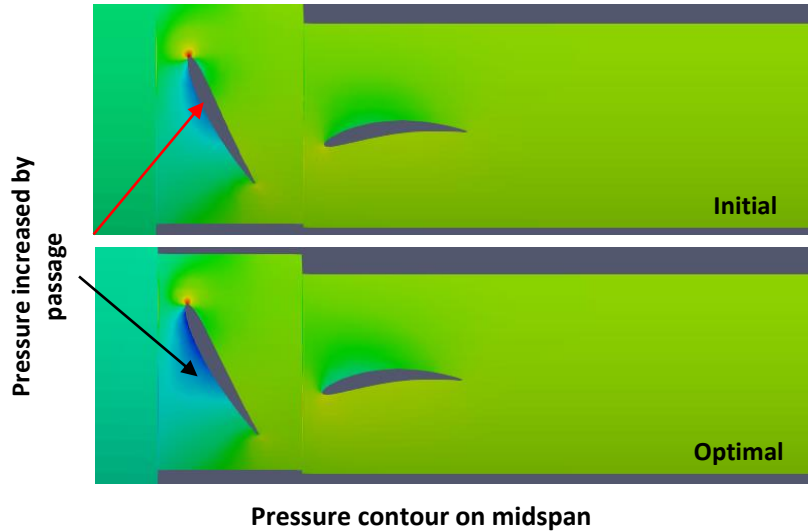
04

Validation

Shape & Performance comparison: Initial vs Optimal

Comparing flow contours

- Increased midspan chord length and optimized setting angles induce the pressure rise of impeller blade
- Recovers more pressure on diffuser vane with less loss



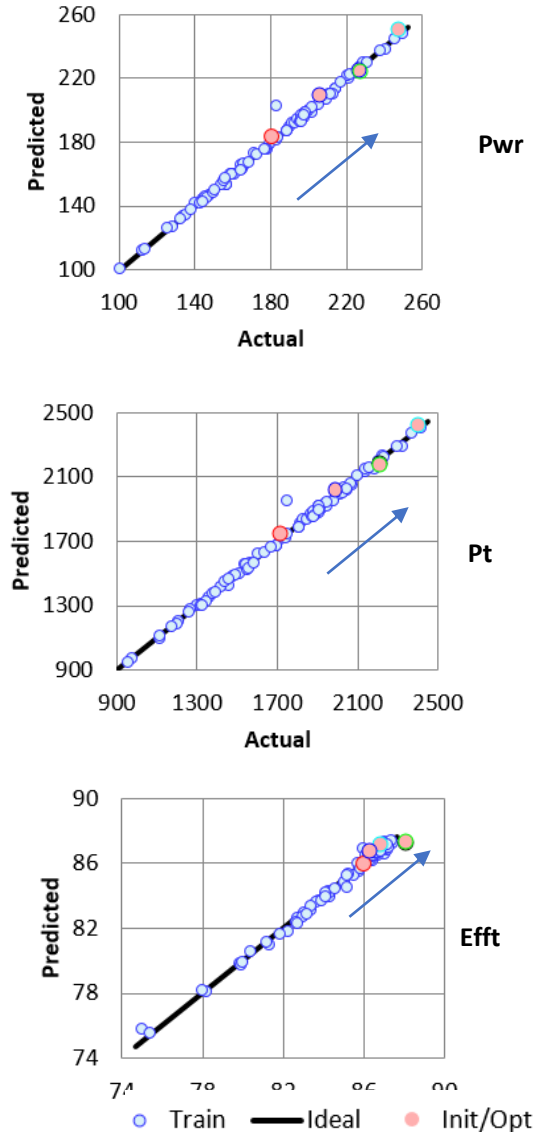
Distribution of mixing plane (rotor outlet)

Shape & Performance comparison: Initial vs Optimal

Validation: initial and optimal

- It tends to underestimate near initial and overestimate nearby optimum
- The errors are acceptable: CFD result follows the tendency of metamodel

	Perform-ances	Metamodel	foam-extend	Error (%)
Initial	Eff	86.00	85.93	0.08
	Pwr	180.94	183.08	-1.17
	Pt	1722.55	1748.03	-1.46
Compro-mised	Eff	88.05	87.29	0.87
	Pwr	227.58	224.97	1.16
	Pt	2212.58	2181.83	1.41
Opt1	Eff	88.05	87.33	0.82
	Pwr	227.61	224.78	1.26
	Pt	2,213.03	2181.10	1.49
Opt2	Eff	86.85	87.20	-0.4
	Pwr	247.41	250.34	-1.17
	Pt	2,407.20	2425.41	-0.75
Opt3	Eff	86.27	86.72	-0.52
	Pwr	205.41	208.79	-1.62
	Pt	1,994.01	2011.67	-0.88



Predicted by Actual graphs

Conclusion

CFD analysis

- steadyCompressibleMRFFoam of Foam-extend 5.0 is selected to apply simplifications
- Validation with CFX result has errors within 3%

Optimization

- Design optimization with AADO processes are executed
- NSGA-II with metamodeling is applied to optimization
- Proper optimum are acquired, the objective Pwr worsened to satisfy the constraints

Validation

- Increased midspan chord length and optimized setting angles induce the pressure rise of impeller blade
- Tends to underestimate near initial and overestimate nearby optimum but CFD result follows the tendency of metamodel