foam-Extend와 AADO 기술을 이용한 축류 송풍기 최적설계

2024. 09. 27

㈜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)

PIDOTECH

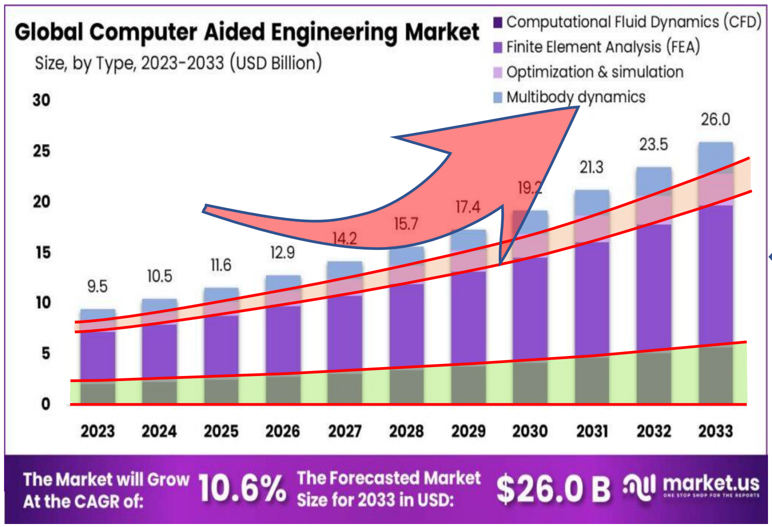
CONTENTS

01

AI-Aided Design Optimization

Design Optimization: Necessity

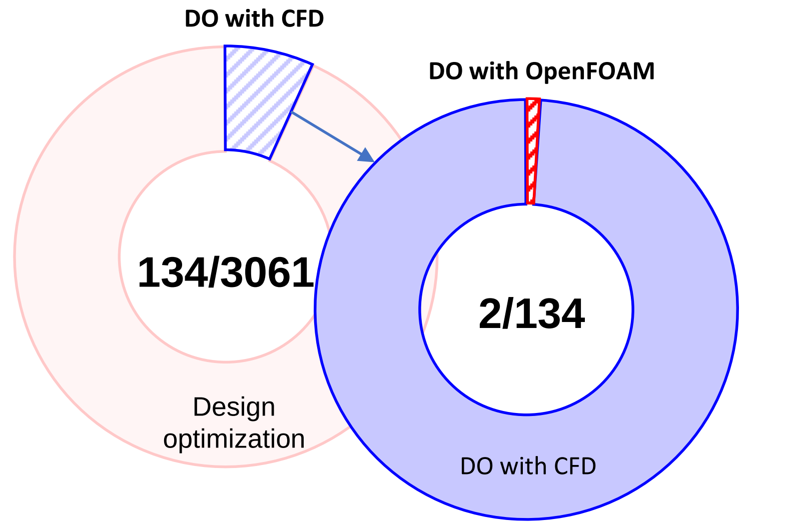
- Demands & Markets of Design optimization increases gradually
- In the other hands, DO based on CFD analysis cannot follow the trends



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

Trends: CAE and Design optimization markets

Versus..

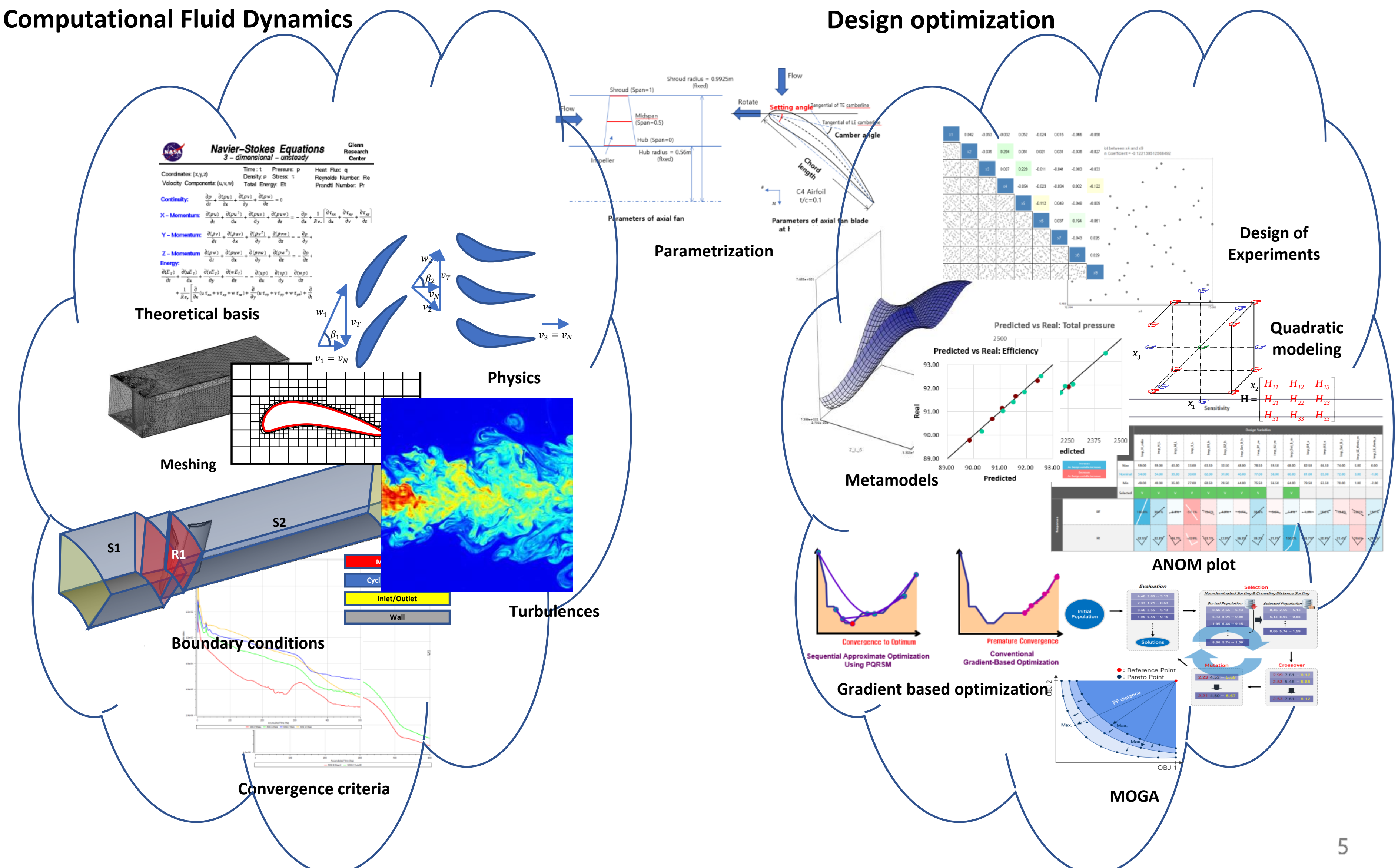


(Result of dbpia paper search
Filters: Design optimization / Design optimization CFD / Design optimization openfoam)

Domestic papers related to design optimization on Recent 5 yrs*

Design Optimization: prerequisites

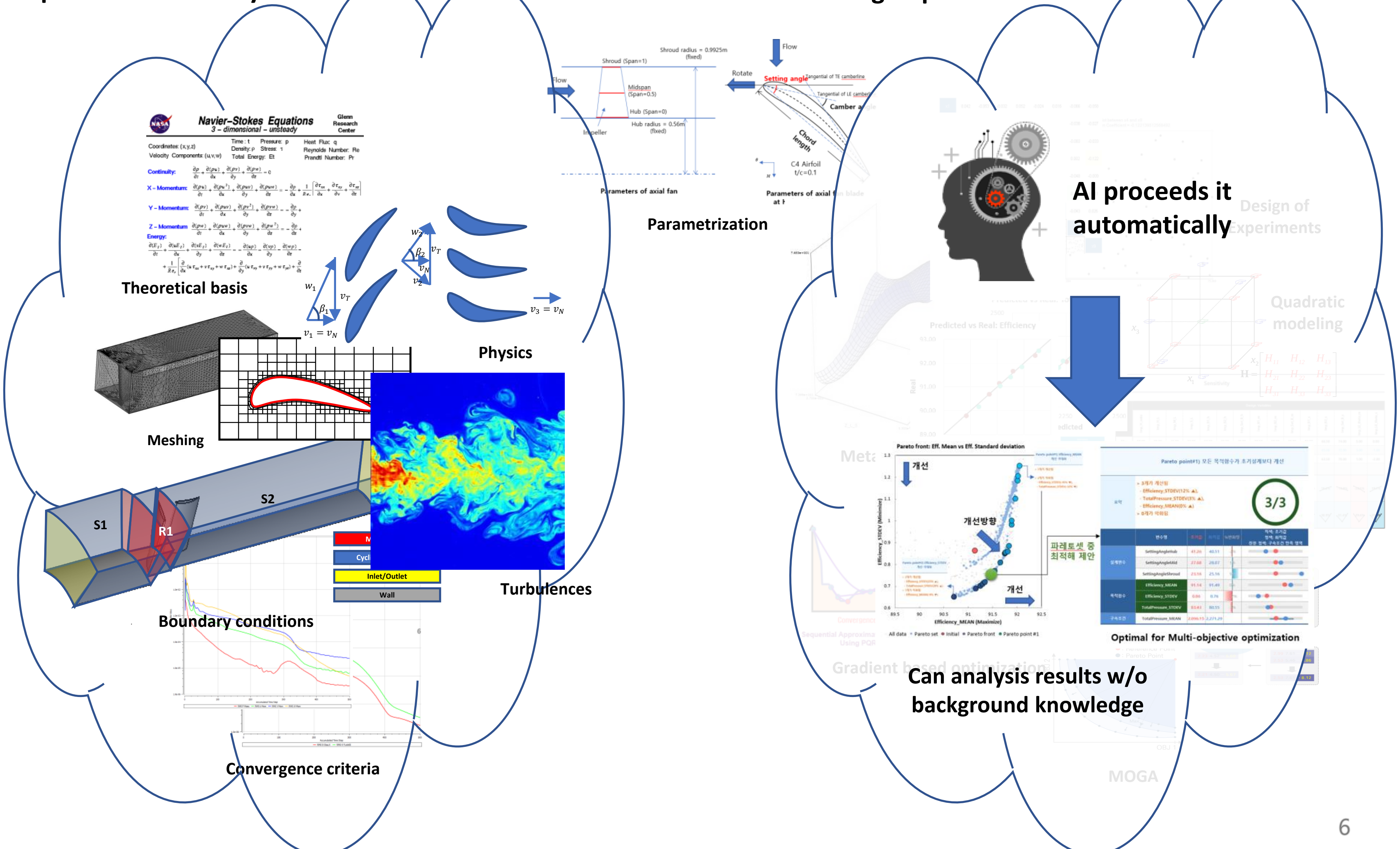
- Base knowledge of CAE process & Design optimization theories
- Difficult to catch both items..



AI-Aided Design Optimization

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

Computational Fluid Dynamics **Design optimization**



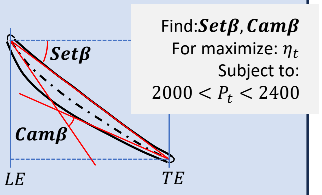
AI-Aided Design Optimization: Process

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

Pre-requisites

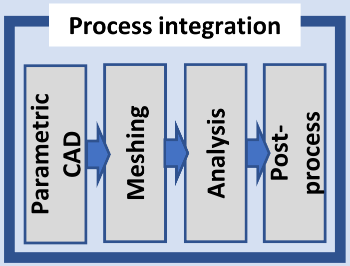
Formulation

Determine what to improve
Set the rule of shape changing



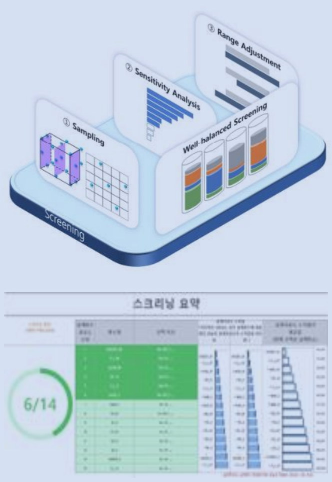
Process integration(PI)

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



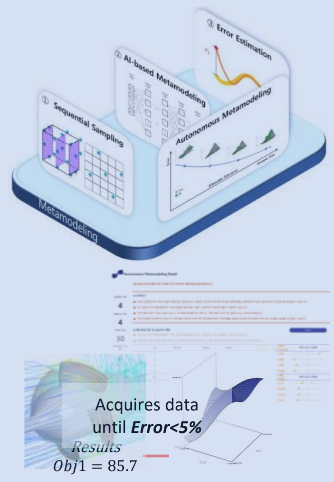
AI- Aided design optimization

Well balanced
Screening



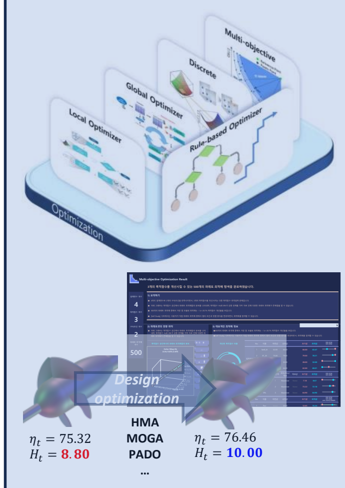
Filters less important parameters
Suggests the parameter ranges

Autonomous
Metamodeling



Sequential sampling by AI
Competitive modeling

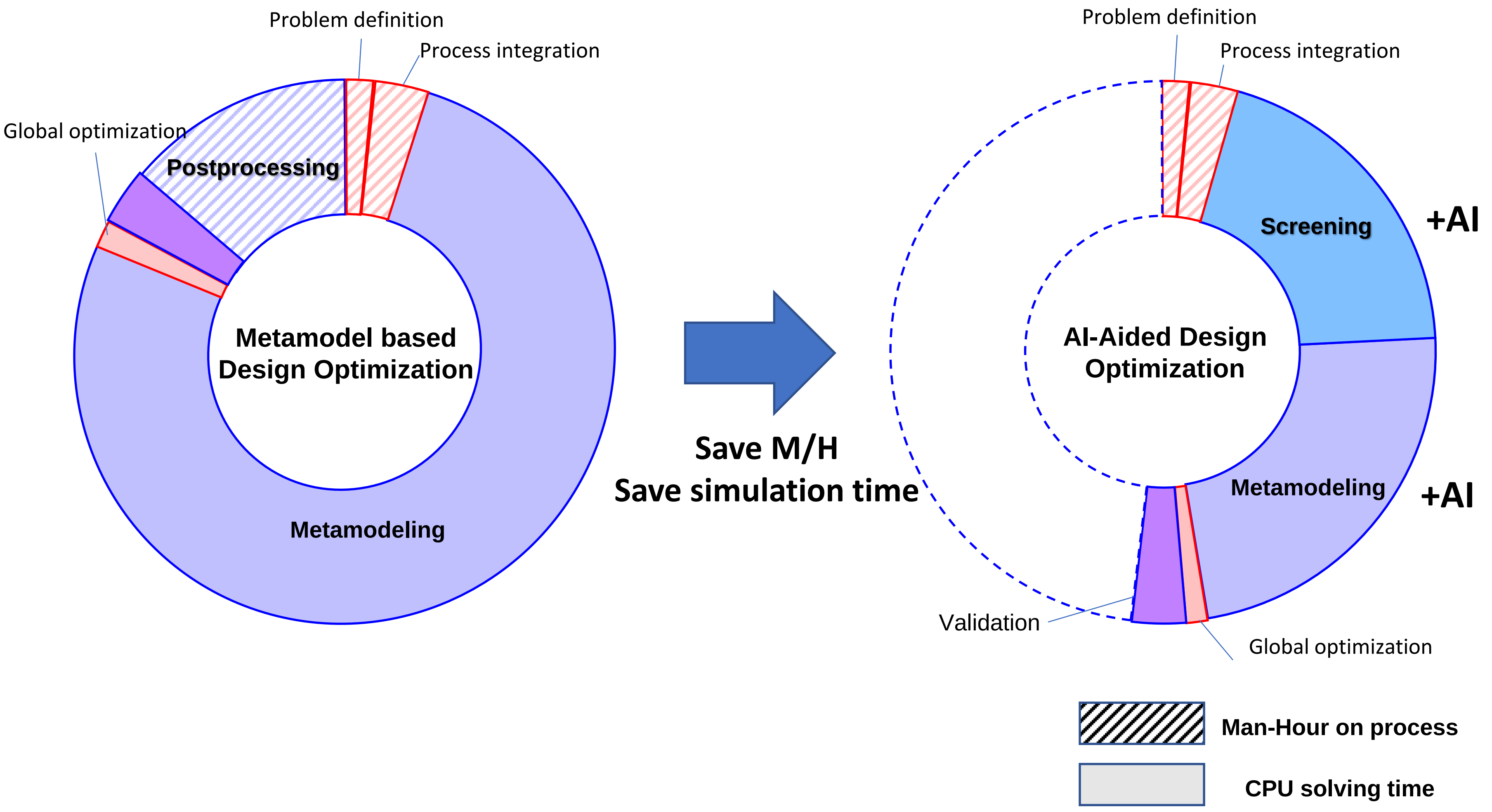
Rule-based
Optimizer



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



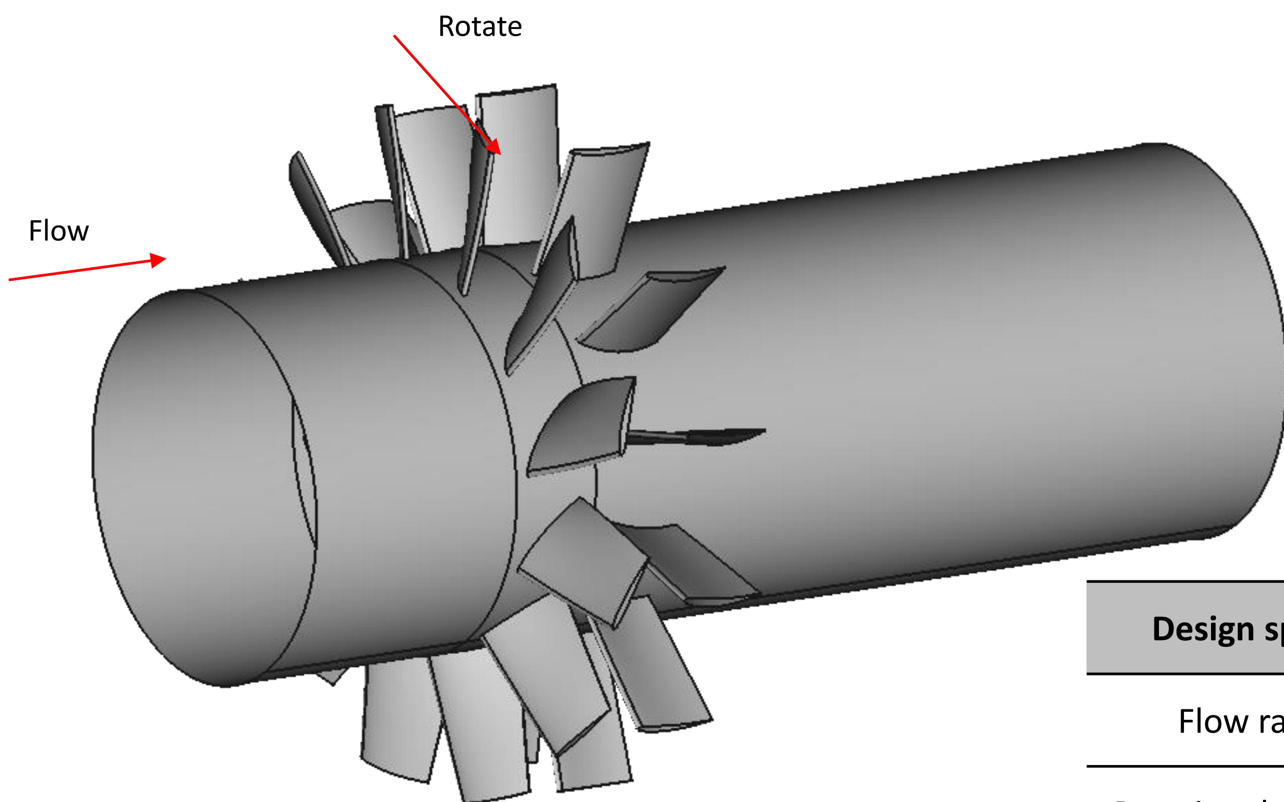
02

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)



Axial fan

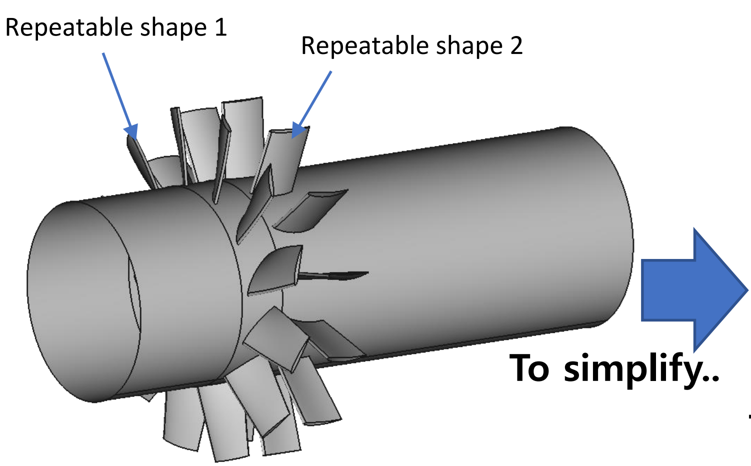
Design specification	Values
Flow rate (CMM)	5400
Rotational velocity (RPM)	1200
Target pressure rise(Pa)	2000

Design specification of axial fan

Solution info.

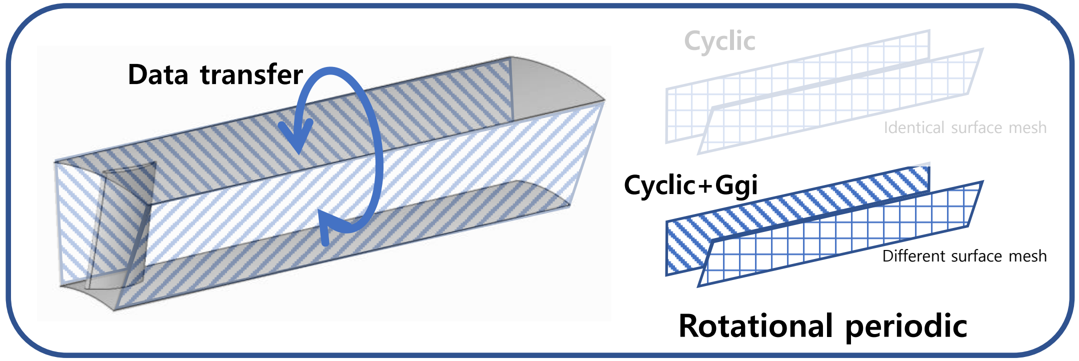
Simplification on turbomachinery

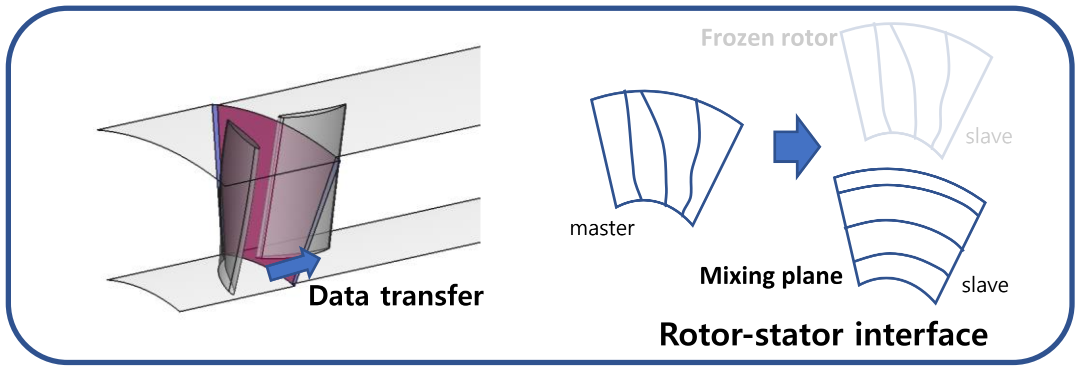
- Periodic and rotor-stator interface for domain
- MRF for timescale



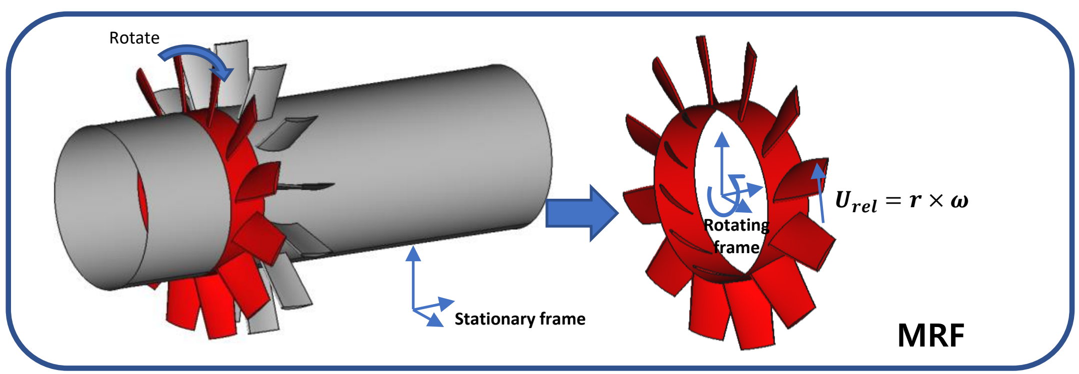
Full component

Domain simplification





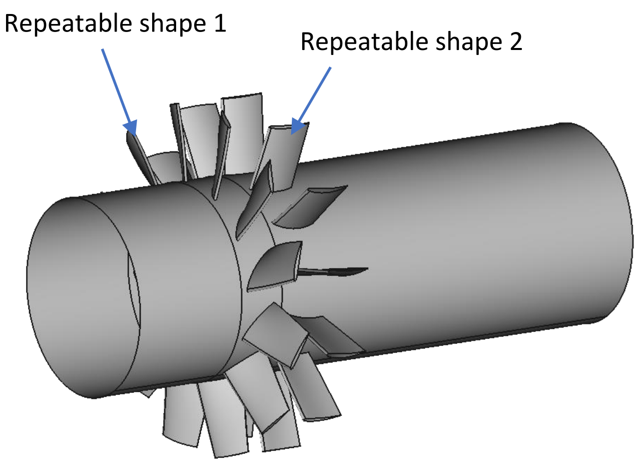
Timescale simplification



Solution info.

Version : foam-extend

- Mixing plane applicable



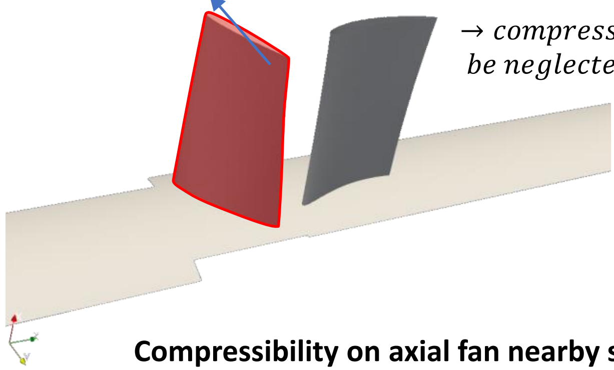
Simplify

Solver : steadyCompressibleMRFFoam

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

$U_{rel} = 131 m/s$ -> $Ma = 0.38$

$\rightarrow$ *compressible effect cannot be neglected*



Compressibility on axial fan nearby shroud

	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)

Rothalpy issues on foam-extend 4.1 and 5.0

Solution info.

Schemes & Solutions:

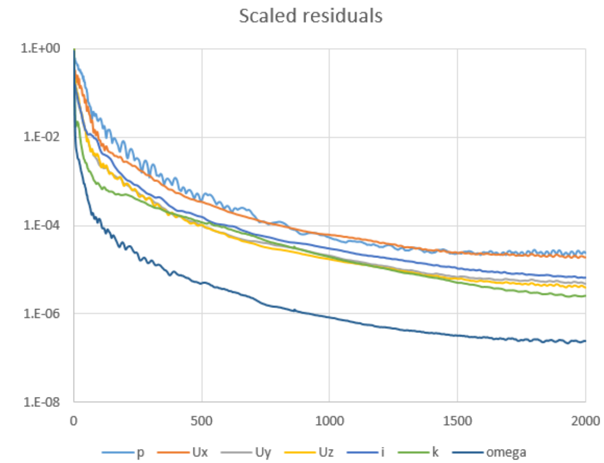
- Second order upwind for P, U, and T
- First order upwind for k and omega

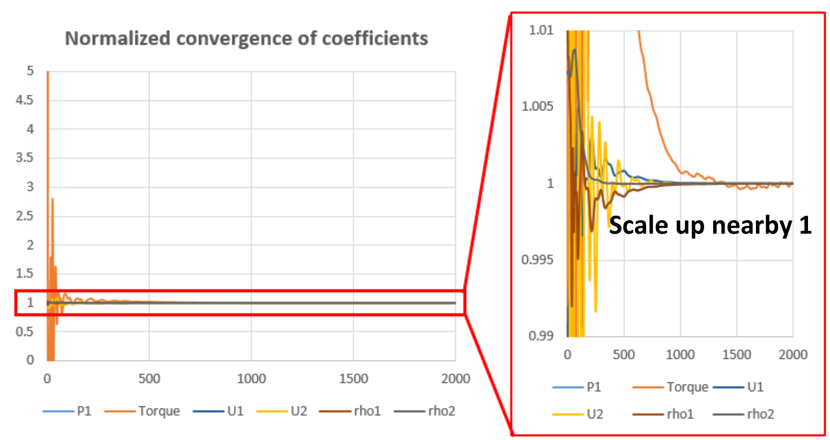
	Scheme
div(phi, U)	linearUpwindV
div(phi, p) div(phi, i)	linearUpwind
div(phi, k) div(phi, ω)	Upwind
div(phi, i) div(phi, T)	linearUpwind

	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)



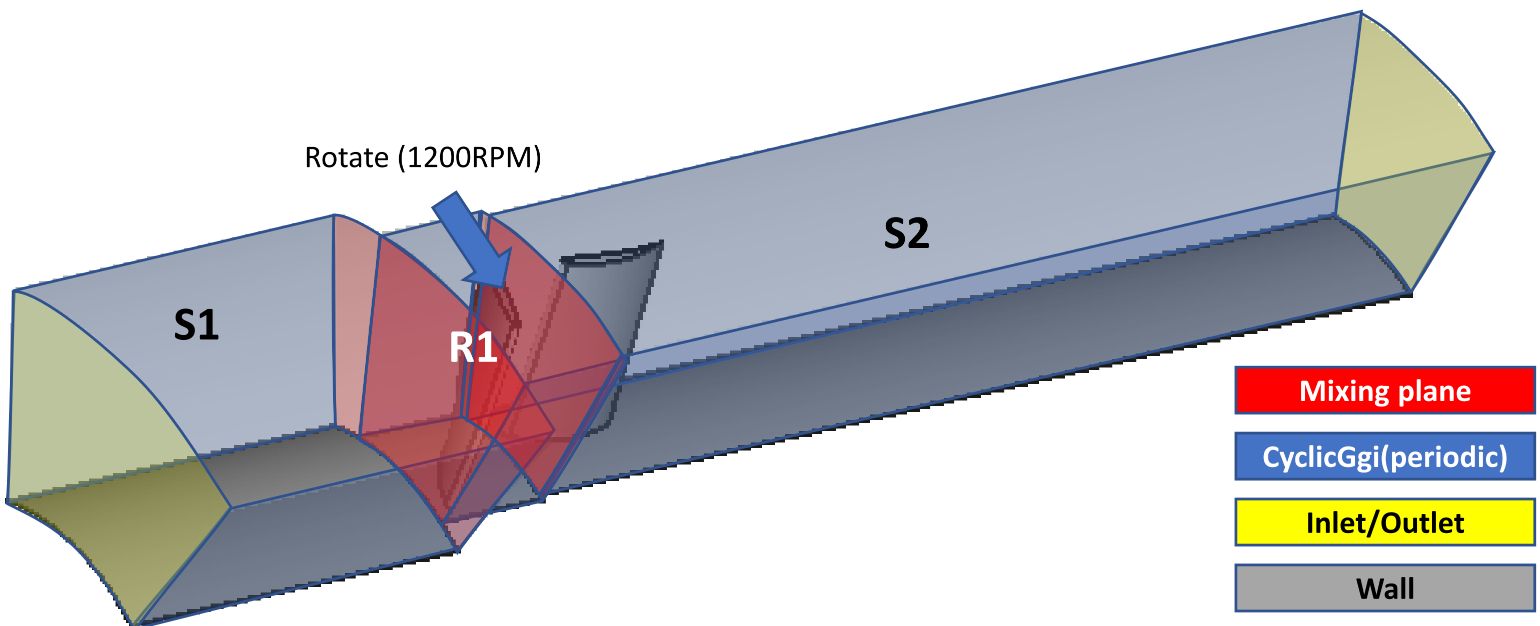


Solution info.

- **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

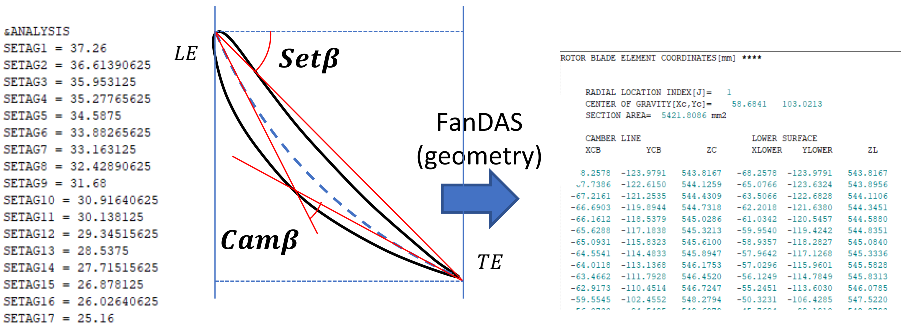
		Type	Value
Inlet	P	zeroGradient	-
	V	flowRateInletVelocity	12.92
	T	fixedValue	300
Outle t	P	fixedValue	101325
	V	inletOutlet	-
	T	zeroGradient	-



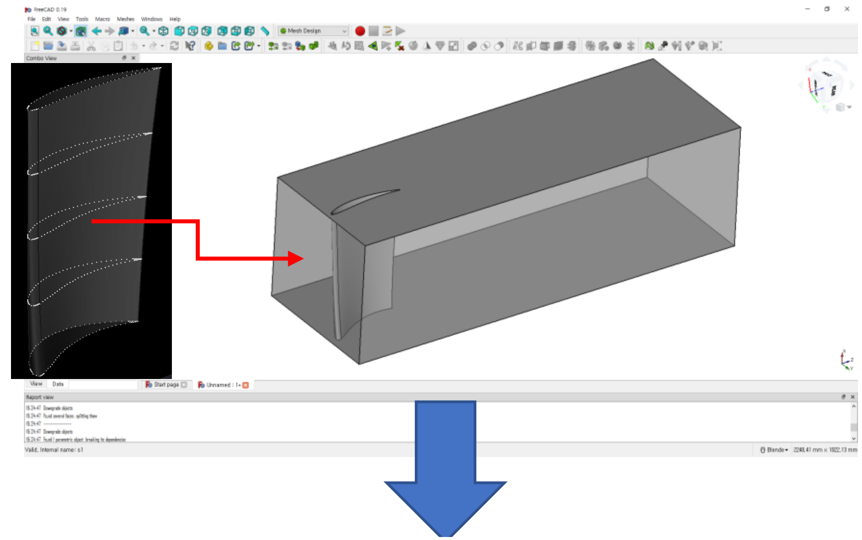
Boundary conditions

Surface meshing automation

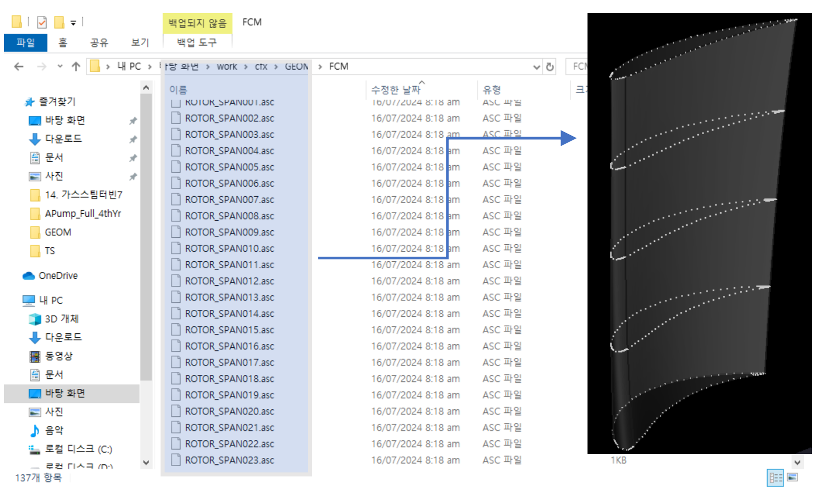
I. Update parameters: FanDAS



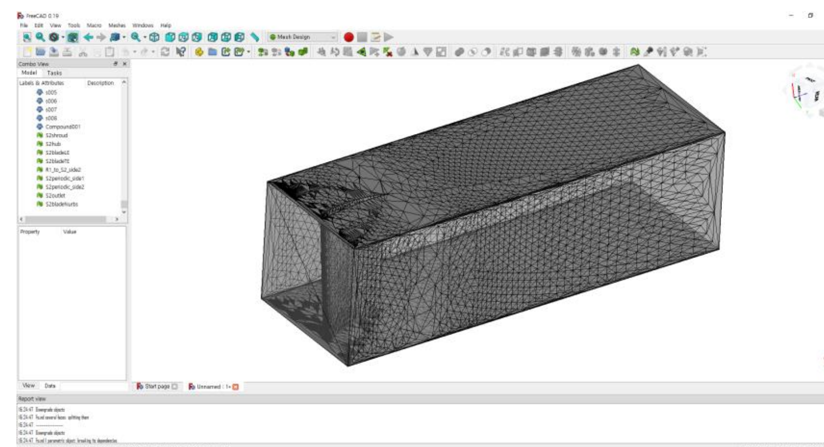
III. Generate analysis domain: FreeCAD macro



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

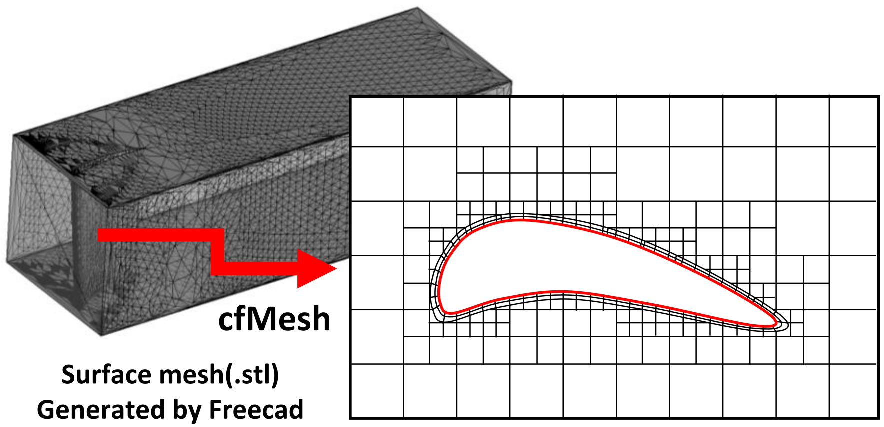


IV. Surface meshing: FreeCAD macro



Unstructured mesh automation

Volume meshing: cfMesh

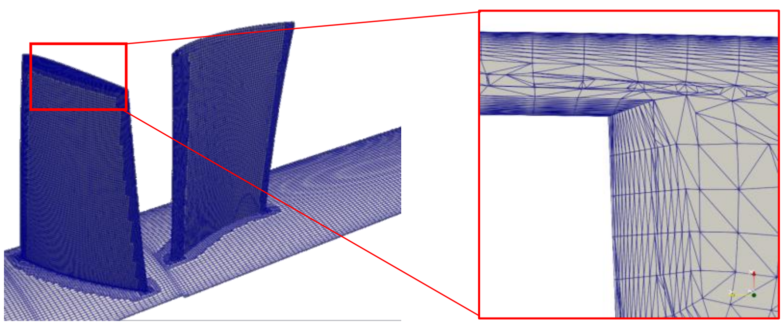


Surface mesh(.stl)
Generated by Freecad

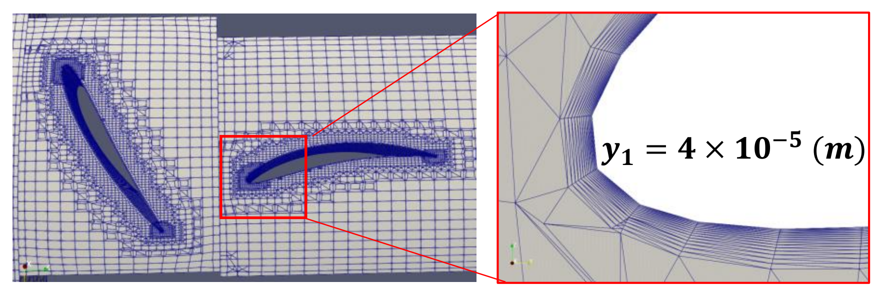
Snap for meshing

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

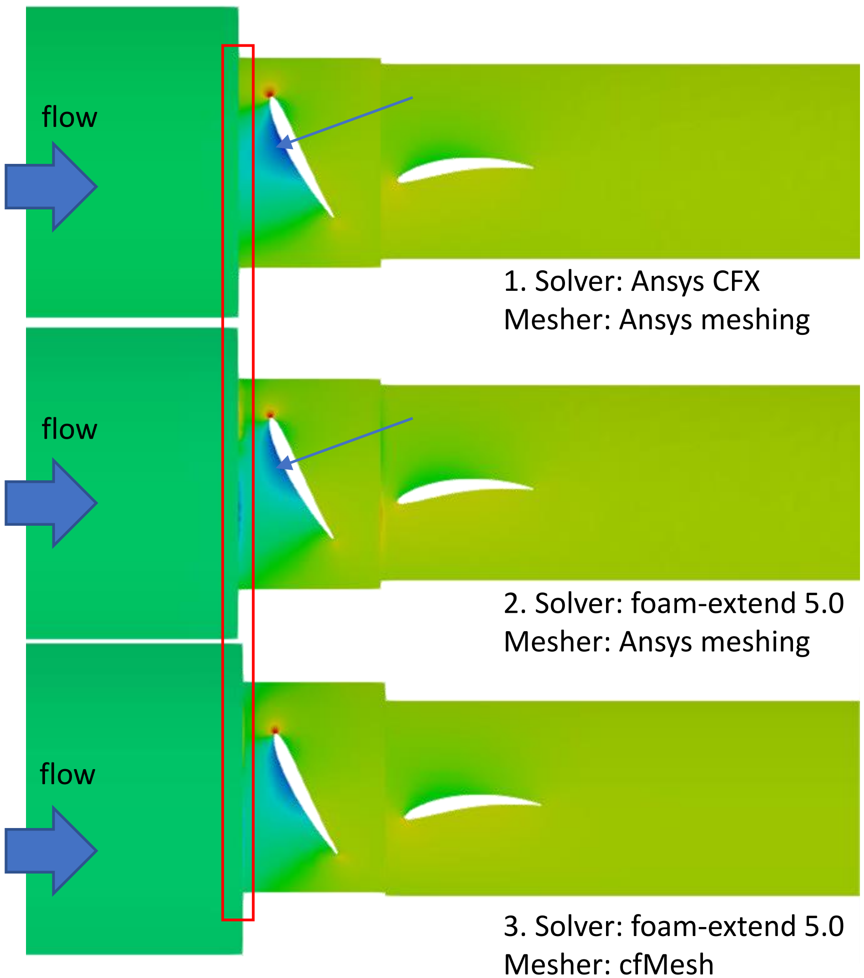


Cross section on midspan

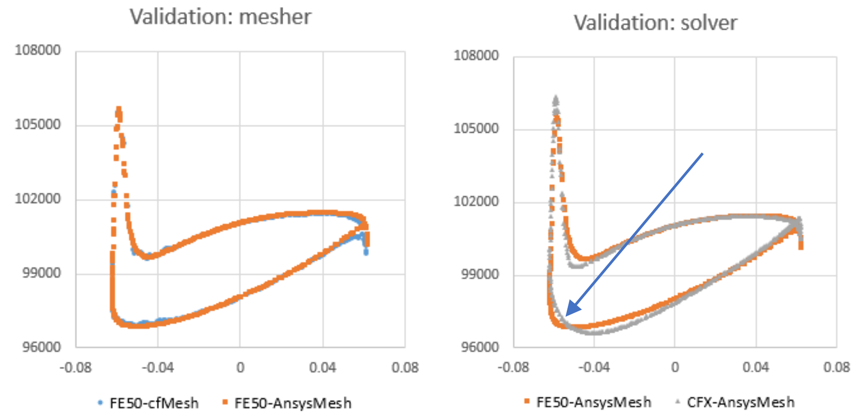
Validation

Solver and Mesher validation

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



Pressure contour on midspan



Blade loading by flow direction on midspan

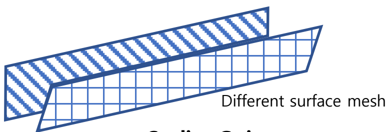
Performances comparison

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		1804.1	15.61	86.68

Summary: CFD analysis

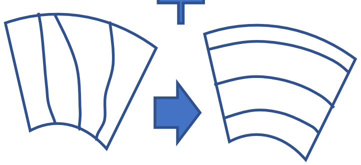
Solver selection

- Selected solver with satisfying all simplification conditions



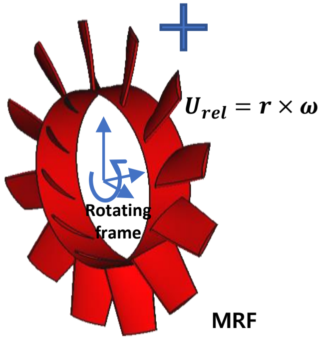
Cyclic+Ggi

+



Mixing plane

+



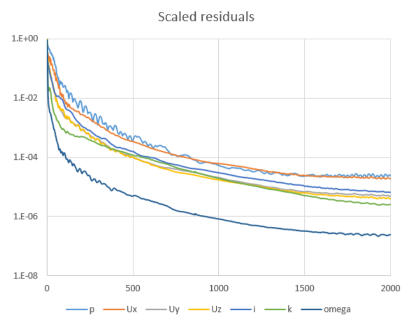
MRF

+ Compressible..

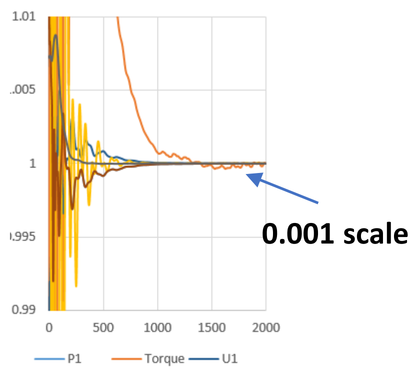
steadyCompressiblMRFFoam on foam-extend

Convergence evaluation

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



Scaled residuals

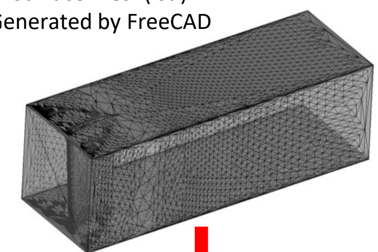


Coefficients convergence

Meshing

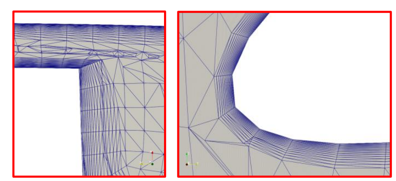
- Mesh constructed by cfMesh
- Boundary layer generated, acceptable quality acqured

Surface mesh(.stl)
Generated by FreeCAD



cfMesh

Volume mesh: nearwall



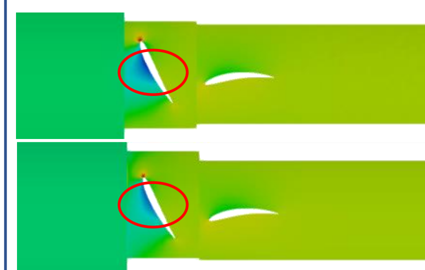
$y_1 = 4 \times 10^{-5}\ (m)$

Volume mesh: quality

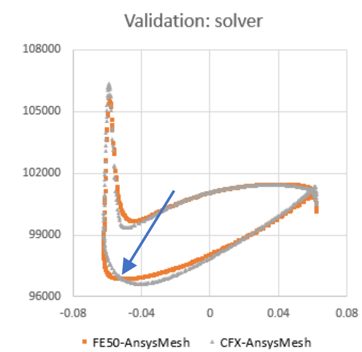
	Baseline	Range
nonOrtho.	78.05	75-80
Skew	2.97	2.7-3.5

Validation

- Pressure distribution slightly differs - > performance differs each other



Pressure contour on midspan



Blade loading by flow direction on midspan

03

Optimization

AADO tool: AIDesigner sim

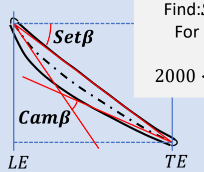
AIDesigner sim

Powered by PIDOTECH

Pre-requisites

Formulation

Determine what to improve
Set the rule of shape changing



Find: $\boldsymbol{Set\beta, Cam\beta}$
For maximize: η_t
Subject to:
$2000 < P_t < 2400$

Process integration(PI)

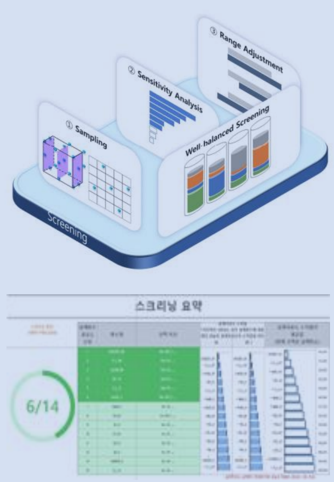
Integrate whole process of CAE analysis
Get simulation results with unified rules

Process integration

Parametric CAD → Meshing → Analysis → Post-process

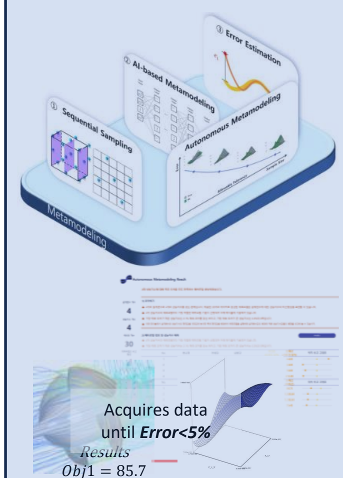
AI- Aided design optimization

Well balanced
Screening



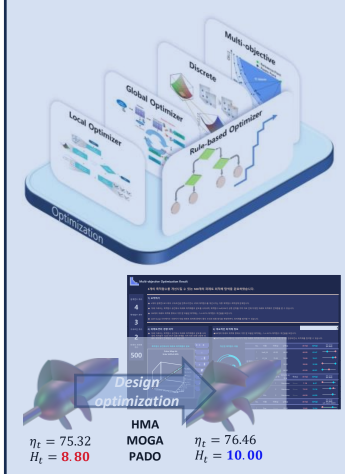
Filters less important parameters
Suggests the parameter ranges

Autonomous
Metamodeling



Sequential sampling by AI
Competitive modeling

Rule-based
Optimizer

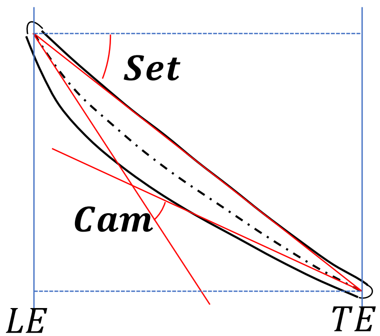


Select optimizer by determined optimization problem

Problem definition

Parametrization

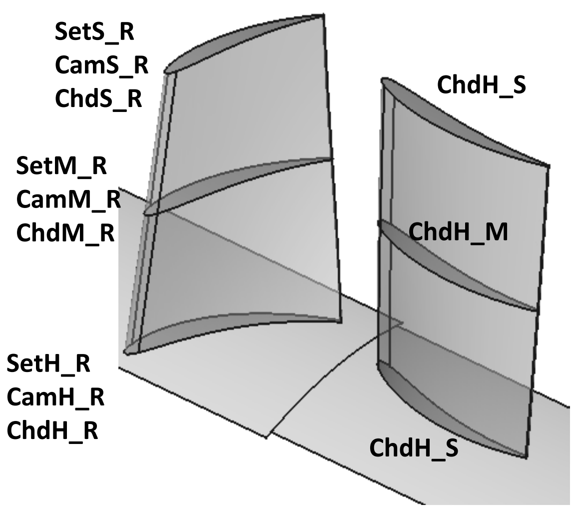
- For design optimization, the shape of impeller is parametrized, 12 design variables acquired by parametrized CAD
- To get global optima with less execution of CAE, global optimizer using metamodel is selected



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

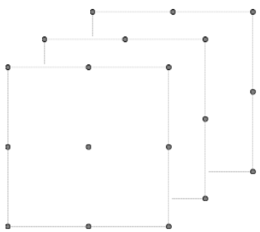
Range of design variables

$* \; ChdM\_R_{real} = ChdH\_R * (1 - ChdM\_R) + ChdS\_R * ChdM\_R$

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



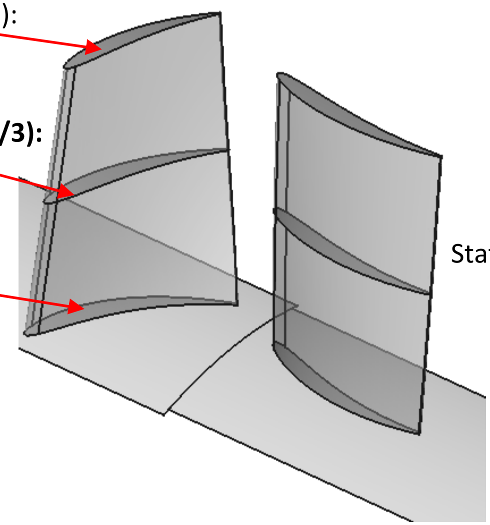
DOE: 3Lv Orthogonal array
$L_{36}(3^{13})$

스크리닝 요약

스크리닝 옵션:
사용자 지정 (40%)

설계변수 중요도 순위	변수명	선택 이유	설계자유도 누적합: Pwr	설계자유도 누적합: Pt	설계자유도 누적합: Efft	설계자유도 누적합의 평균값	
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) 설계변수가 커질수록 성능값 증가 설계변수가 커질수록 성능값 감소		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
	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				
성능	Pwr	12.9%	100.0%	37.9%	3.7%	19.7%	8.6%	2.4%	9.9%	11.5%	-2.1%	-1.5%	-2.7%
	Pt	12.2%	100.0%	37.9%	3.4%	19.3%	8.2%	1.6%	8.9%	10.6%	-2.1%	-2.4%	-3.1%
	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

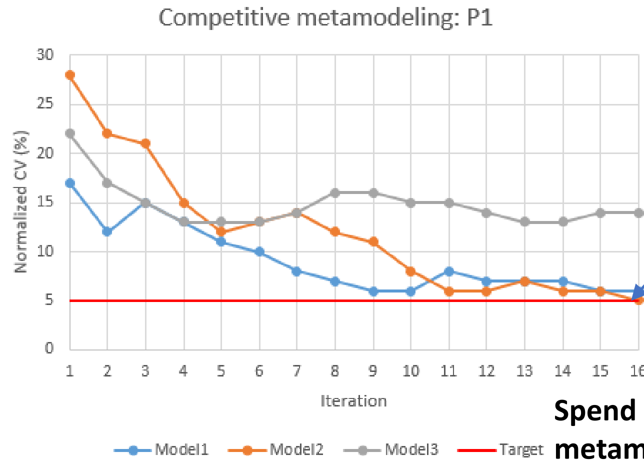
Variables	Nominal
CamH_R	31.00
CamM_S	19.61
ChdH_R	290.00
ChdS_R	239.50
ChdH_S	270.00
ChdM_S	270.00
ChdS_S	270.00

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



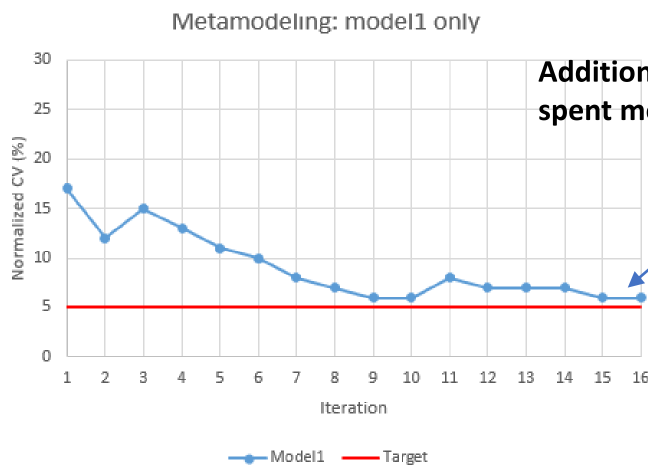
Model 2 Converged

Spend some time on metamodeling

Faster than traditional metamodeling!

To get metamodel of..

P1=f(x1,x2)
f is unknown



Additional CAE analysis: spent more time..

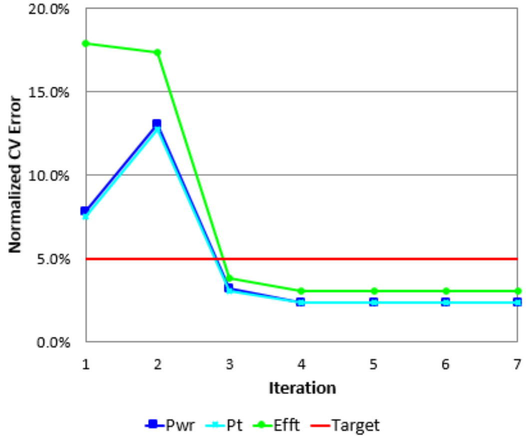
Model 1 not converged

Metamodeling

Result

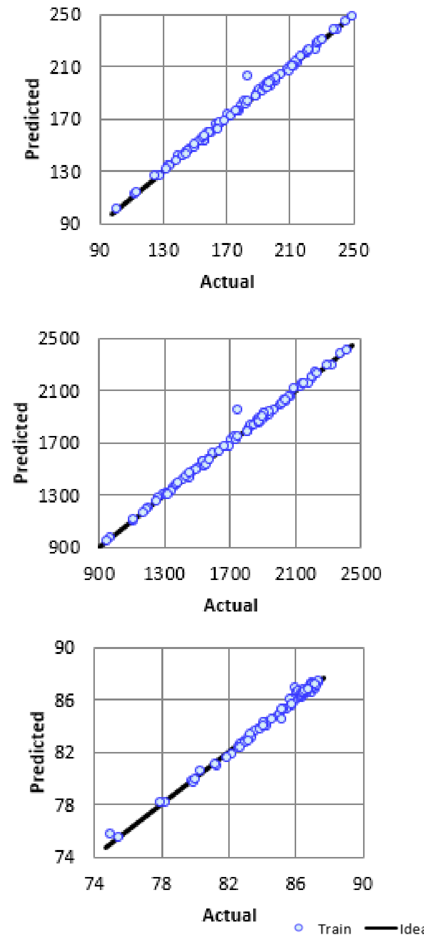
- Normalized CV error converged normally on 7th iterations, **Polynomial regression** is selected for all performances
- Metamodels can predict the tendencies with predicted vs actual chart

Normalized CVe of best metamodel

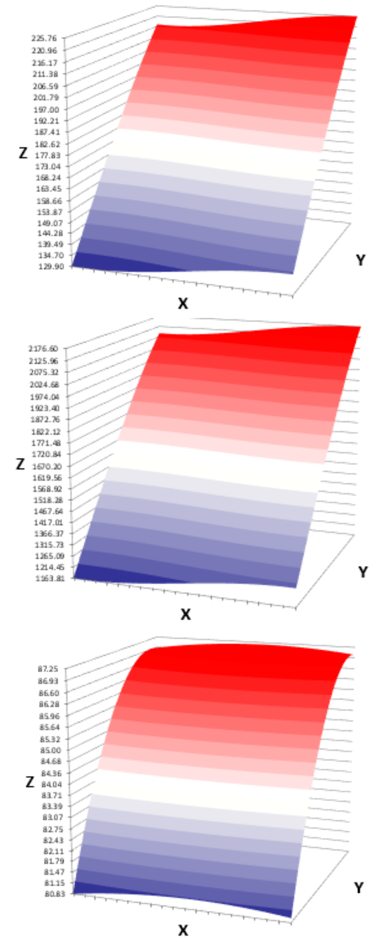


Normalized CVe on final iteration (unit: %)

	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



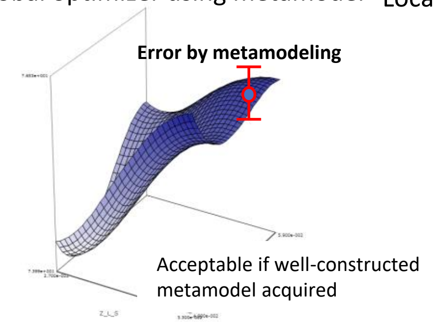
Response surfaces of generated metamodels

Design optimization

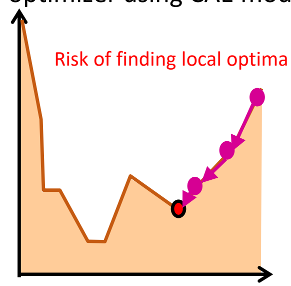
Pareto optimization: NSGA-II

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

Global optimizer using metamodel

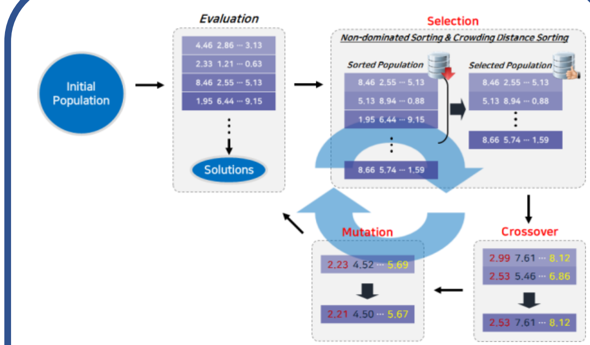


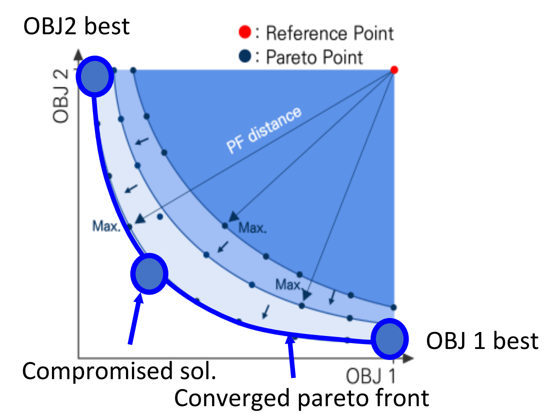
Local optimizer using CAE model



	Global + MM	Local + CAE
CAE cases (Estimated)	68 (36 for screening, 32 for MM)	>137 (for optimizer, 0.75*(n+1)(n+2))
Error Lv. (from global optima)	Metamodel error	Unknown
Optimum	Global	Local
Analyze tendency	O	X
Re-use acquired data	O	X

Analysis time: metamodel based vs CFD based





Process: multi-objective design optimization, NSGA--II

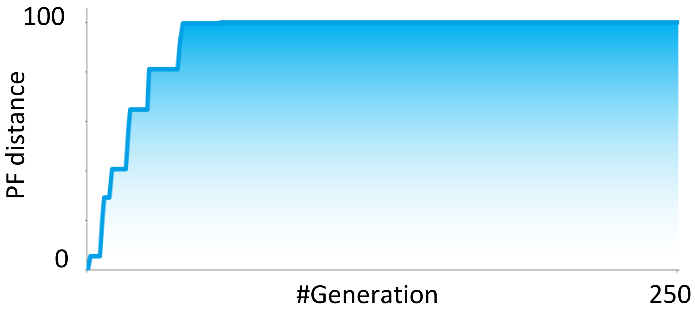
Design optimization

Overall results

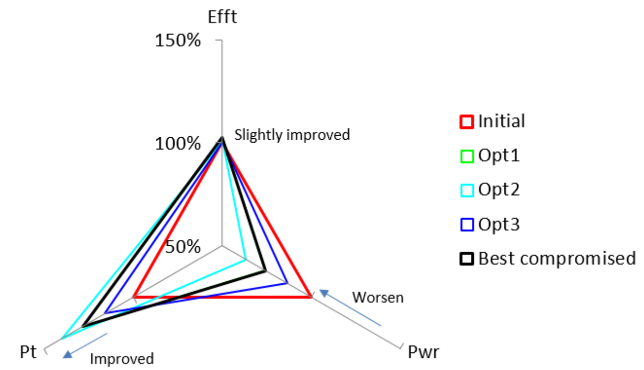
- Design optimization is successfully finished, **Pwr is worsened** on whole pareto sets **for satisfy constraints**
- Compromised solution has similar tendencies to the ideal solution of Efft

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

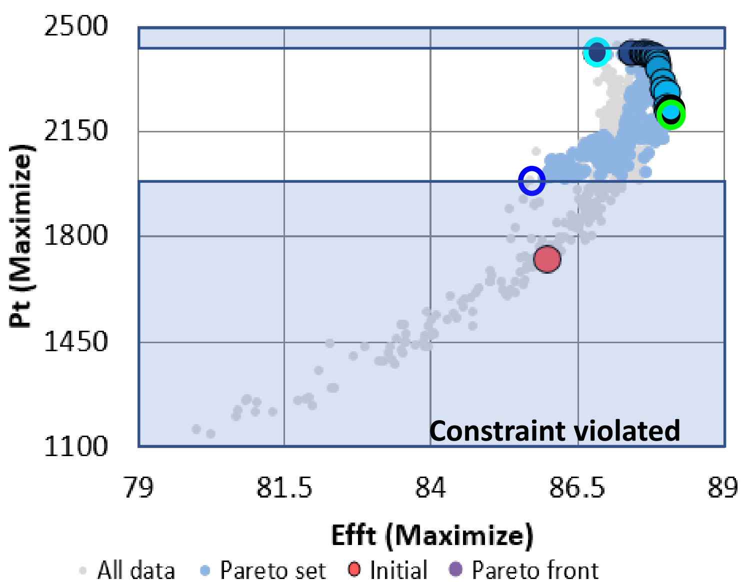
Convergence of MOGA



Improvement of objectives (larger: improved)



Pareto front: Efft vs Pt



Design variables and performances: Initial-optimum

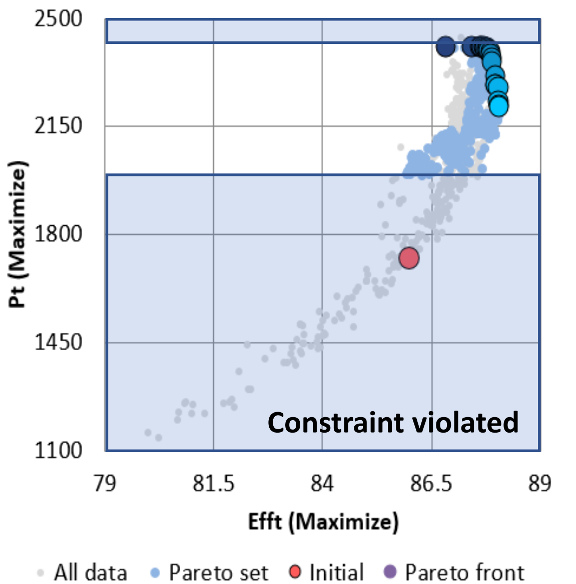
	Initial	Eff (Opt1)	Pt (Opt2)	Pwr (Opt3)	Compro-mised
SetH_R	41.26	42.92	44.09	38.50	42.89
SetM_R	27.68	29.08	30.35	30.32	29.09
SetS_R	23.16	26.16	25.73	20.25	26.16
CamM_R	15.09	14.24	18.05	18.05	14.20
ChdM_R	0.50	1.00	0.77	0.60	1.00
Eff	86.00	88.05	86.85	86.27	88.05
Pwr	180.94	227.61	247.41	205.41	227.58
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

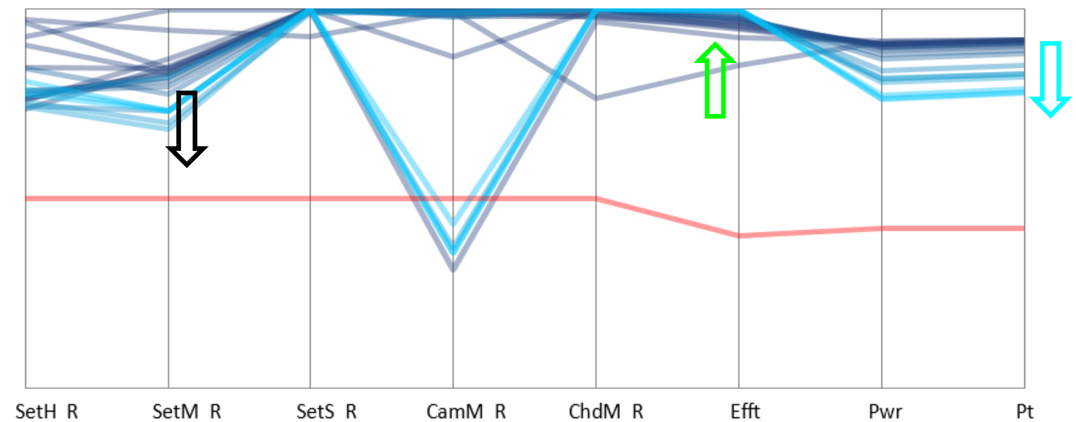
Pareto fronts: Efft vs Pt

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

Pareto front

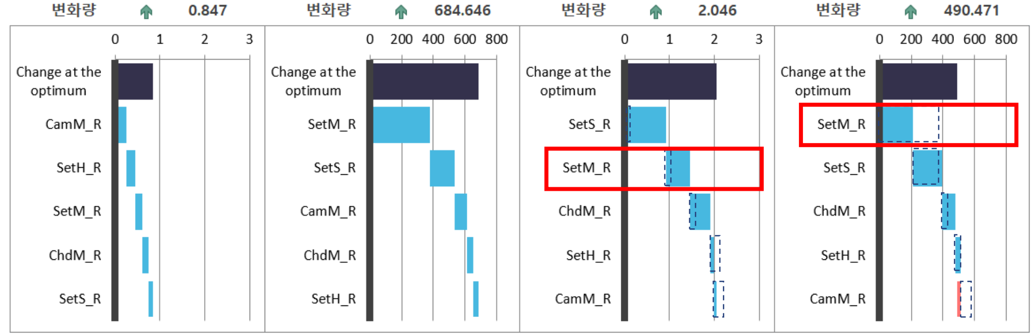


Parallel plot



Contribution analysis

Opt2				Opt1			
Efft Improved (Maximize)		Pt Improved (Maximize)		Efft Improved (Maximize)		Pt 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

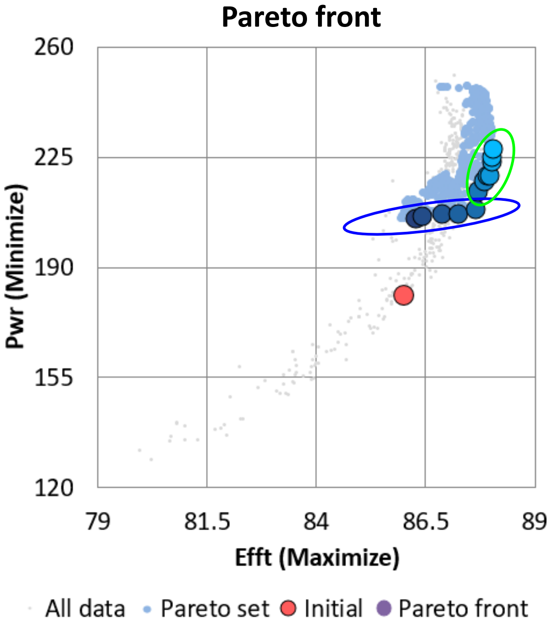


Dotted: OPT#1 data

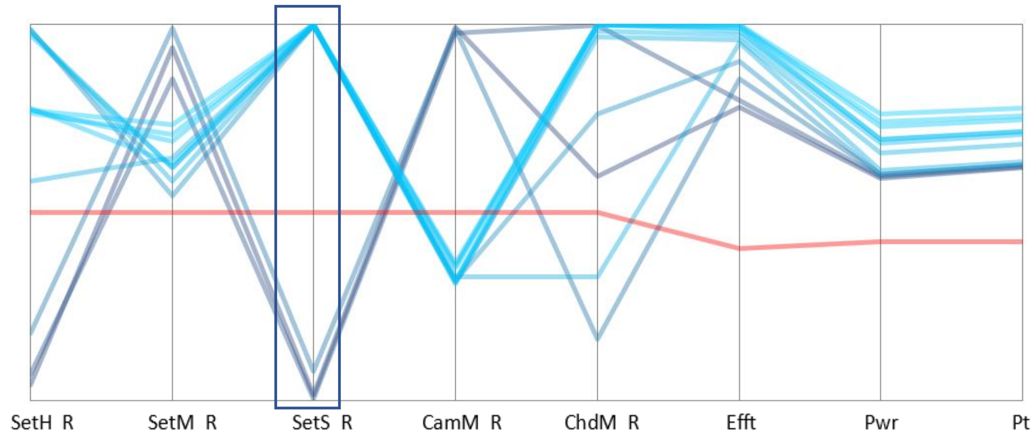
Design optimization

Pareto fronts: Efft vs Pwr

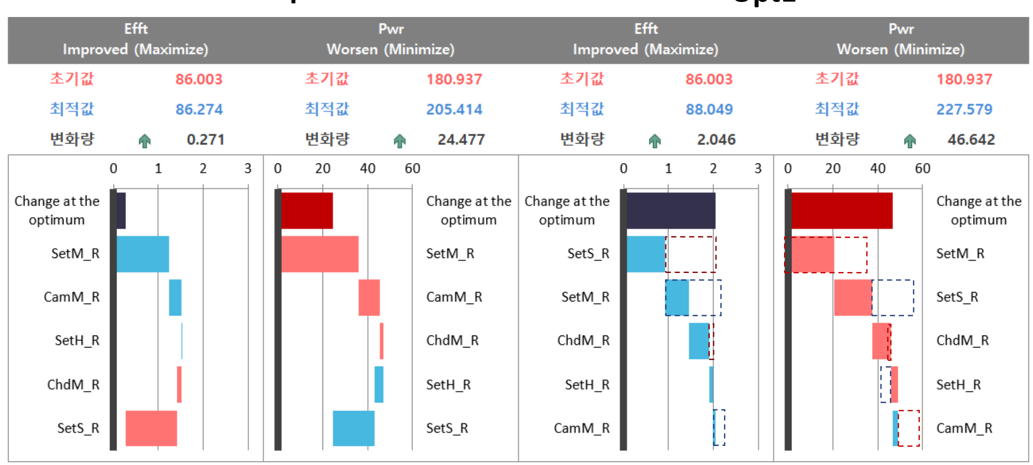
- Pareto front has two regions: less worsen Pwr(blue, max SetS_R) and improve Efft(green, min. SetS_R)
- The contribution of SetS_R has completely opposite between two optimum



Parallel plot



Contribution analysis



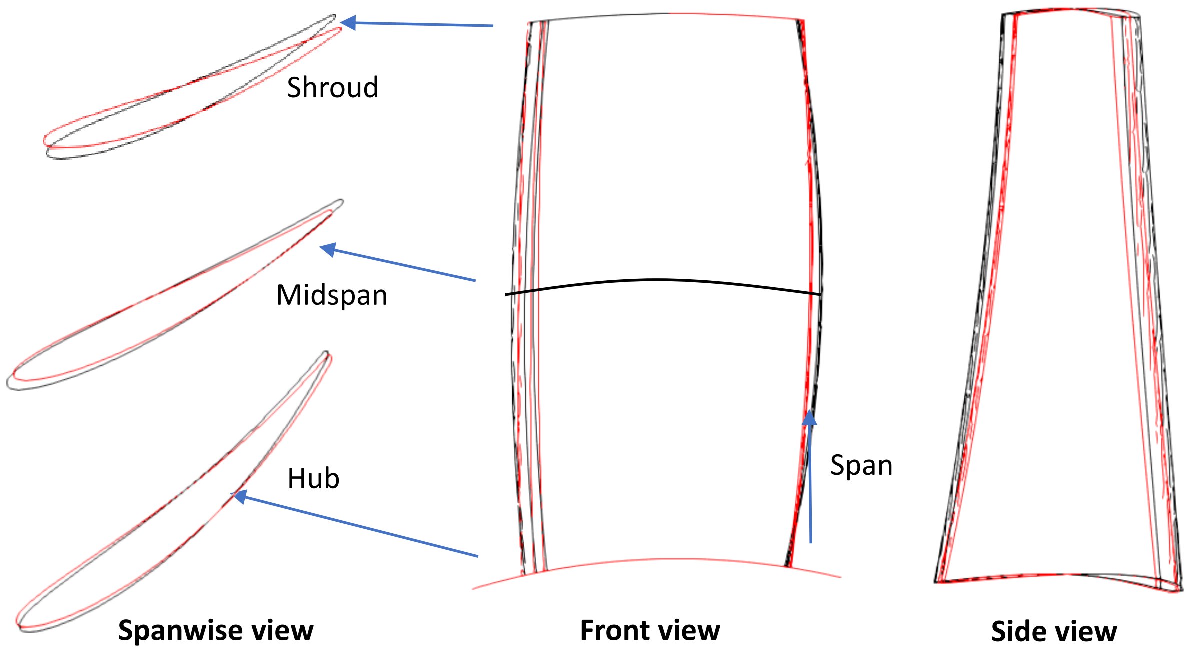
Dotted: OPT#3 data

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

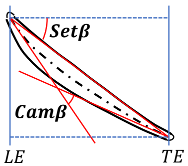
	Initial	Compro-mised
SetH_R	41.26	42.89
SetM_R	27.68	29.09
SetS_R	23.16	26.16
CamM_R	15.09	14.20
ChdM_R	0.50	1.00
Eff	86.00	**88.05**
Pwr	180.94	**227.58**
Pt	1,722.55	**2,212.58**



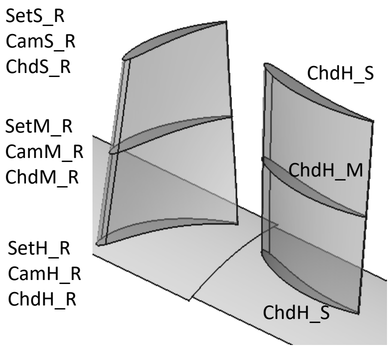
Summary: Optimization

Problem definition

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



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

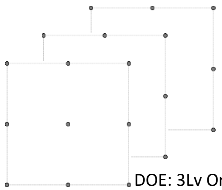


No. of design variables: 12
No. of objectives: 3
No. of constraints: 1

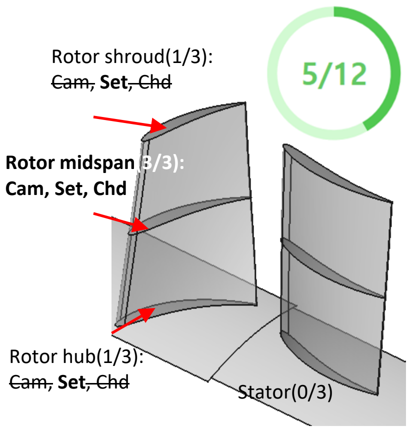
Multiobjective optimization
MOGA

Well balanced screening

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

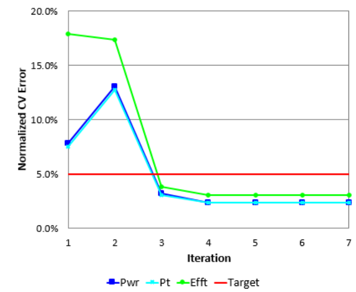


DOE: 3Lv Orthogonal array
$L_{36}(3^{13})$

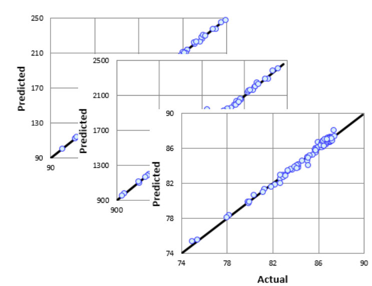


Metamodeling

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



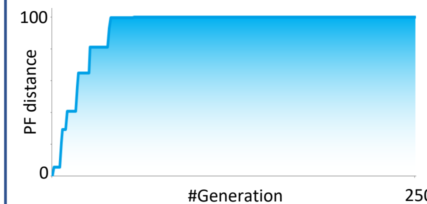
Normalized CVe on final iteration (unit: %)

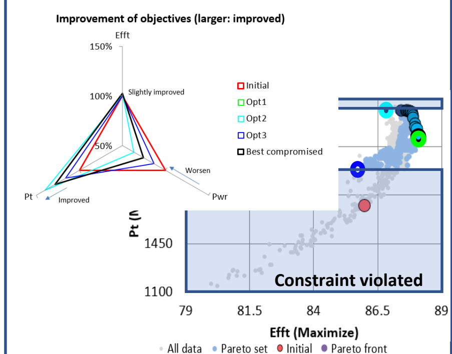


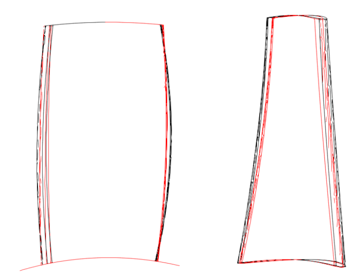
Predicted by actual

Pareto optimization

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







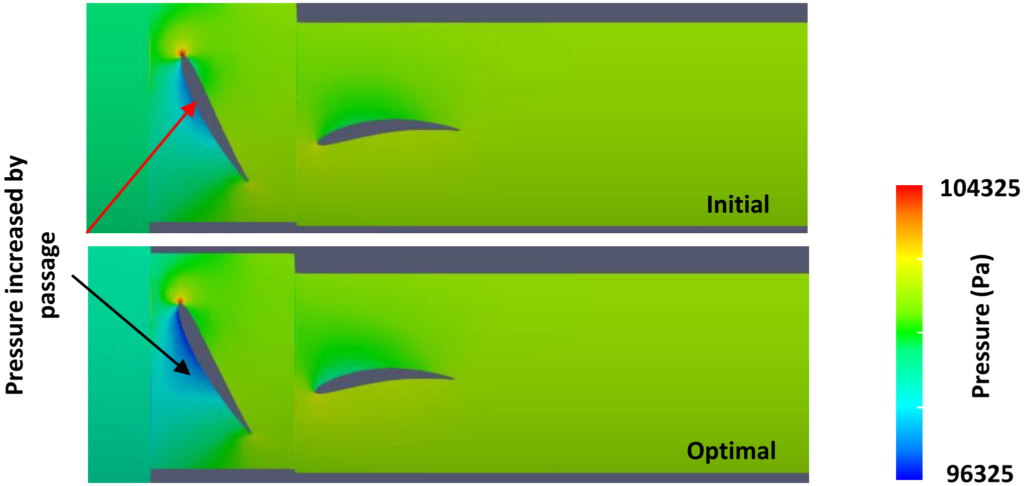
04

Validation

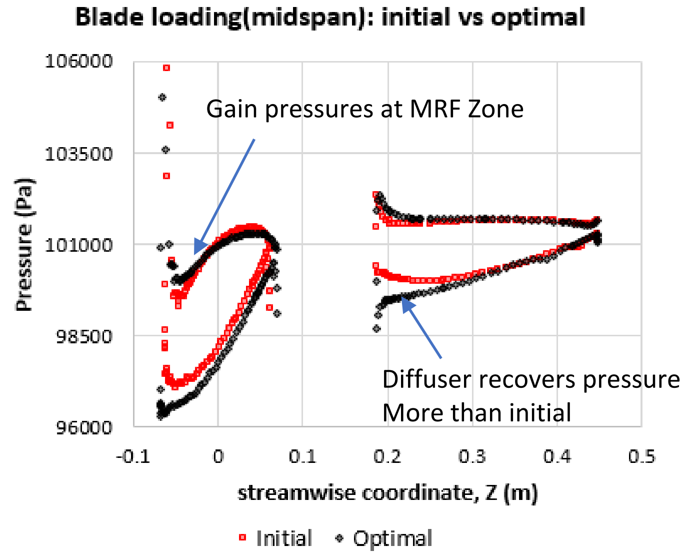
Shape & Performance comparison: Initial vs Optimal

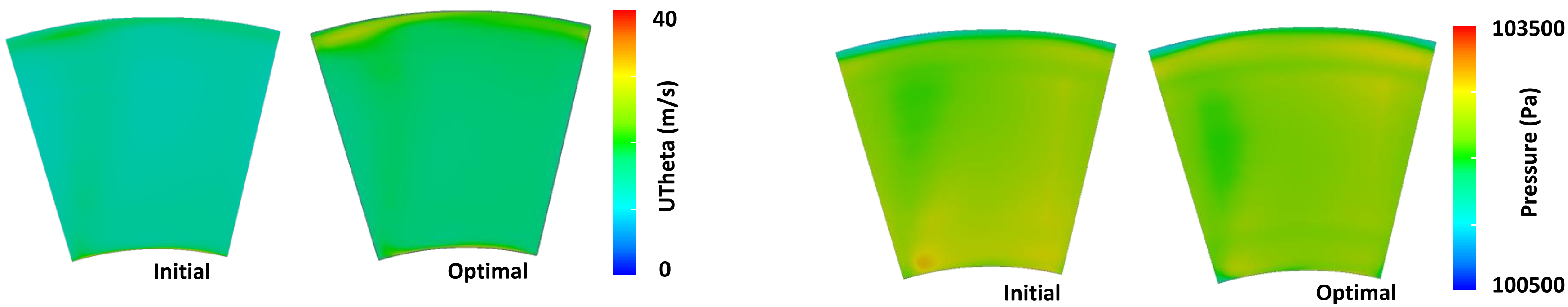
Comparing flow contours

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



Pressure contour on midspan





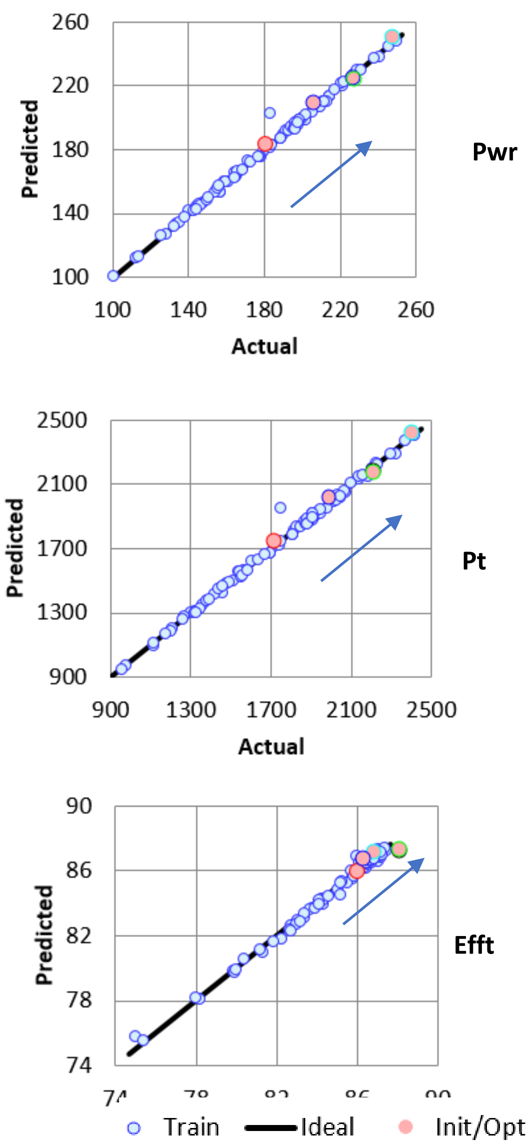
Distribution of mixing plane(rotor outlet)

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