Erasmus Mundus Double Degree Master's in Advanced Mechanical Engineering Specialization in Marine & Offshore Hydrodynamics

Speeding-Up Simulation-Driven Designs for High-Speed Planing Boat

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MSc Naval Architecture and Offshore Engineering

Specialized in Hydrodynamics and Optimization

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Today's Agenda

- Problem Statement
  - Introduction to Planing Vessels
  - Model Principal Dimensions
- Parametric Modeling
  - Geometrical Features of the Model
  - Design Variables and Objective Function
- Mesh Discretization
- Numerical Modeling and Validation
- Optimization Studies
  - Design of Experiment and Exploitation
  - Data-Driven Optimization Methods
  - Response Surface Optimization

Let's Start the Boat!

Displacement Vs Planing Vessels

Displacement Vessels

https://www.passagemaker.com/cruiser-reviews/full-displacement

Works on Archimedes Principle

Froude Number < 0.1-0.7

Container Ships, Large Bulk Carrier,
Ferrys and Passenger Vessels

Planing Vessels

https://mboat.eu/planing-hull/

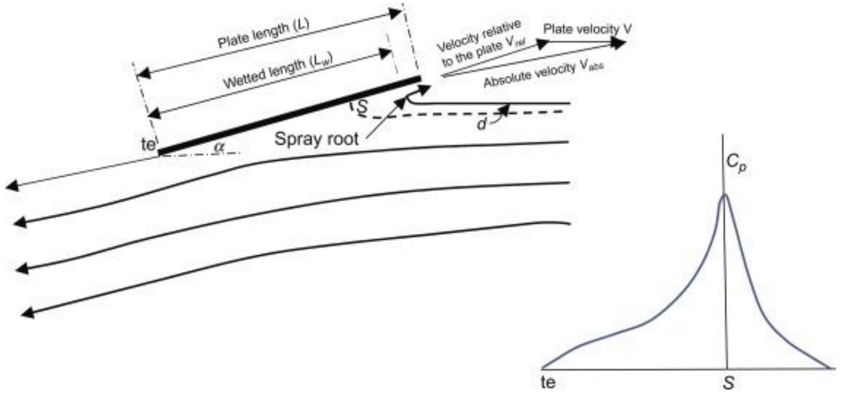
Works on Dynamic Lift Generation

Froude Number > 1 -1.2 (Volumetric / Beam)

Pilot Boats, Naval Ships, Police Boats,
Pleasure Crafts

Planing Vessels in real conditions

https://mboat.eu/planing-hull/



https://www.sciencedirect.com/topics/engineering/planing-hull

- Highly turbulent and Dynamic Fluid Structure Interaction Model with large DFBI Motions

Challenges to Simulate?

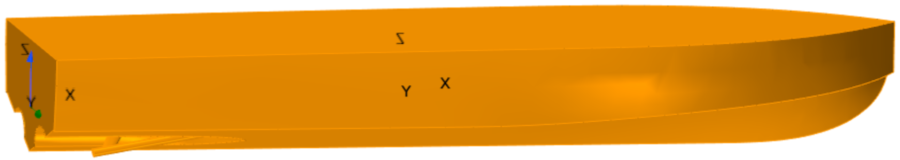
Very high computational time!!

- Stationary mesh strategy encounters distortion for large dynamic motions
- Proper care is required to capture the flow dynamics near the flow boundary between two phases to avoid possible Numerical Ventilation.
- Very fine discretization and special CFD Solvers requires for accurate predictions

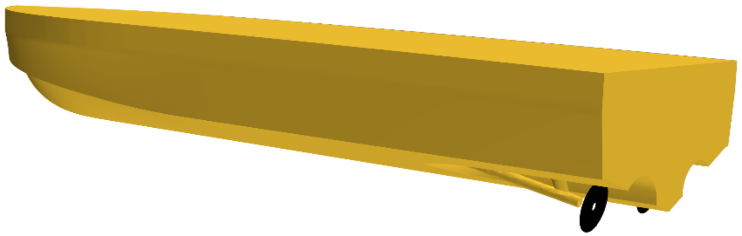
Principal Dimensions of the Vessel

	Full Scale	Model Scale	
Peak Length	11.058	3.364	m
Beam	3.500	1.065	m
Displacement	9.500	0.267	ton
Draft	0.611	0.186	m
LCG	4.945	1.504	m
VCG	0.700	0.213	m
Speed	27.500	15.168	Knots
Fr (Length)	1.358	1.358	
Attachment Point X	5.529	1.682	m
Attachment Point Z	0.611	0.186	m

- Scale = 3.2871
- Design Speed = 27.5 Knots for Full Scale
- Froude Number = 1.36



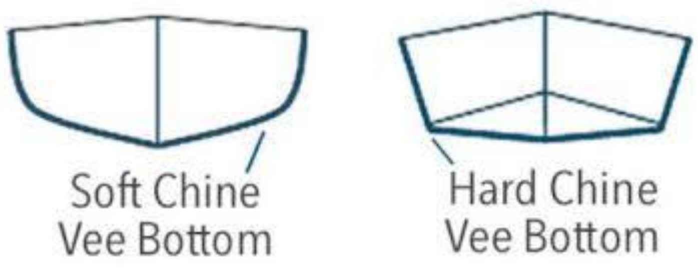
Geometry With Appendage



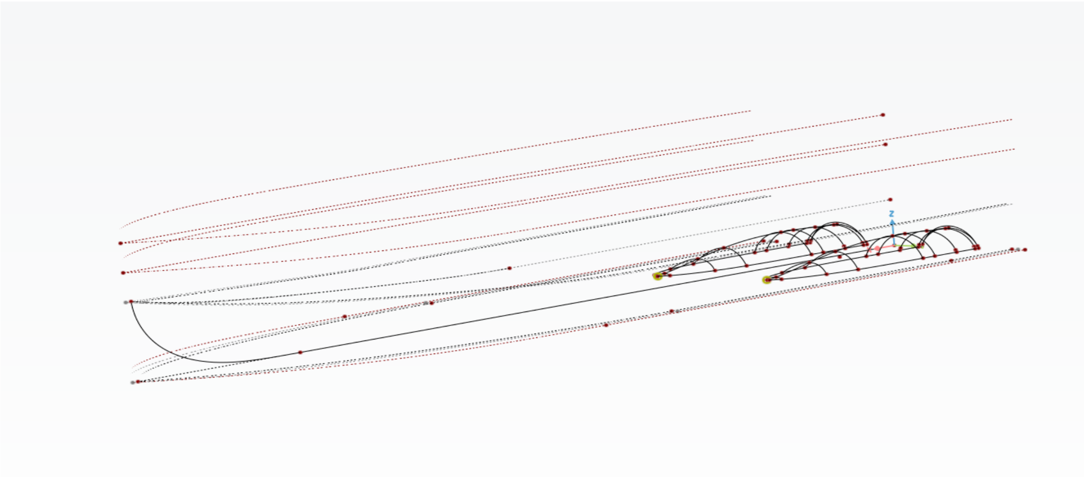
Geometry With Appendage and Propeller Disk

Parametric Modeling: Geometrical Features

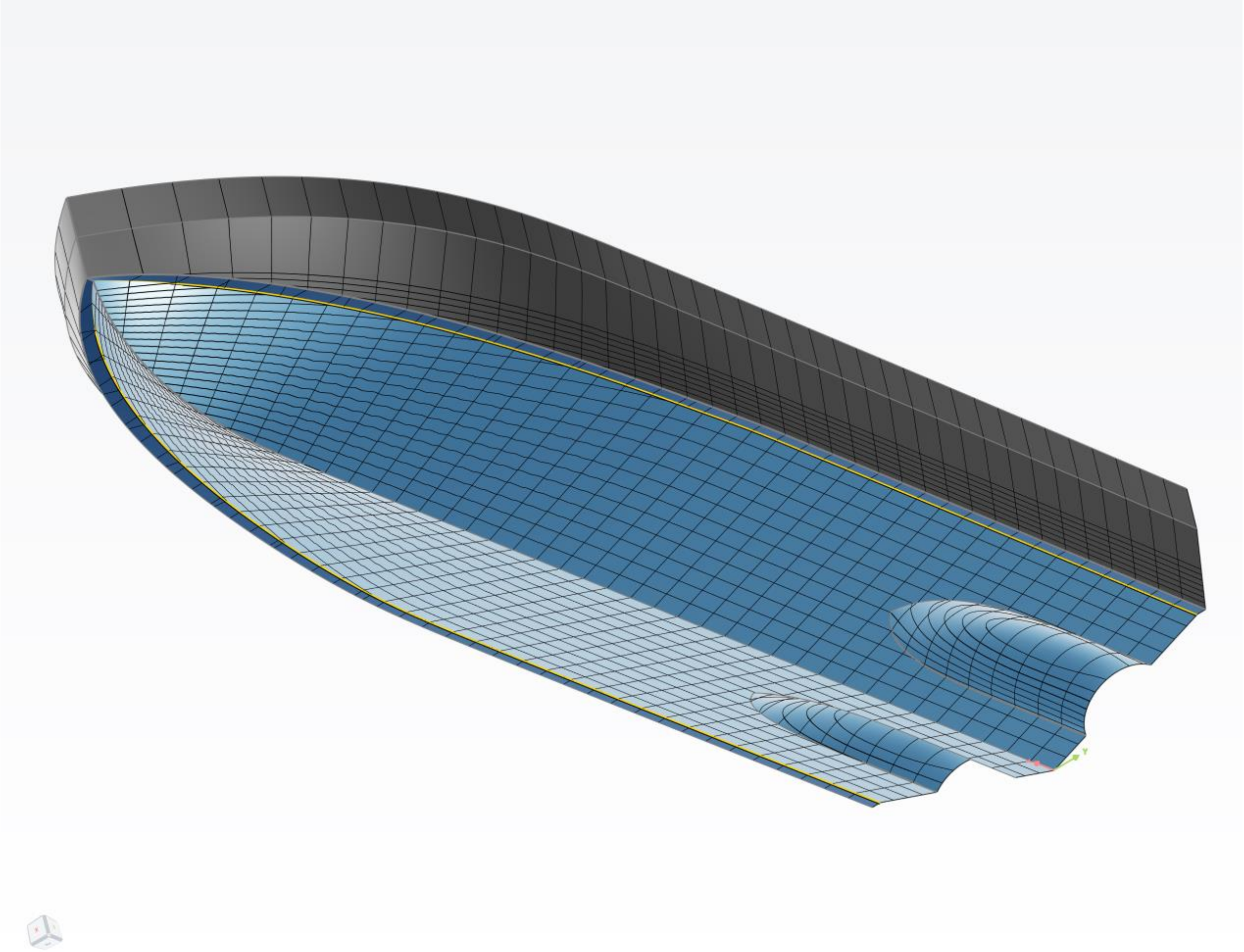
- Hard Chine vs Soft Chine



http://kth.diva-portal.org/smash/get/diva2:1527828/FULLTEXT01.pdf



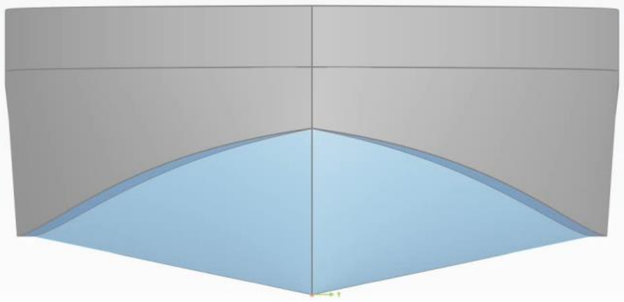
- Parametric Curves



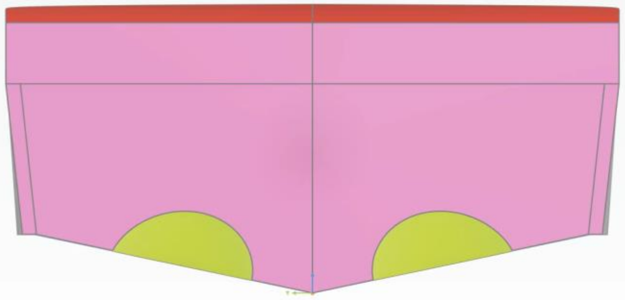
- Chine

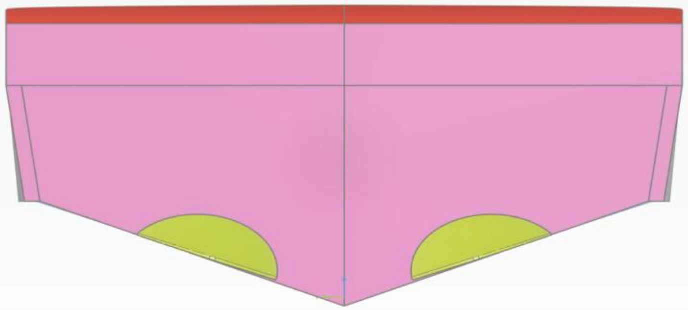
Parametric Modeling: Geometrical Features

- Deadrise Angle



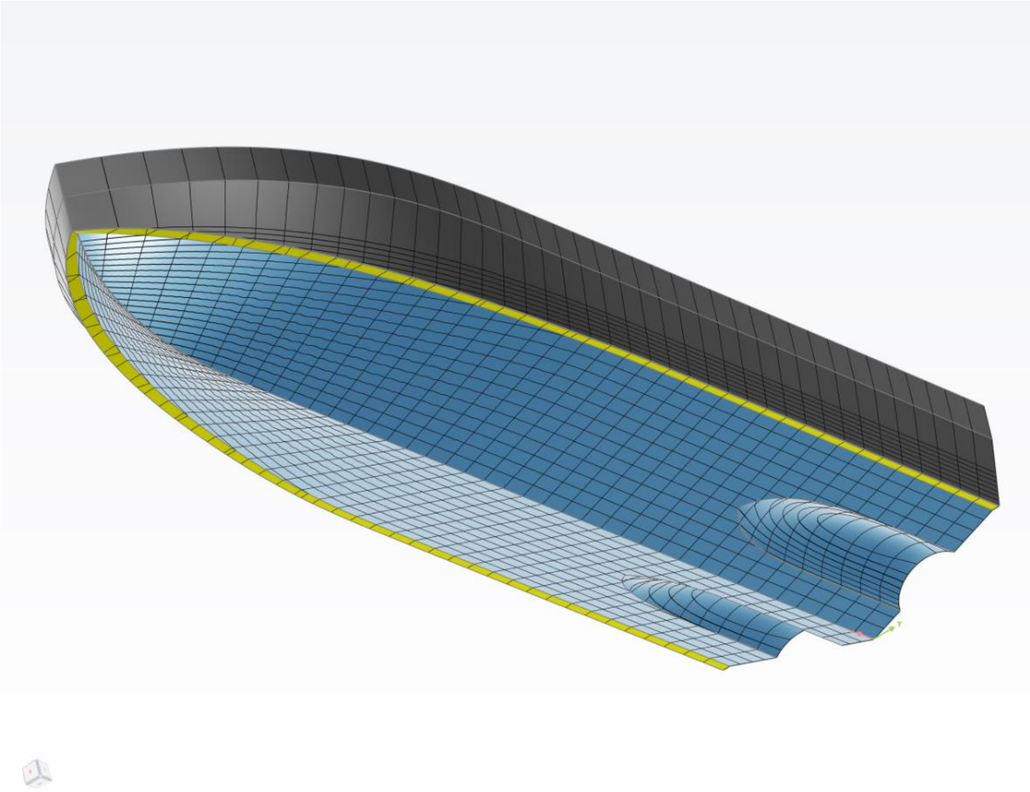
- Keel line Depth



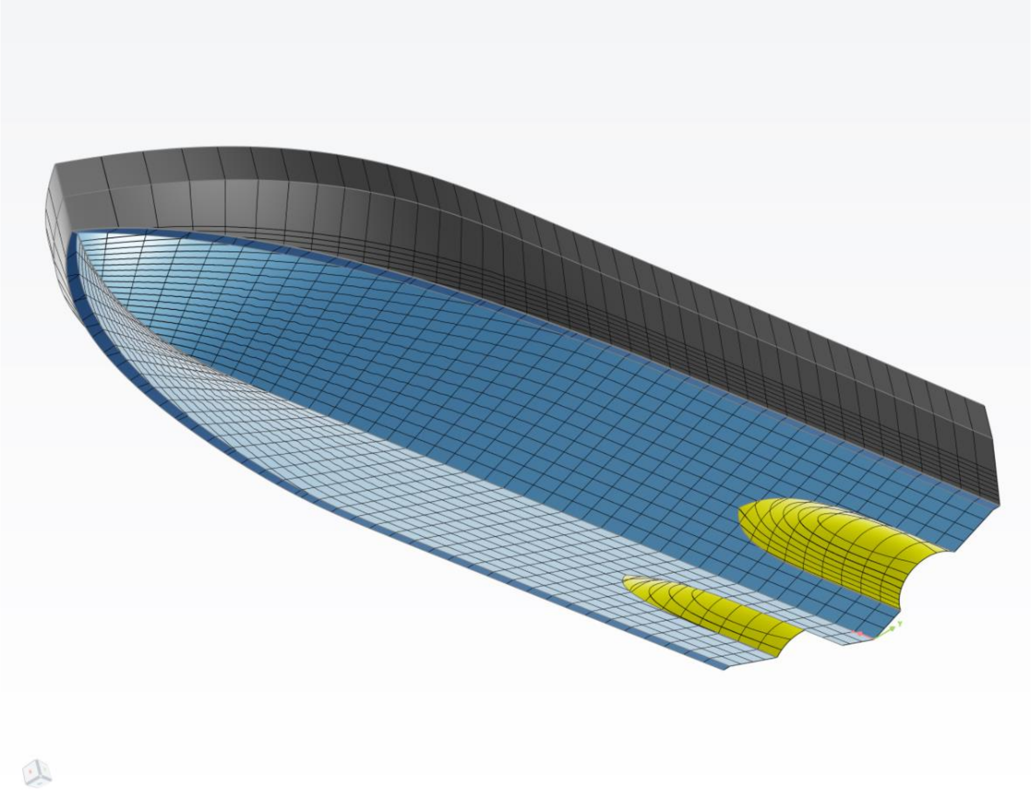


Parametric Modeling: Geometrical Features

- Spray Rails



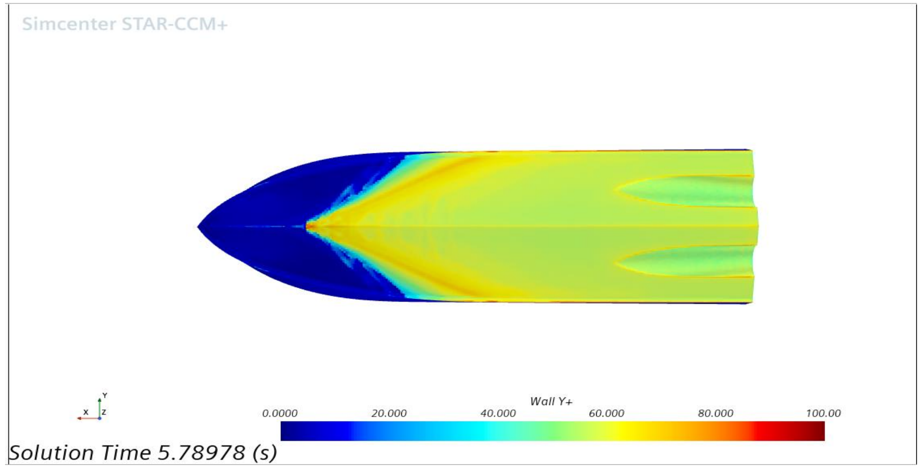
- Tunnel

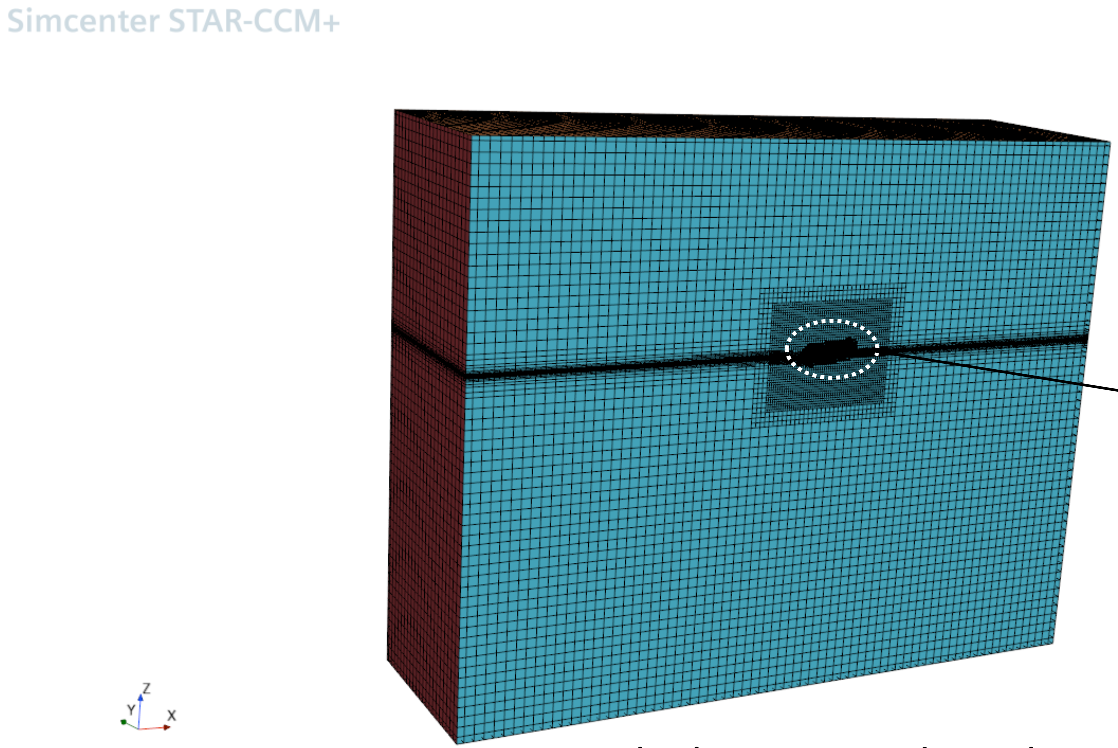


- Parametric Model with 18 design variables
  - 8 for Hull
  - 10 for tunnel

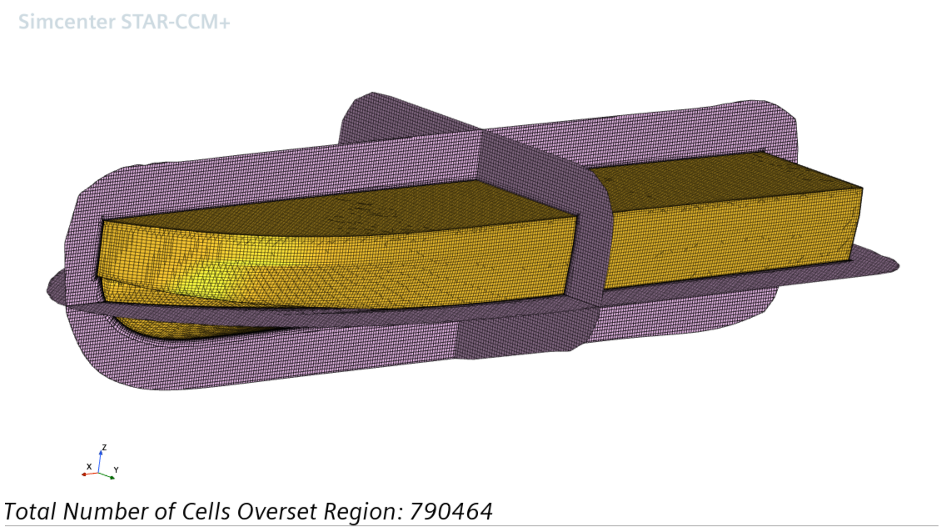
Numerical Modeling : Mesh Discretization

- Dynamic Overset Grid with Adaptive Mesh Refinement
- Symmetry along y axis
- AMR for overset grid as well as Free Surface
- Target Wall y+ of around 70, with wall functions



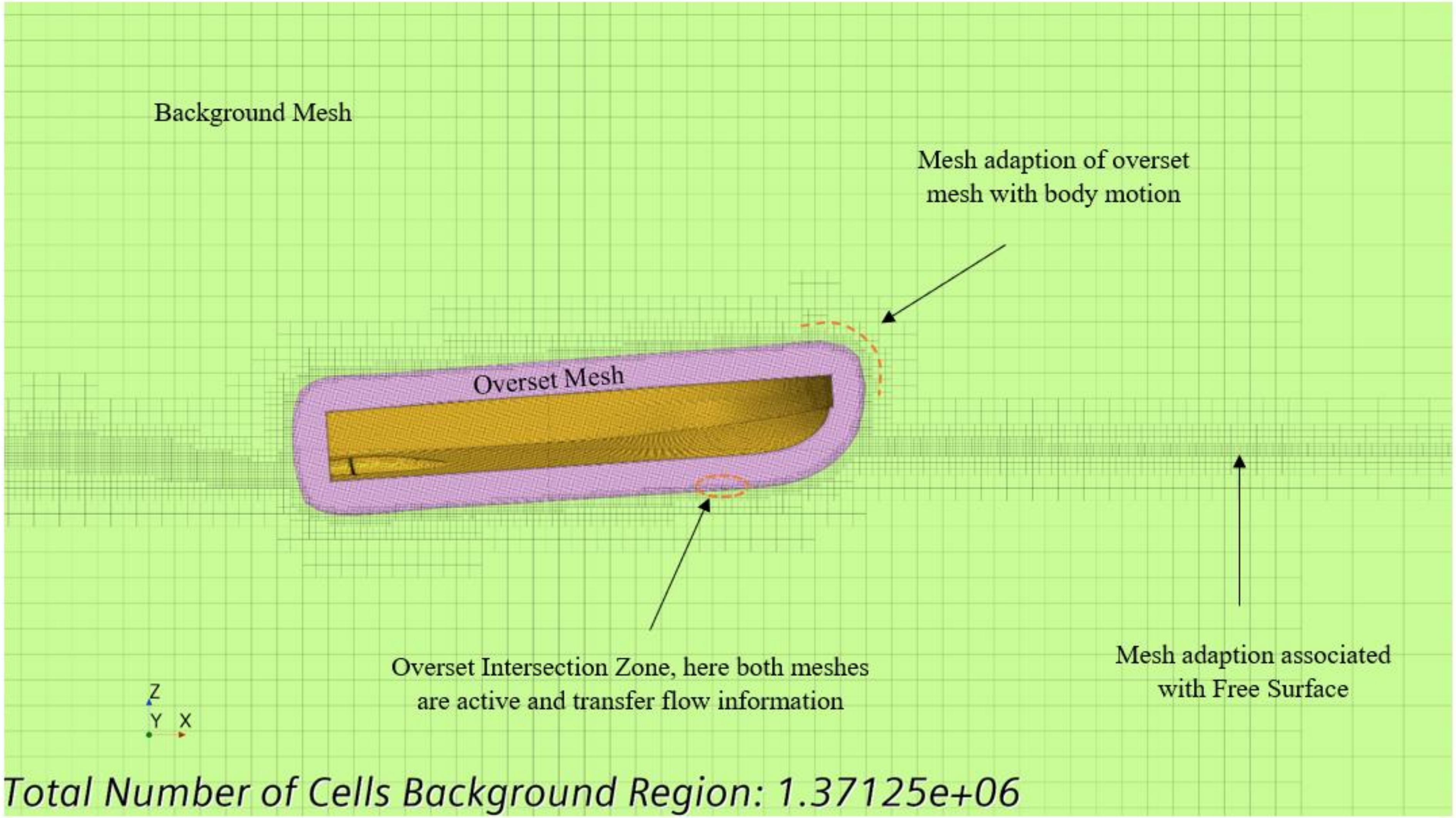


Block Structured Mesh



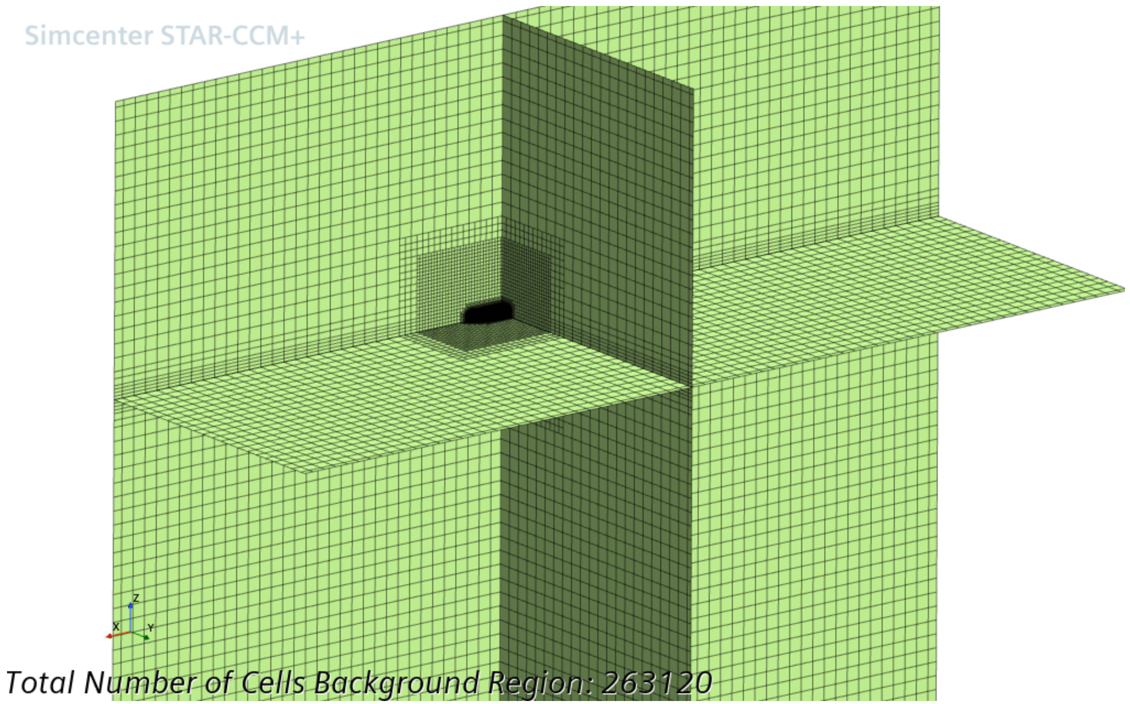
Overset Grid

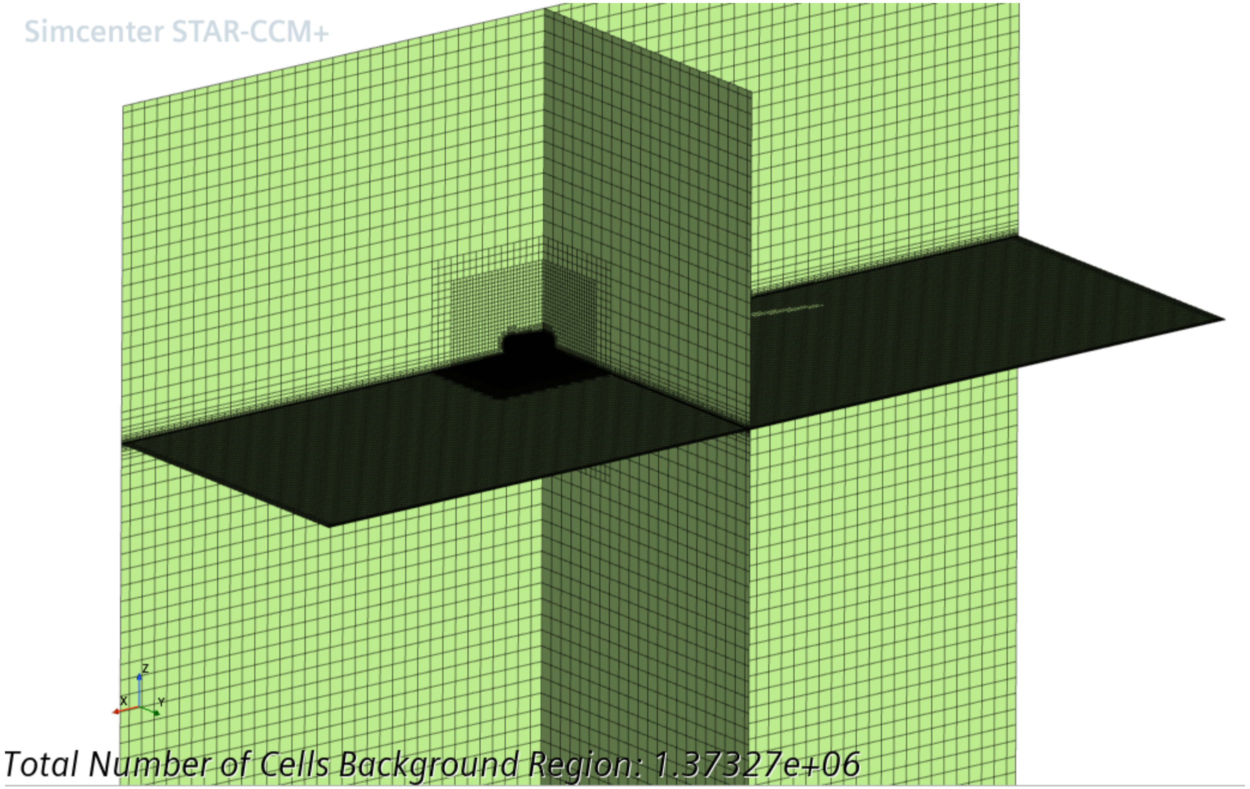
Numerical Modeling : Mesh Discretization



Numerical Modeling : Mesh Discretization

- Overall Tank and Overset Mesh, Initial Vs Final

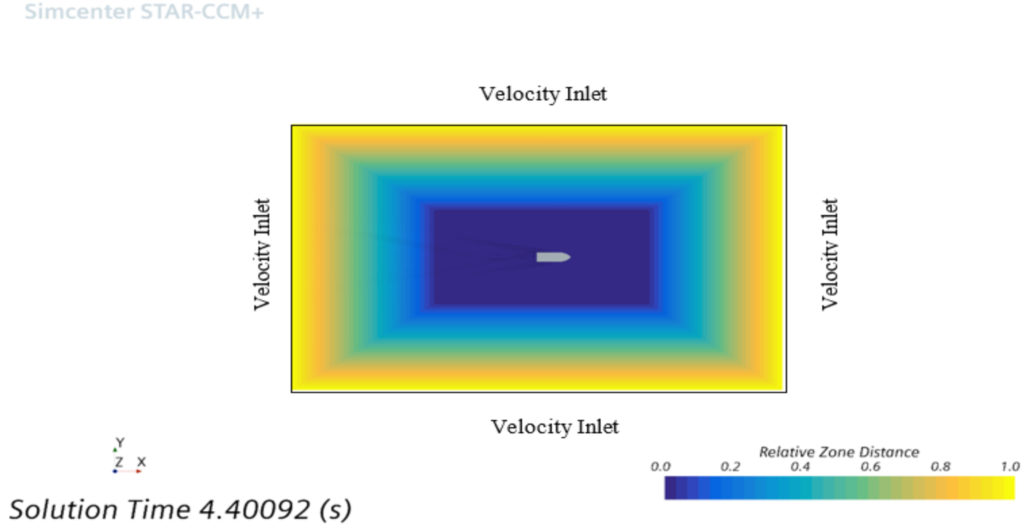


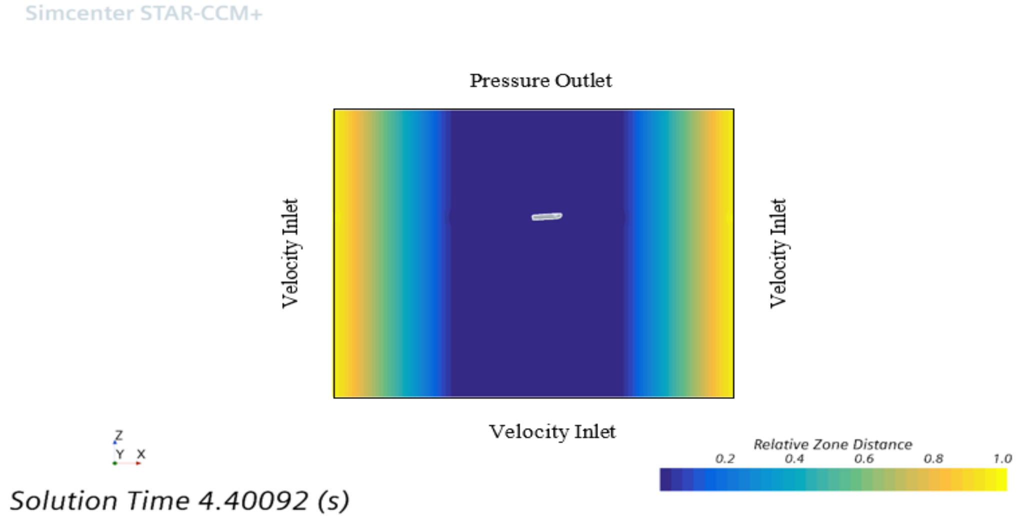


- Initial Background Mesh
- Final Background Mesh

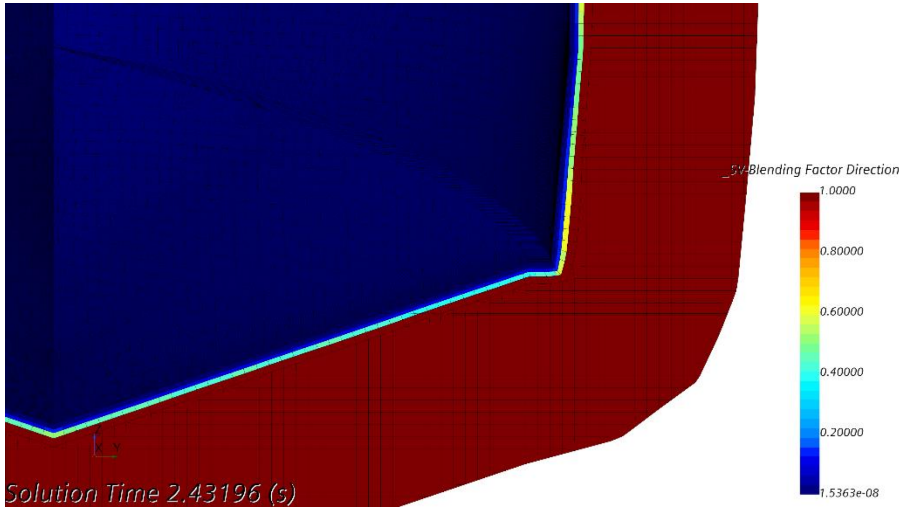
Numerical Modeling : Physical Setup

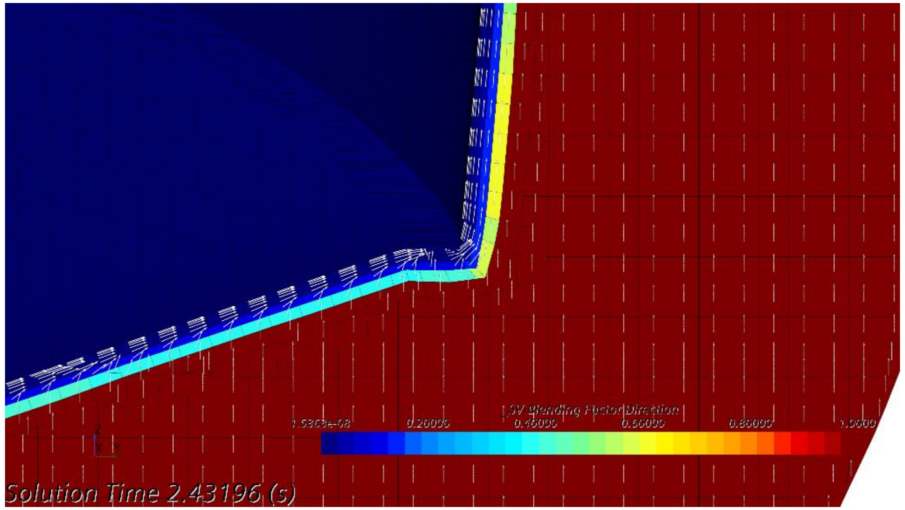
- Boundary Conditions and Forcing Zones



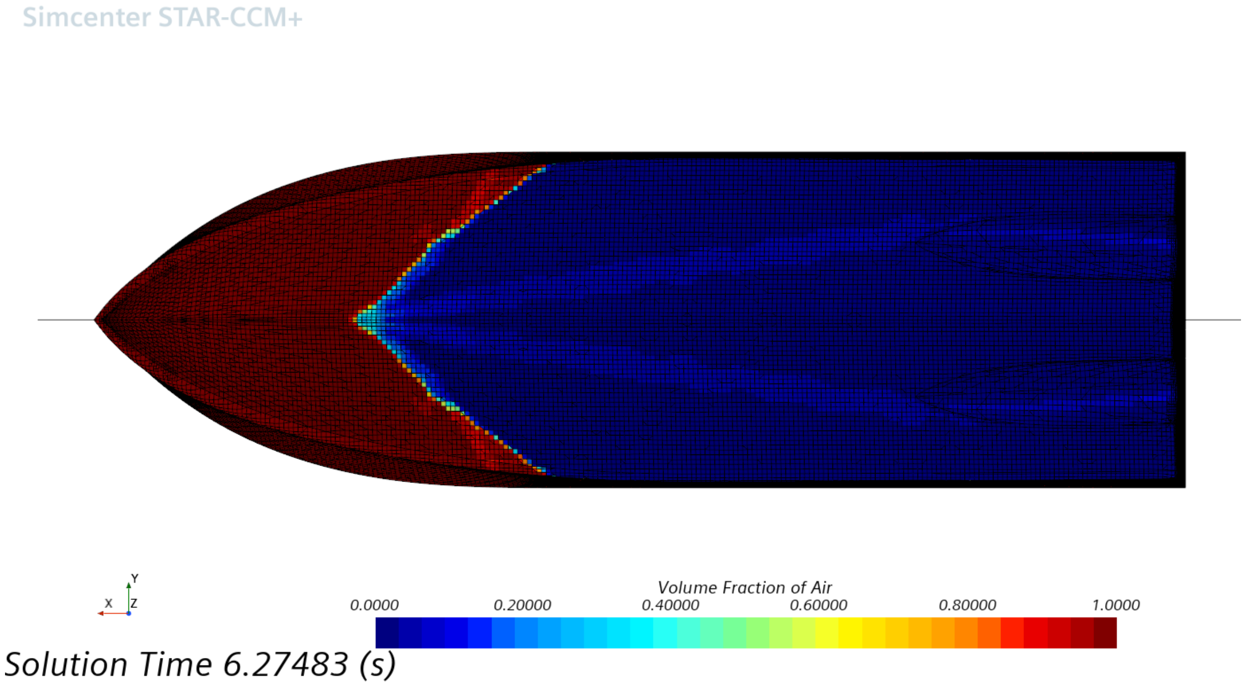


- VOF Slip Velocity Method, to avoid Numerical Ventilation



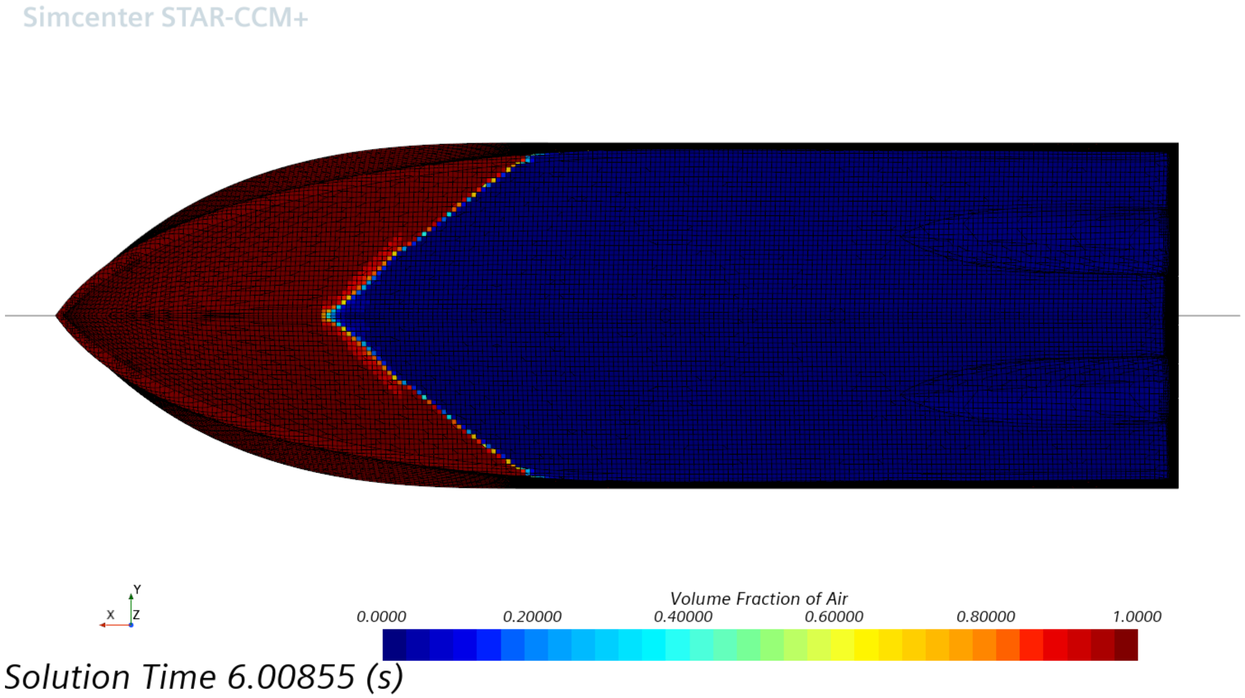


Numerical Modeling : Physical Setup

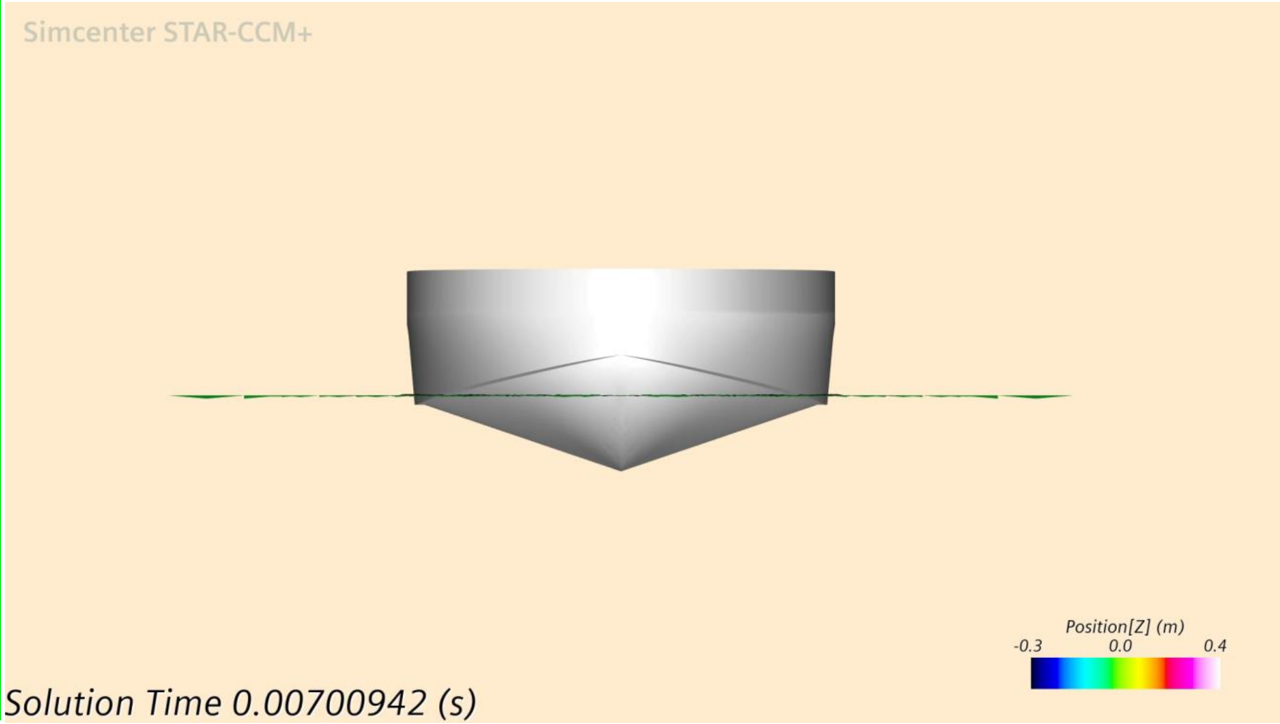


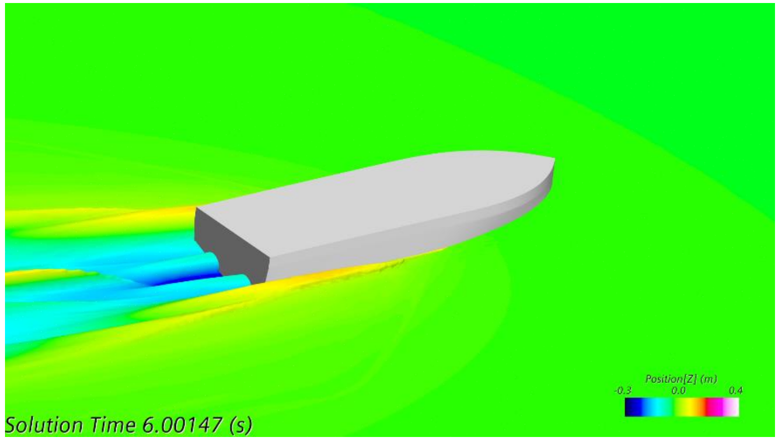
- Hull with Numerical Ventilation

- Hull without Numerical Ventilation

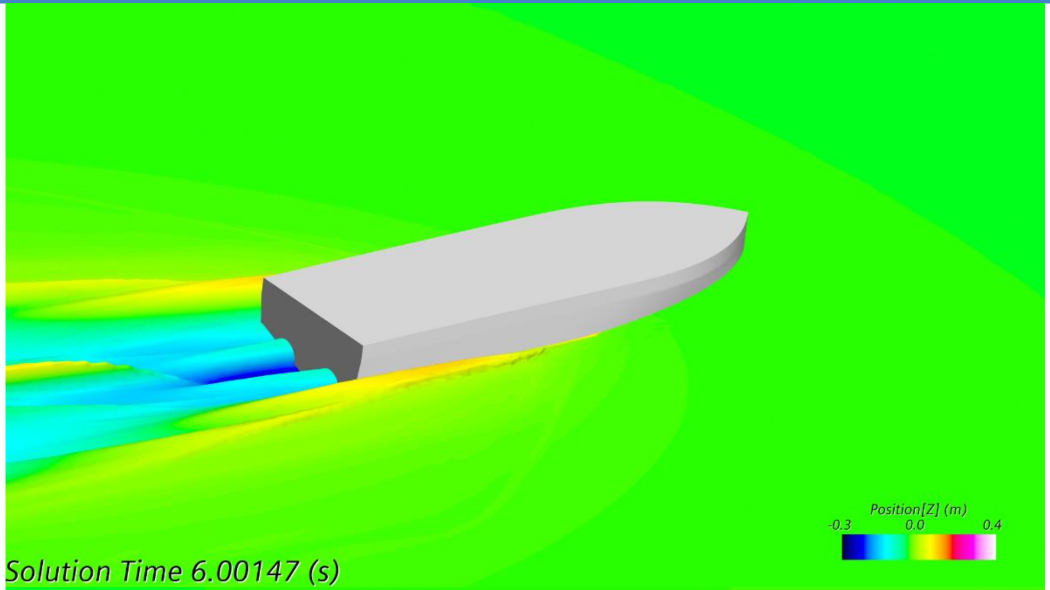


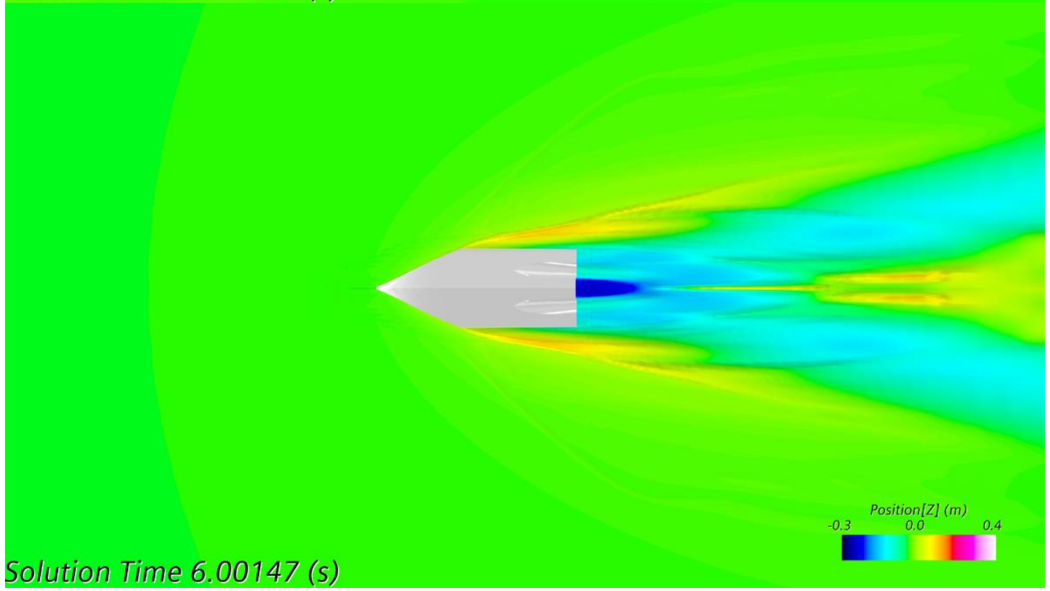
Simulation Results : Post Processing

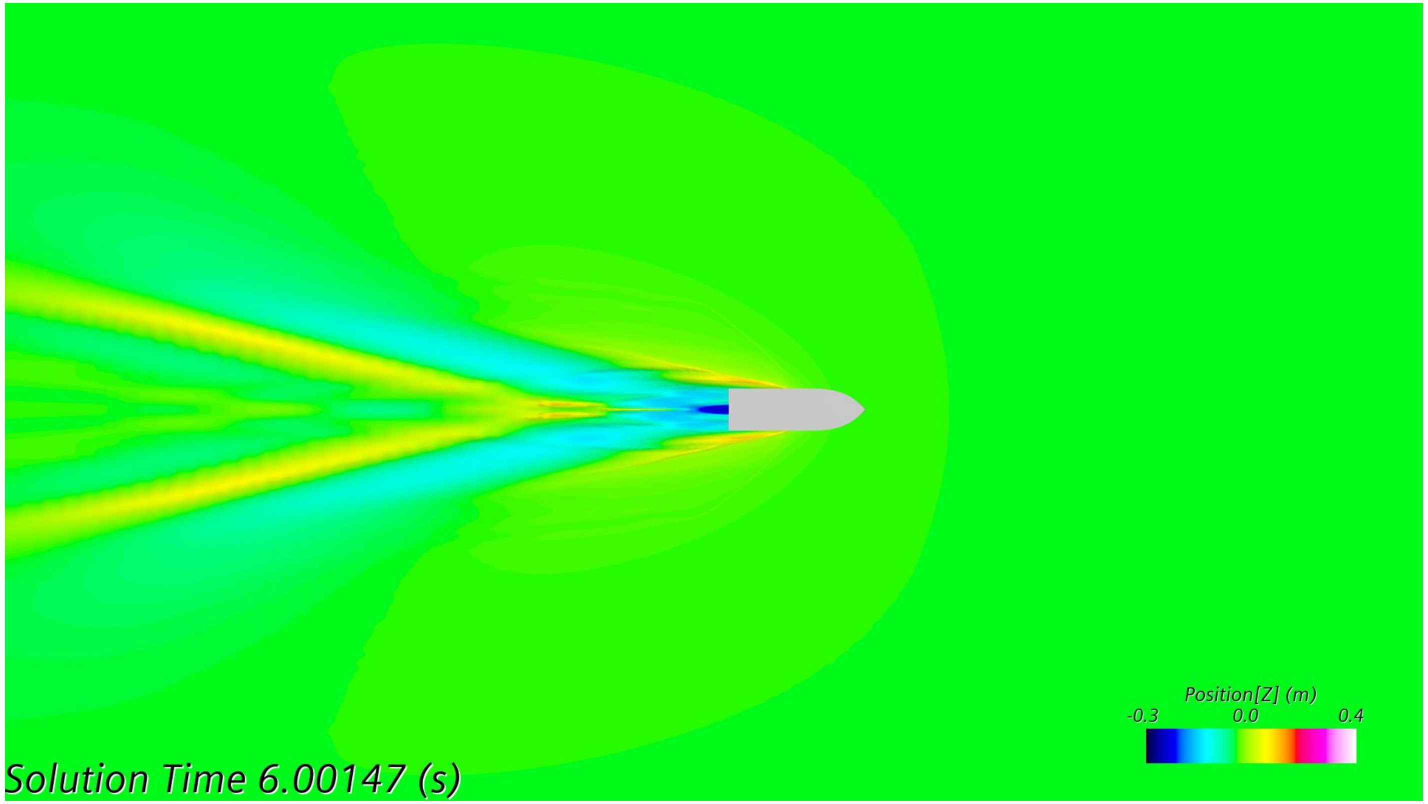




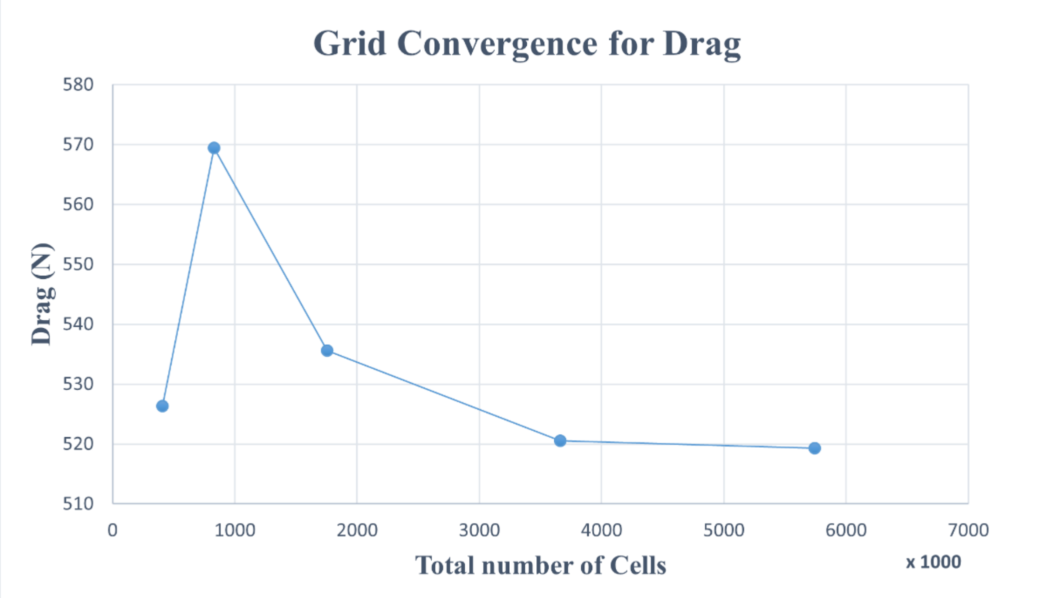
Simulation Results : Post Processing

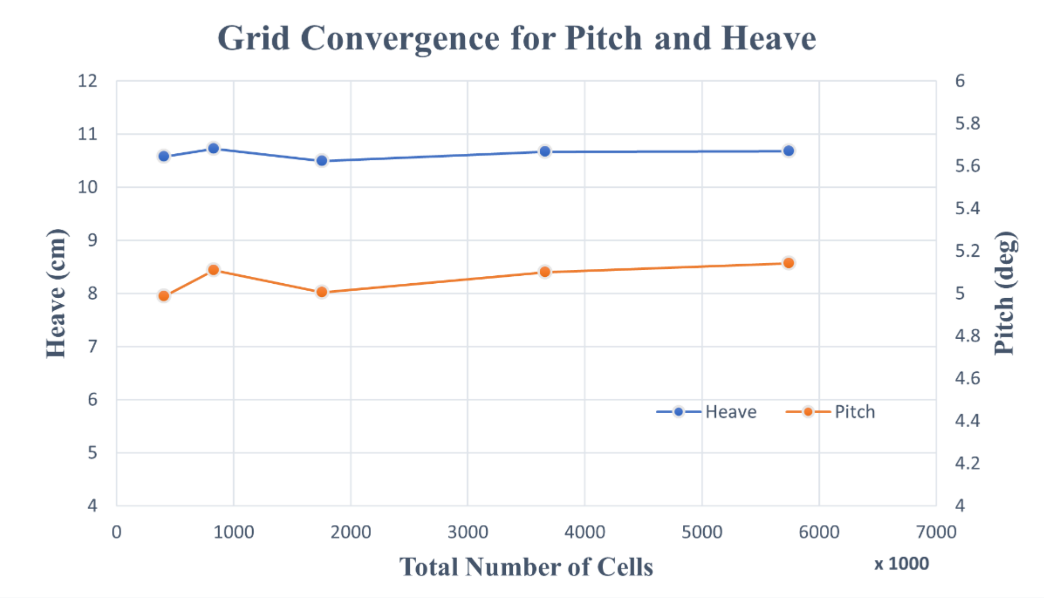




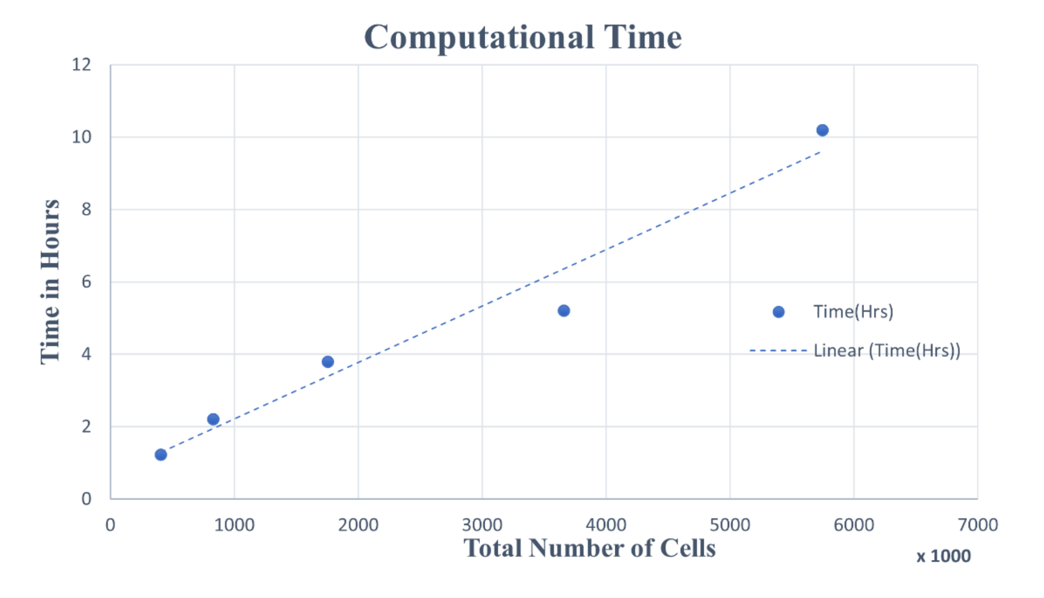


Verification : Grid Convergence Studies

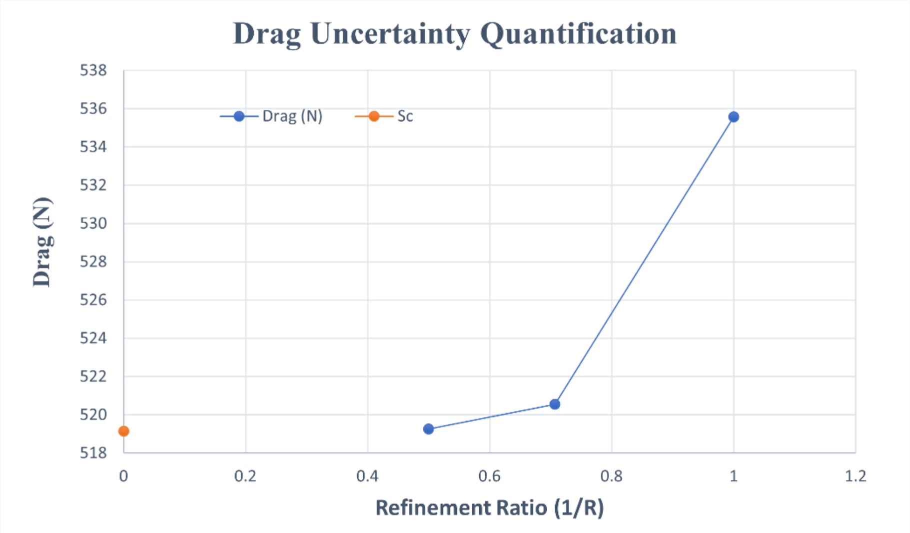


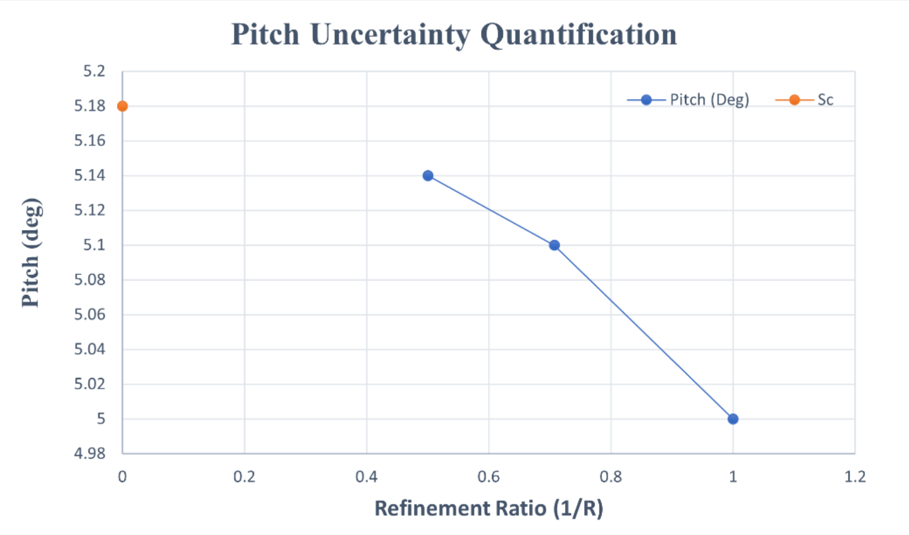


- Grid size of 0.5 – 5.5 Million
- Computational Time of 1 – 10 Hours
- Mesh 4 is used for better compromise between accuracy and computational time

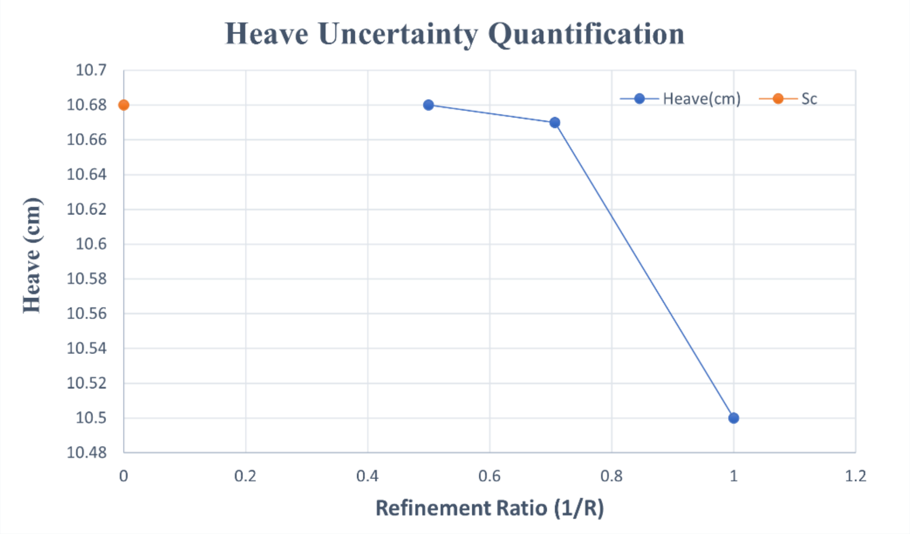


Verification : Grid Uncertainty Quantification



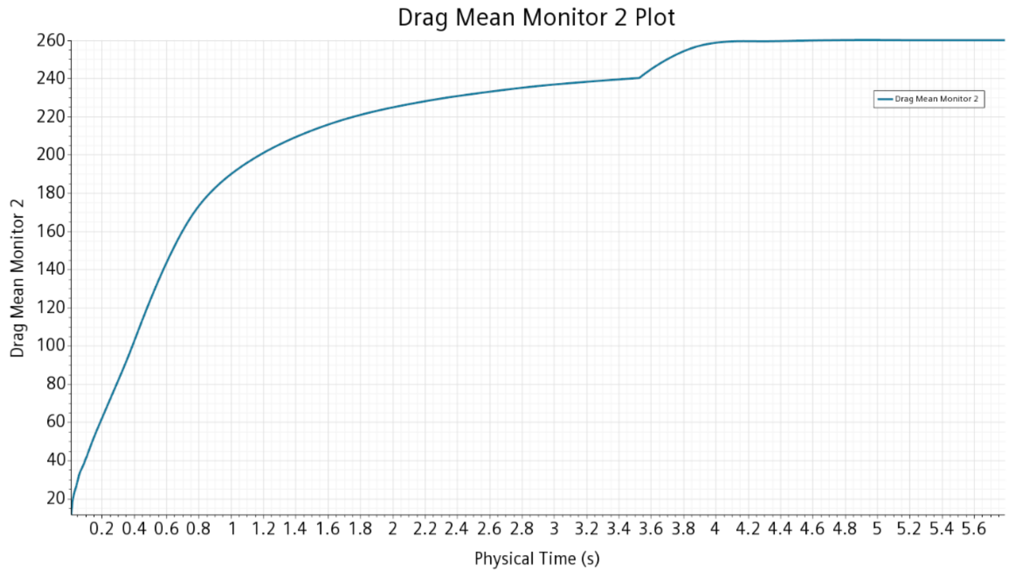


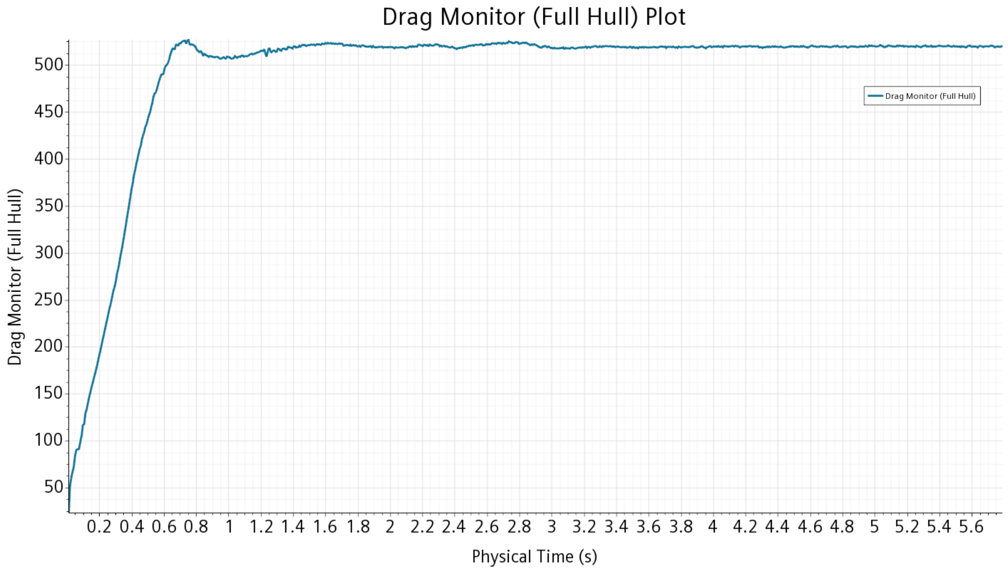
- Richardson Extrapolation FOS Method
- At Design Speed of 27.5 Knots
- For Hull with Appendages
- R = $\sqrt{2}$

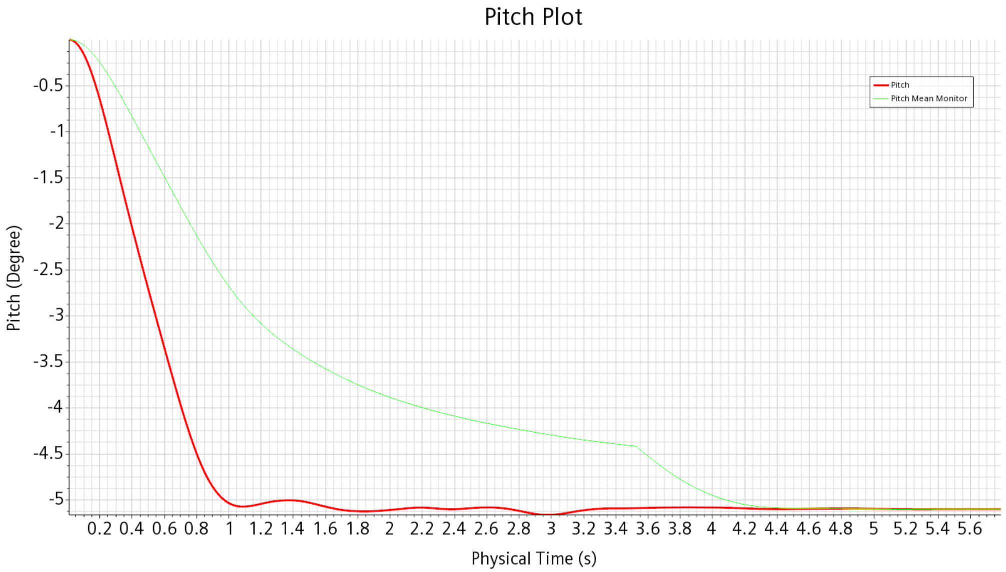


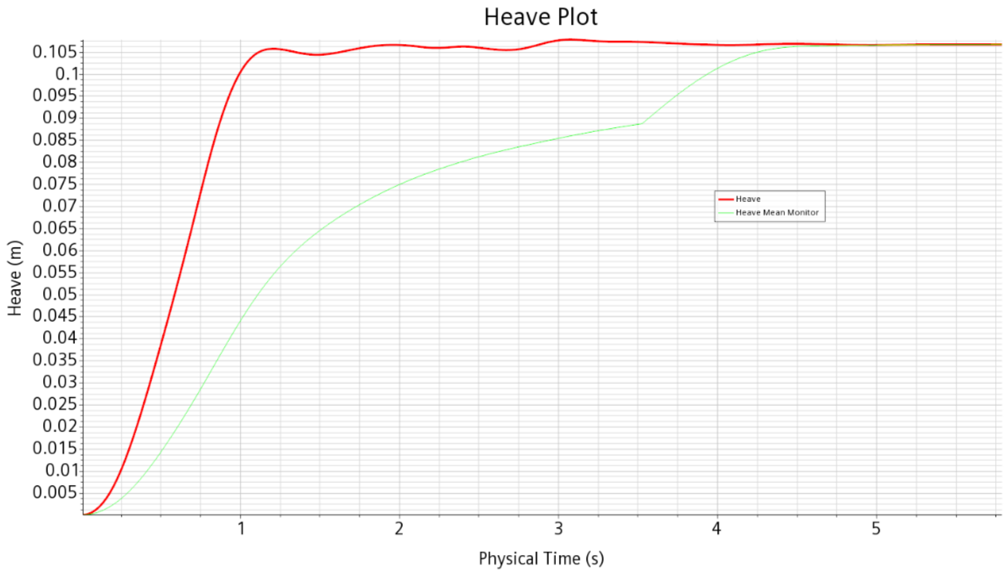
# of Cells	R	Heave(cm)	Pitch (Deg)	Drag (N)
1.76E+06	1	10.50	5.00	535.57
3.66E+06	1.4142	10.67	5.10	520.56
5.75E+06	2	10.68	5.14	519.27
Uncertainty_FS	%	**0.310**	**4.647**	**0.753**
Uncertainty_GCI	%	**0.011**	**2.867**	**0.029**

Verification : Convergence Histories

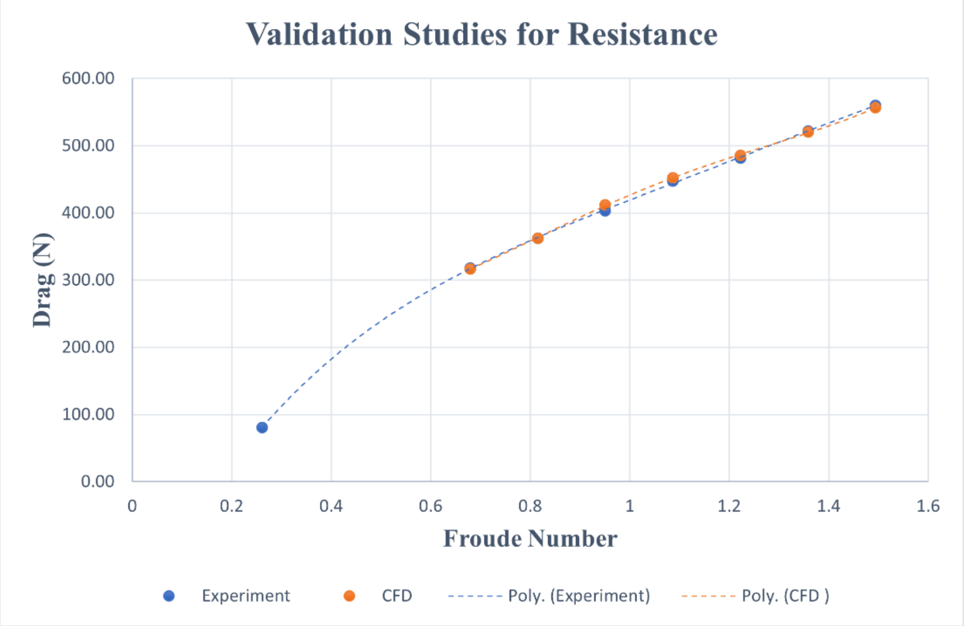


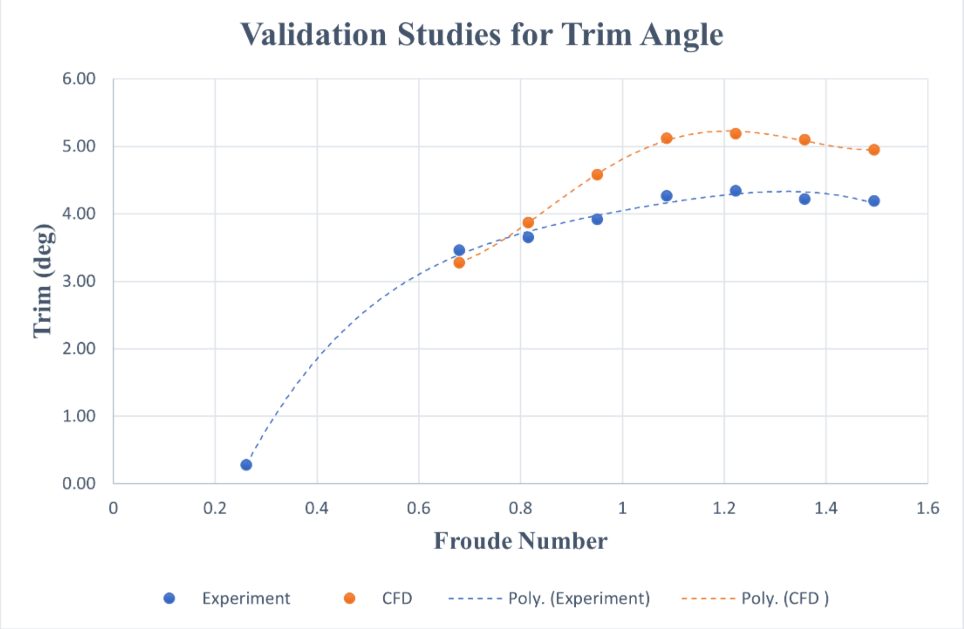


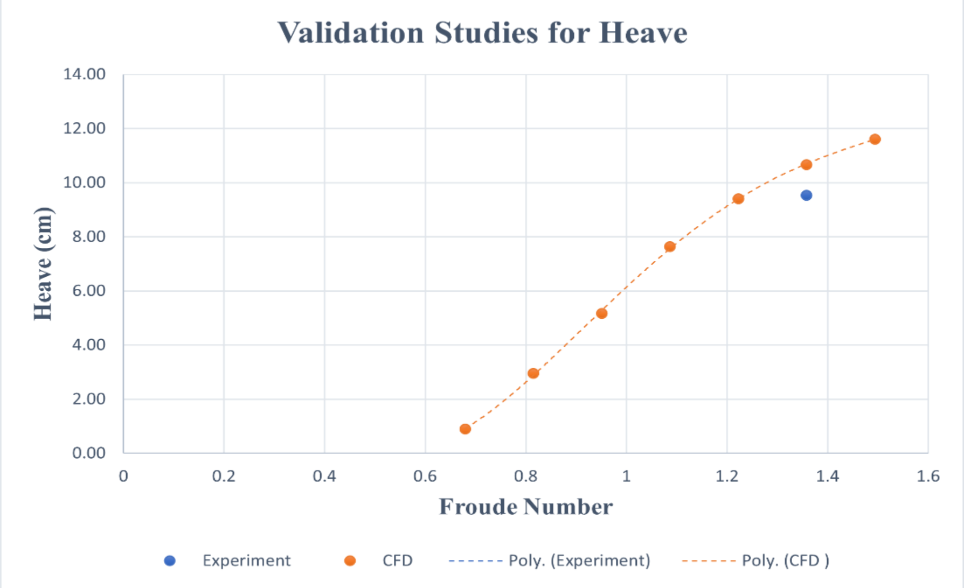




Validation Studies:



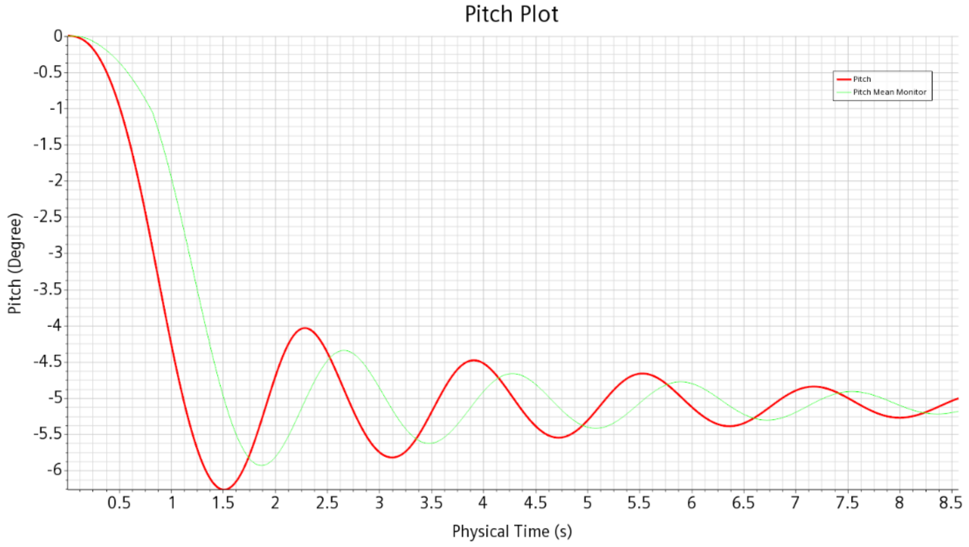


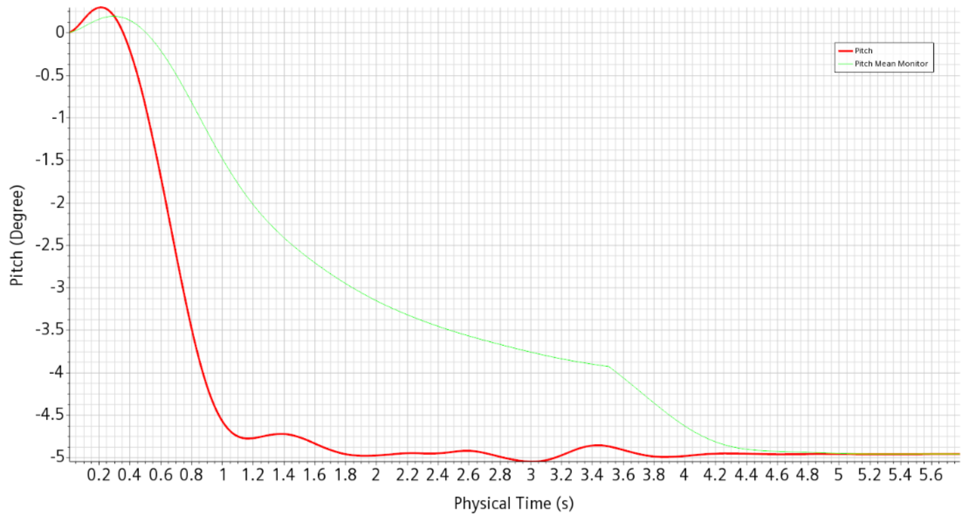


- At Design Speed,
  - Percentage difference in Resistance < 1 %
  - Absolute difference in Pitch Angle < 0.9 deg
  - Absolute difference in Heave < 1.2 cm

Speeding-Up CFD Computations:

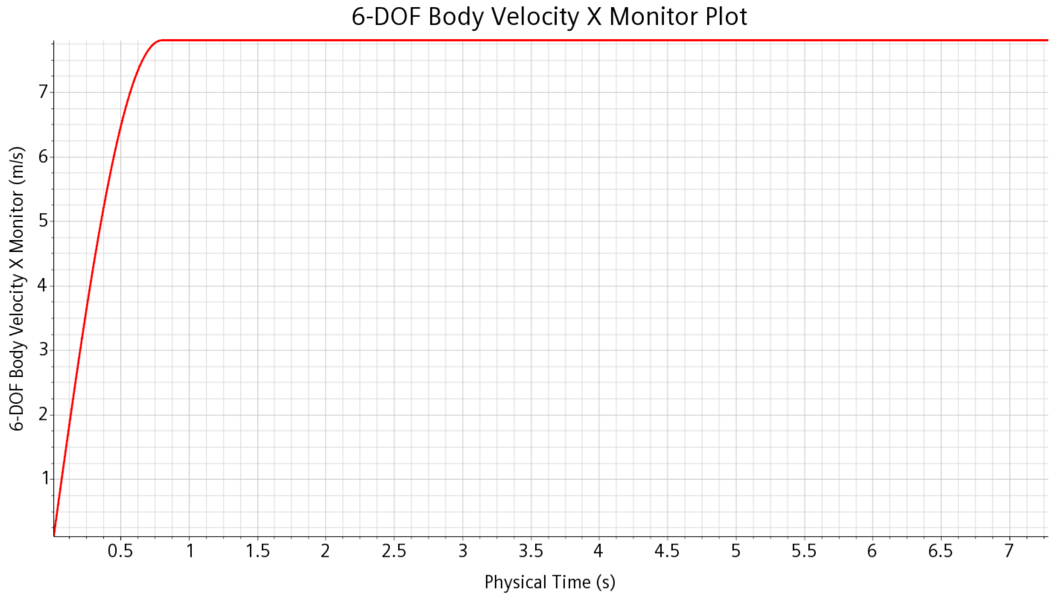
- Speeding Up CFD tasks:
  - Use of AMR Techniques with combination of Overset Mesh to refine the Mesh Locally where needed.
  - Use of Implicit Multi-Step with adaptive Time step
  - Artificially damping the motions by modifying Inertia





Speeding-Up CFD Computations:

- Speeding Up CFD tasks:
  - Ramping Up of Velocity for better and fast Solution Convergence
  - Appendages can be neglected for Design Exploration.
  - Using Coarser Grid for optimization framework.
- Simulation time decreases by a factor of around 2 for each simulation.



Simulation-Driven Design - Workflow

Geometric modeling

- Simulation-ready
- Robust

Variable Geometry → Pre-processing

Simulation

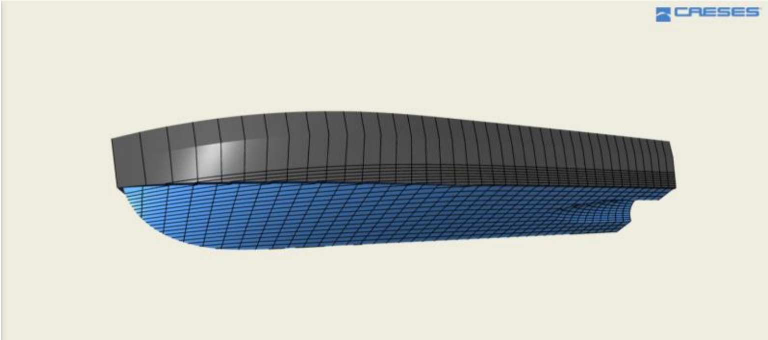
- Auto meshing
- Batch processing

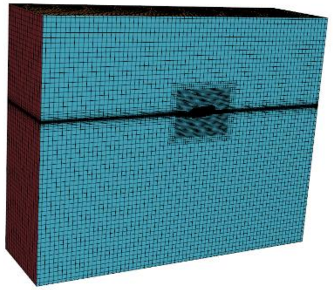
Mesh Generation → Flow Solver

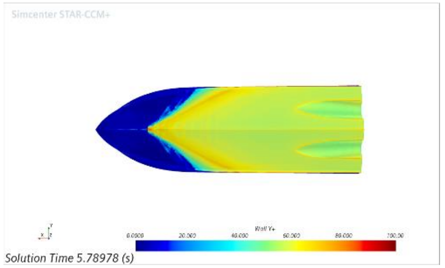
Exploration and exploitation

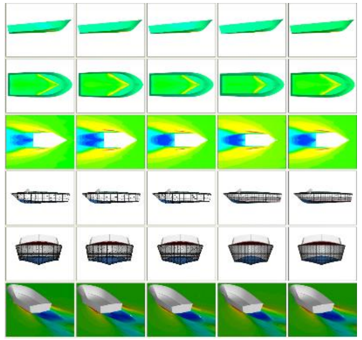
- Design-of-Experiments
- Formal optimization

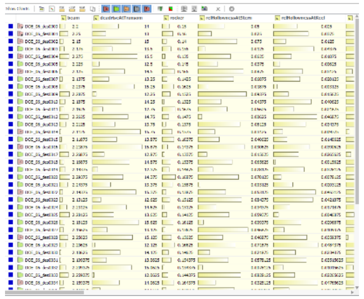
Post-processing → Optimization & Assessment





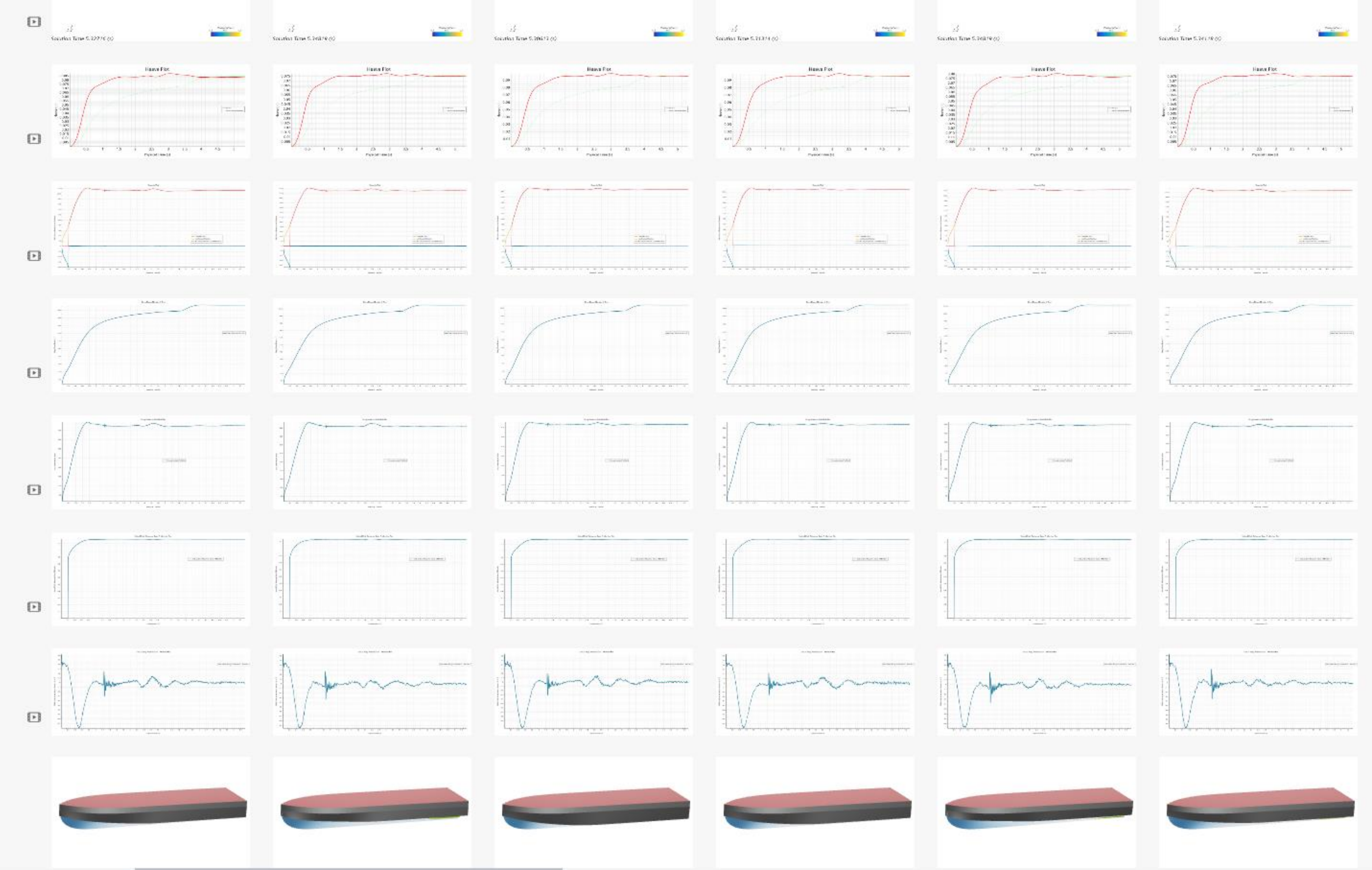




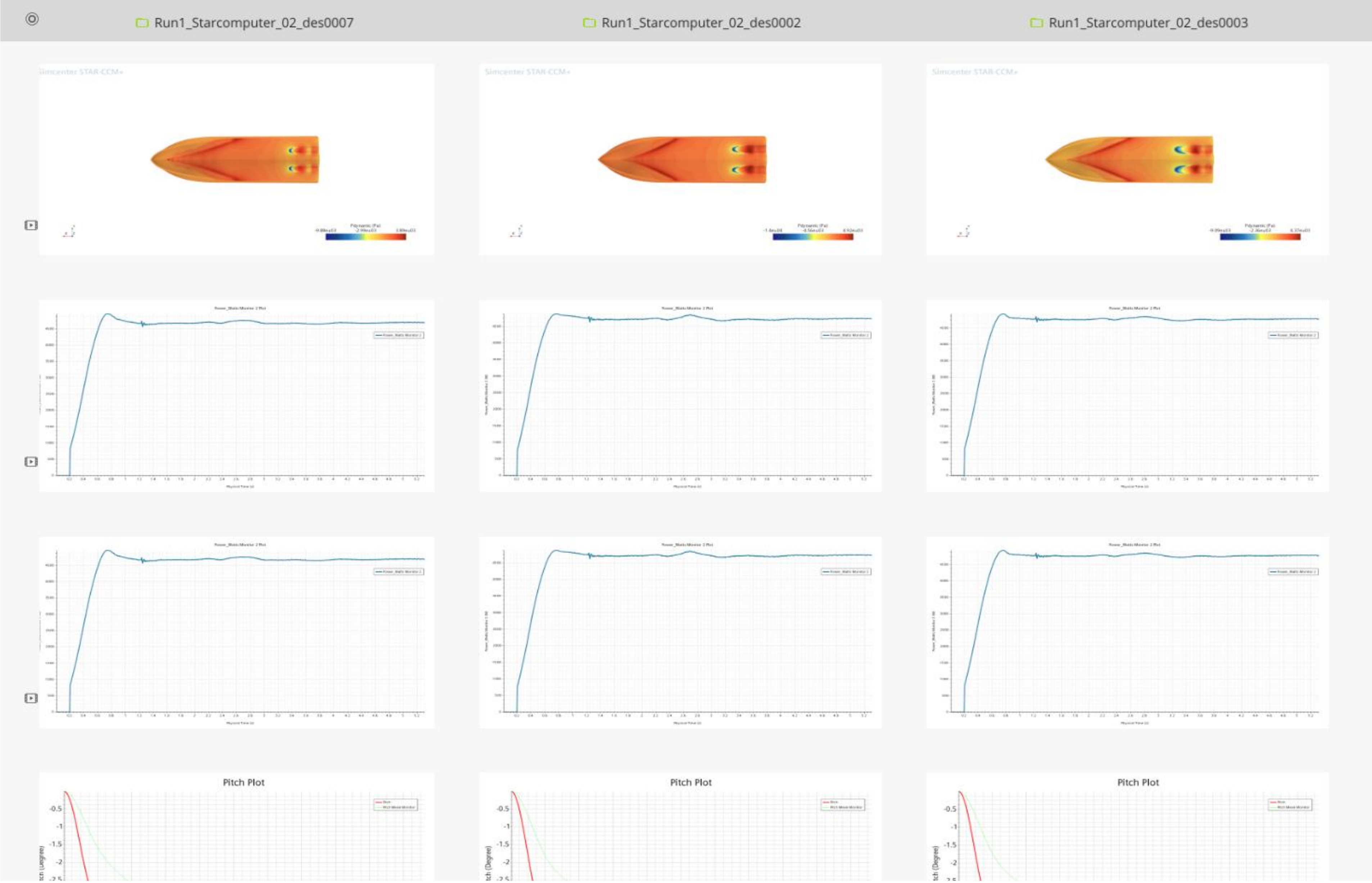


Automated Software Connection by linking STAR-CCM+ with CAESES by means of JAVA Script and batch processing in LINUX

Automated Software Connection: Convergence Histories

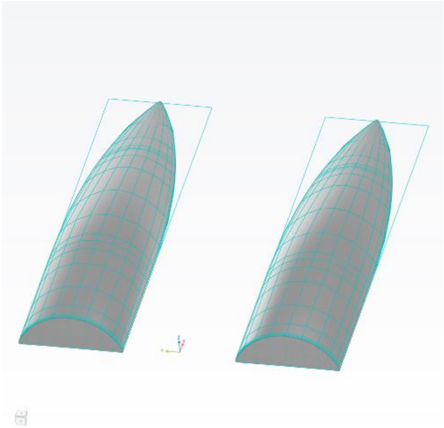


Automated Software Connection: Convergence Histories

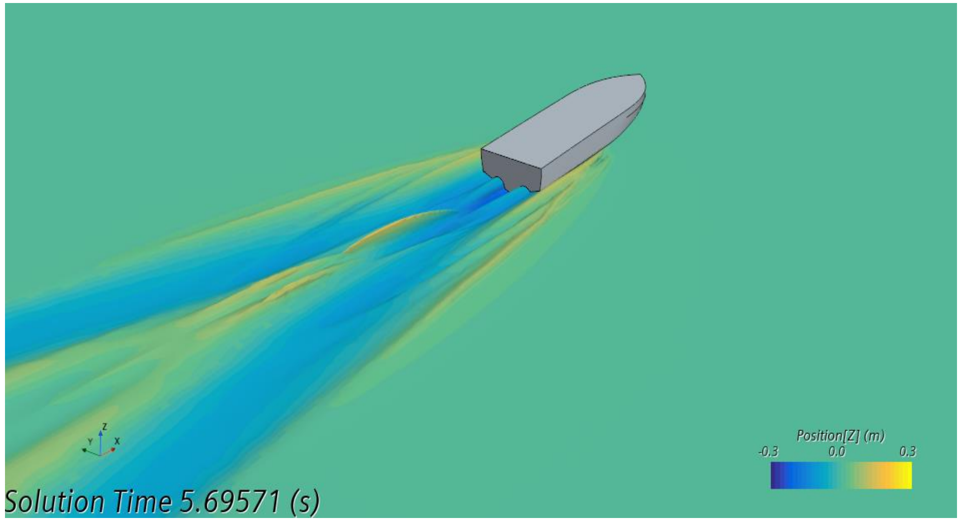


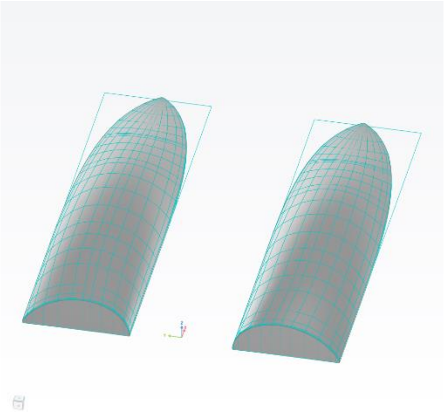
First Optimization Study:

- Based on initial results from tank tests and validated CFD Setup

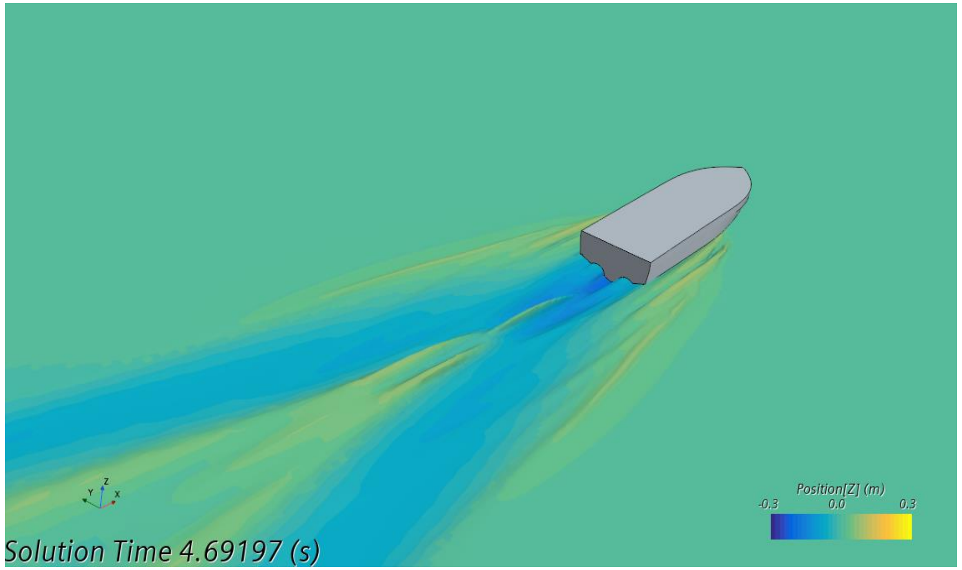


- Free Surface Representation with Old Tunnel
  - Sharp Wave Breaking
  - Cross Flow At Wake



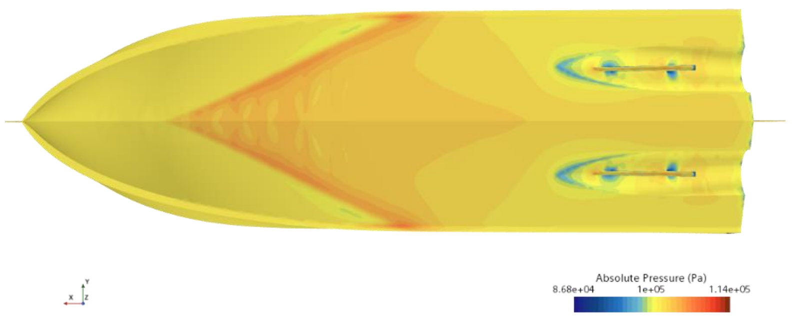


- Free Surface Representation with New Tunnel
  - Smoother Flow
  - Cross Flow is reduced

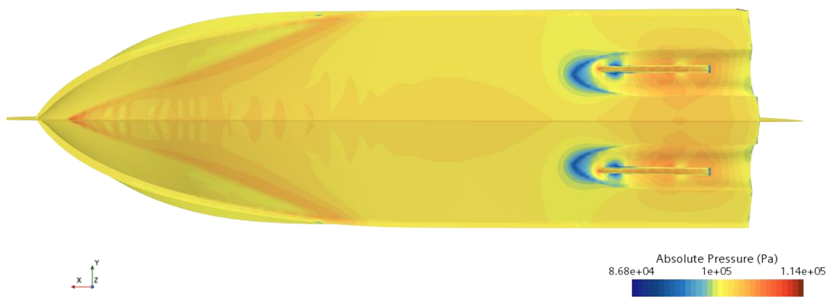


First Optimization Study:

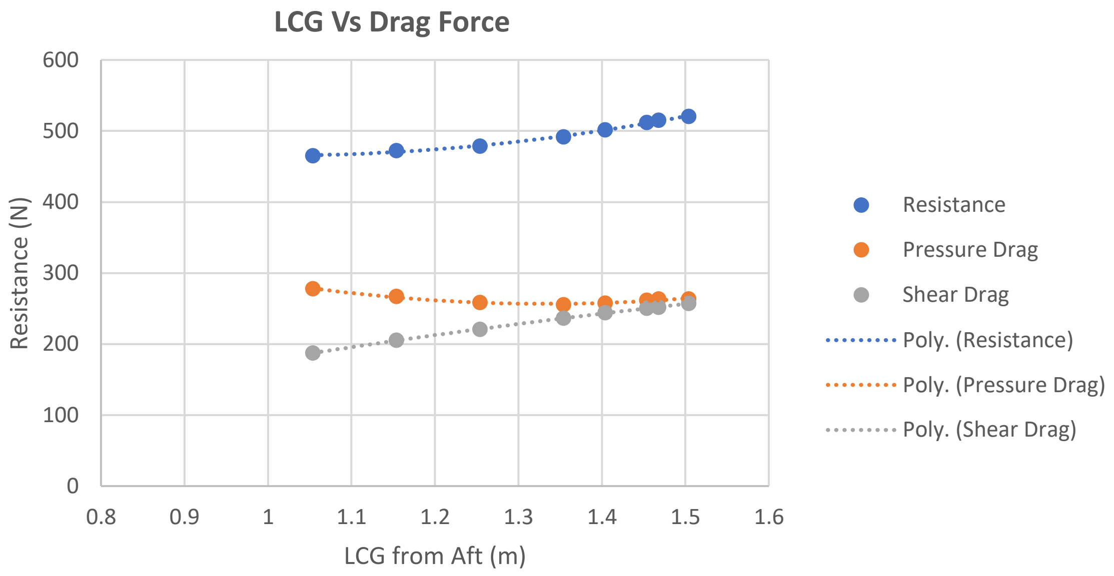
	LCG (m)	XCB (m)	Resistance (N)	Trim (Deg)	Heave (cm)	Pressure Drag (N)	Shear Drag (N)
Old Tunnel	1.504	1.4681	**521.52**	5.09	10.06	**311.68**	**209.84**
New Tunnel	1.504	1.4681	**520.62**	2.98	6.96	**263.38**	**257.24**



Pressure Distributions for Old Tunnel

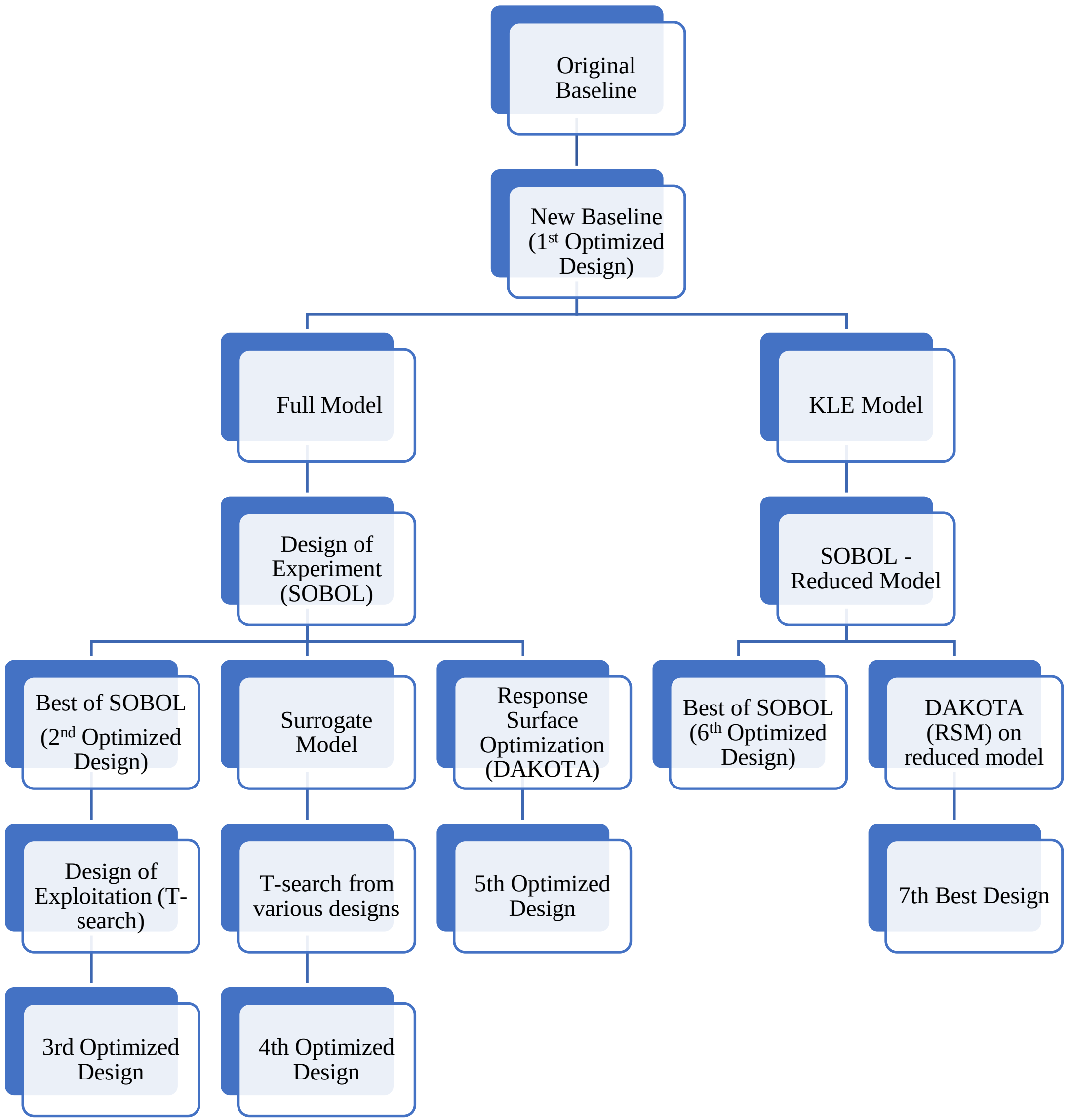


Pressure Distributions for New Tunnel



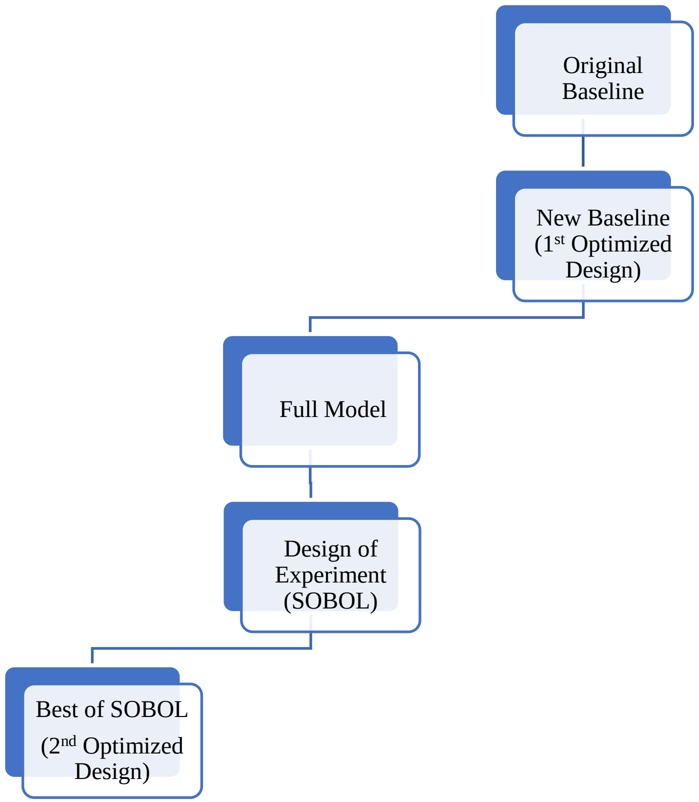
- Proposed LCG location , 15cm aft.
  - New LCG position at 1.354m at model scale
  - Combination of New Tunnel and LCG Shift gives around 5% of propeller thrust reduction

Optimization Framework:



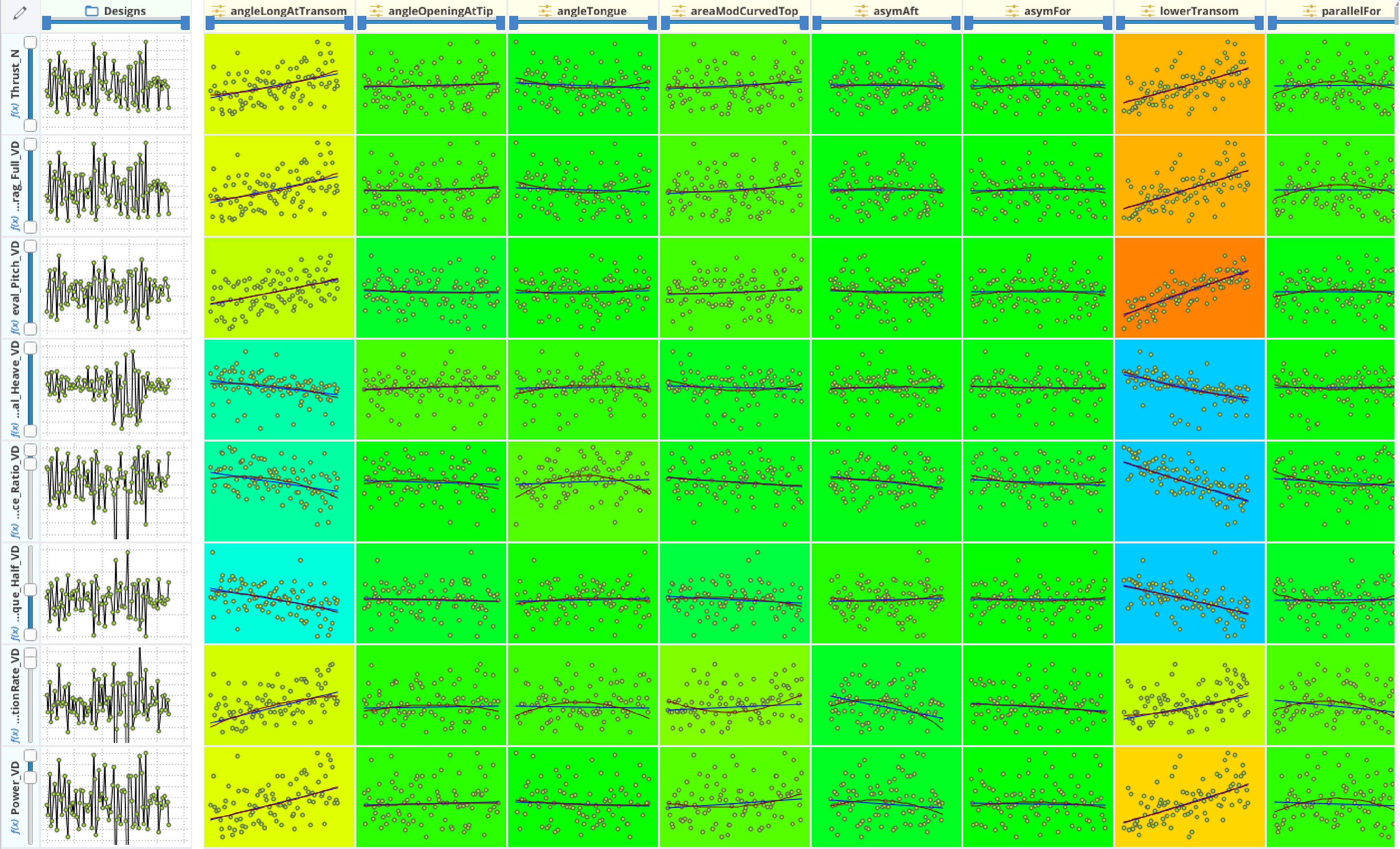
- 1st optimized design, is the new baseline for optimization
- Using Automated Software Connection of CAESES and STAR-CCM+ to run it in Batch Mode.
- Propeller thrust reduction as an objective function.

Optimization Framework: 2nd Optimized Design

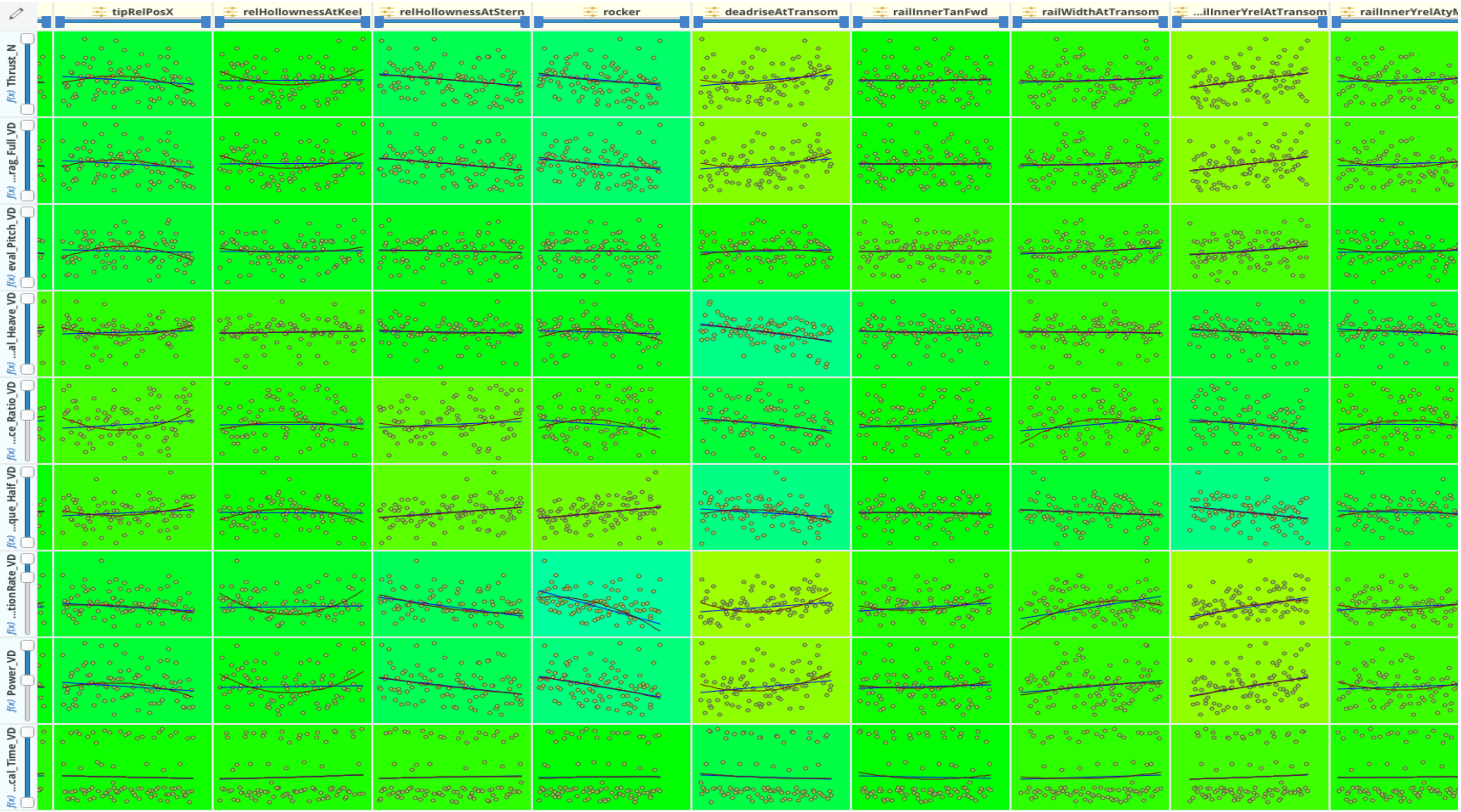


- 1st optimized design, is the new baseline for optimization
- Using Automated Software Connection of CAESES and STAR-CCM+ to run it in Batch Mode.
- Propeller thrust reduction as an objective function.

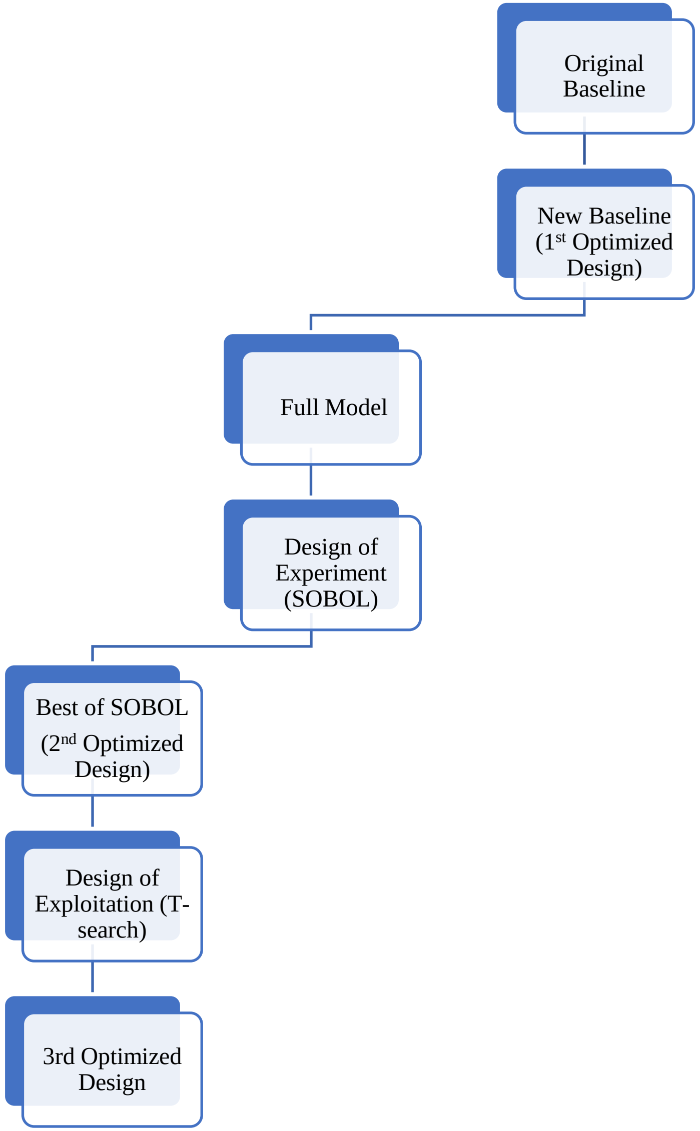
Design of Experiment : SOBOL



Design of Experiment : SOBOL

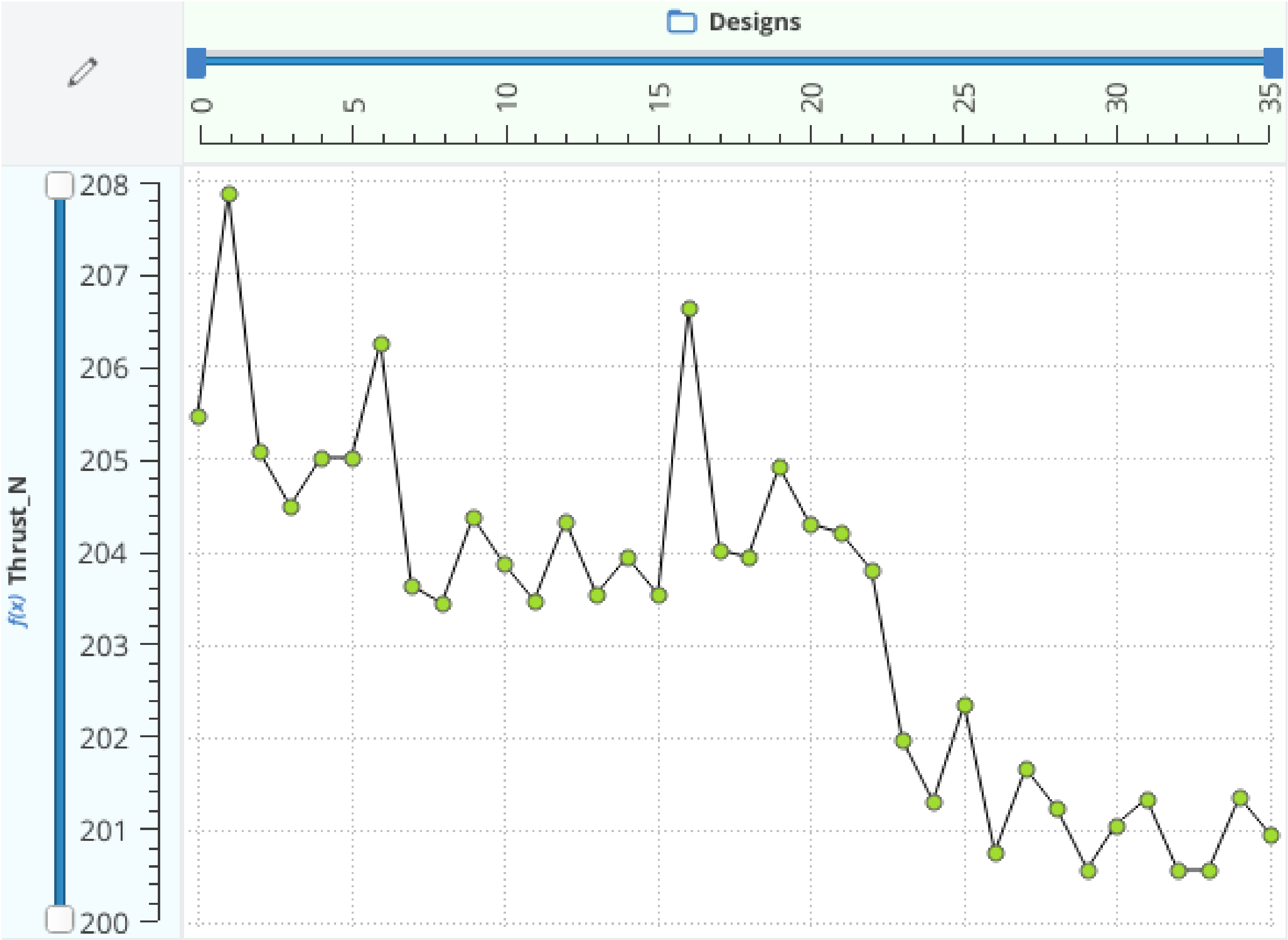


Optimization Framework: 3rd Optimized Design



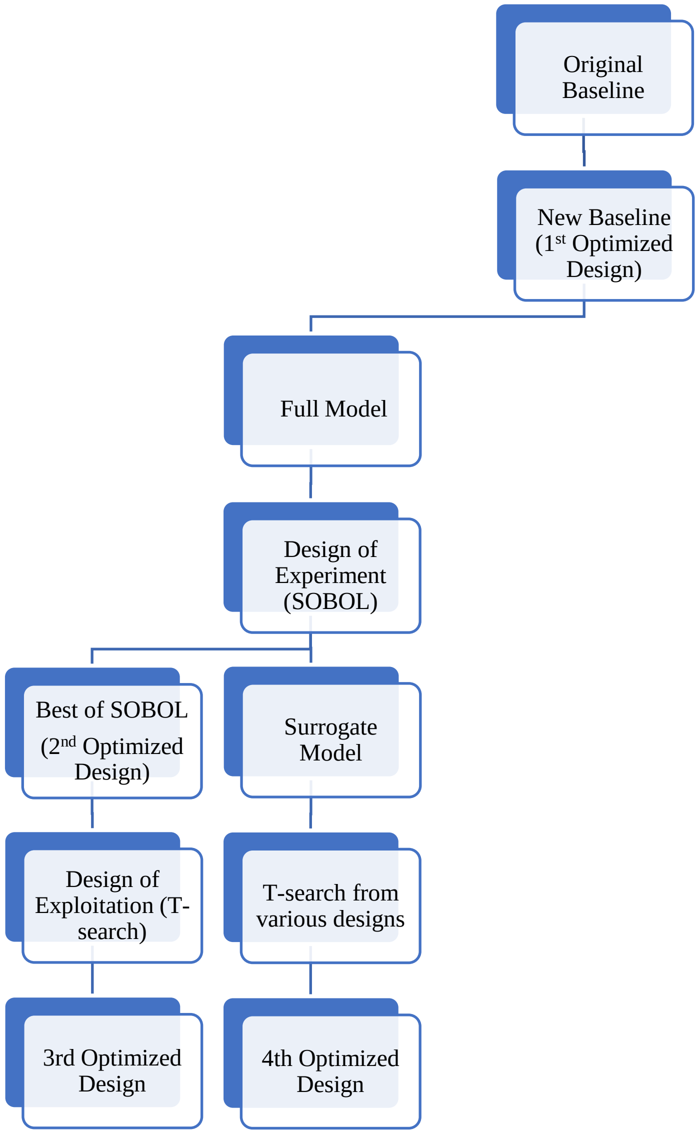
- 1st optimized design, is the new baseline for optimization
- Using Automated Software Connection of CAESES and STAR-CCM+ to run it in Batch Mode.
- Propeller thrust reduction as an objective function.

Design of Exploitation: T-search



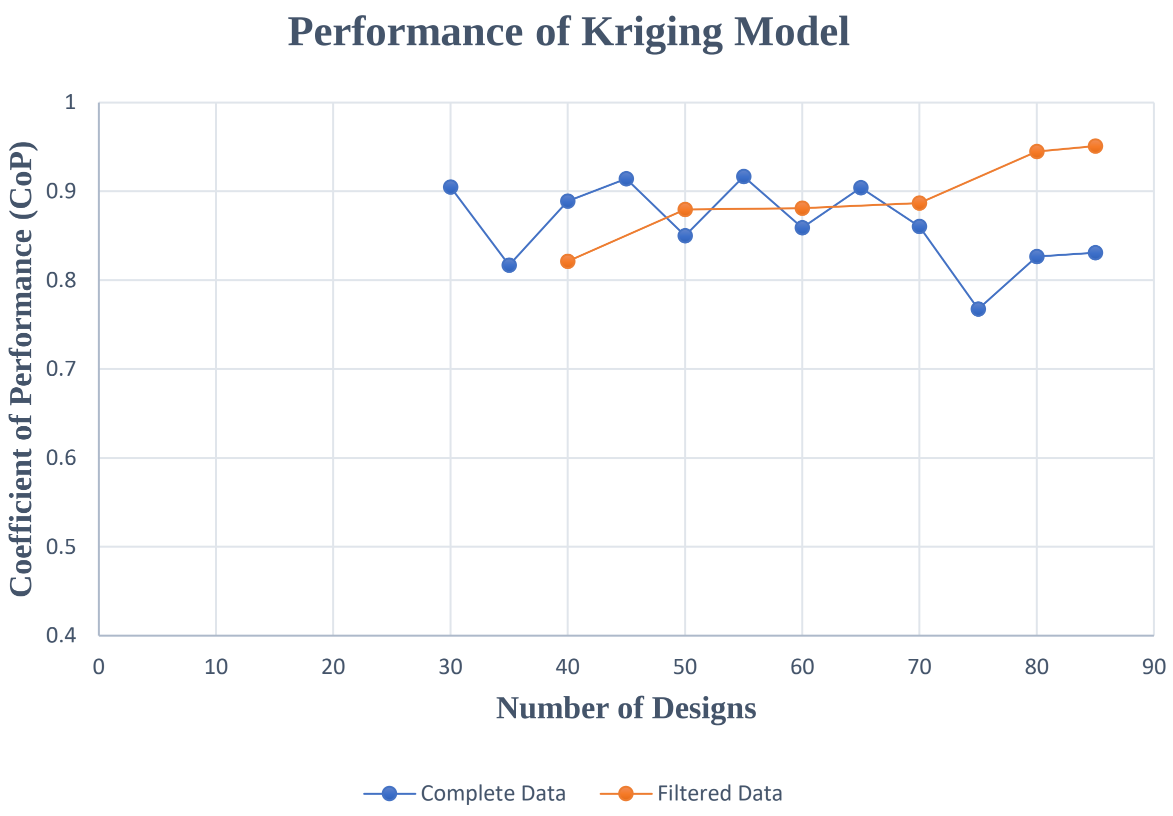
- T-search using CFD
- 12 design variables out of 18 selected for T-search
- Starting from best of SOBOL
- Maximum iterations limited to 35

Optimization Framework: 4th Optimized Design



- 1st optimized design, is the new baseline for optimization
- Using Automated Software Connection of CAESES and STAR-CCM+ to run it in Batch Mode.
- Propeller thrust reduction as an objective function.

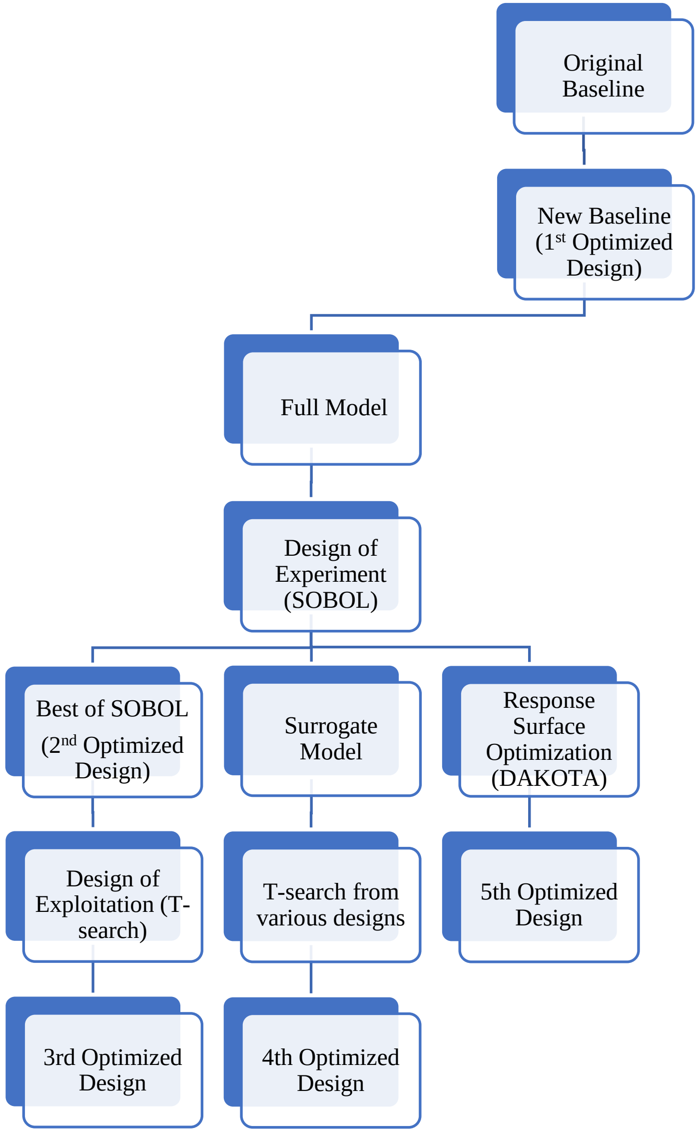
Machine Learning Based Optimization: Data Filtering



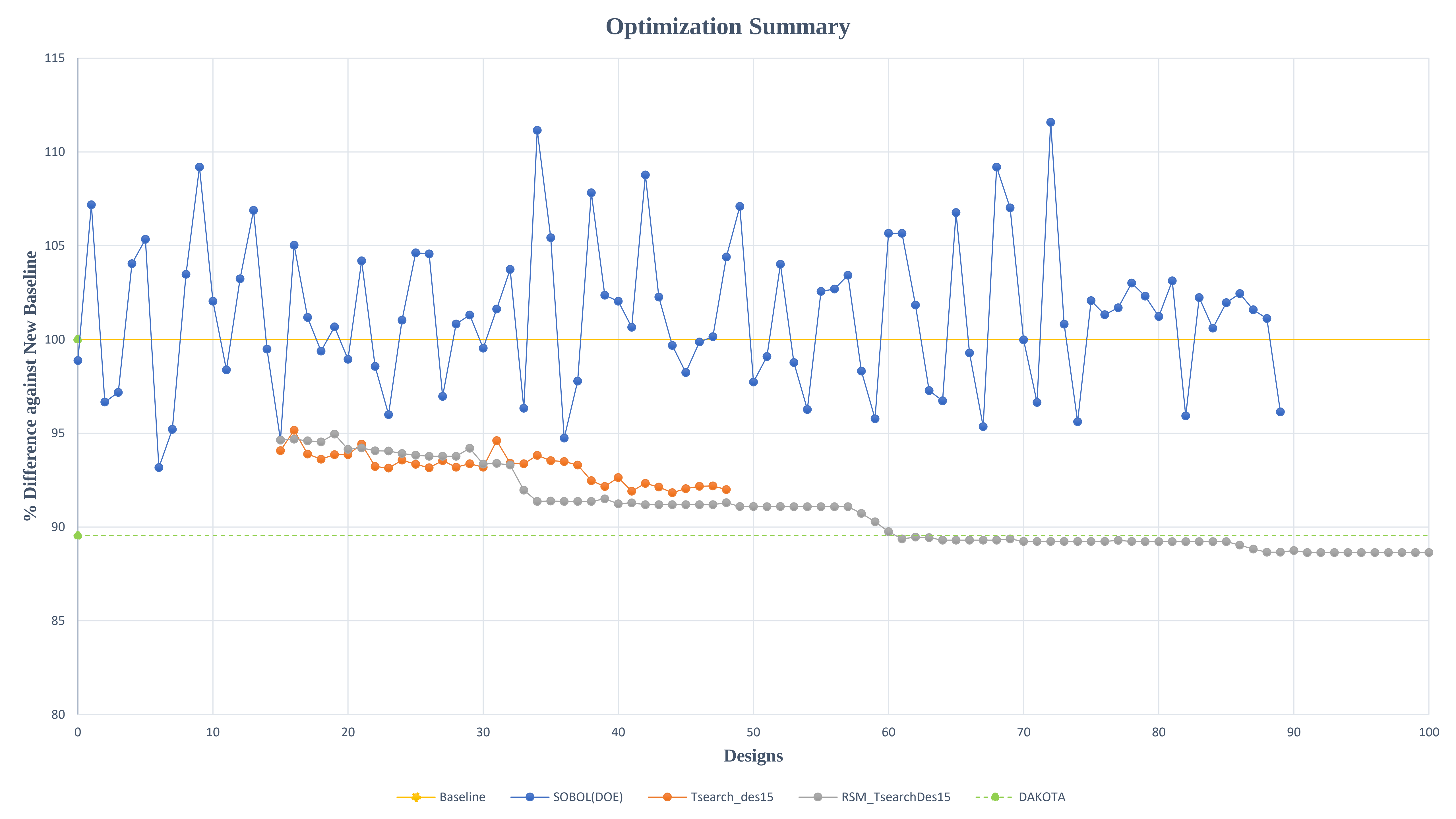
- Filtered Data
- COP Value = 0.9446

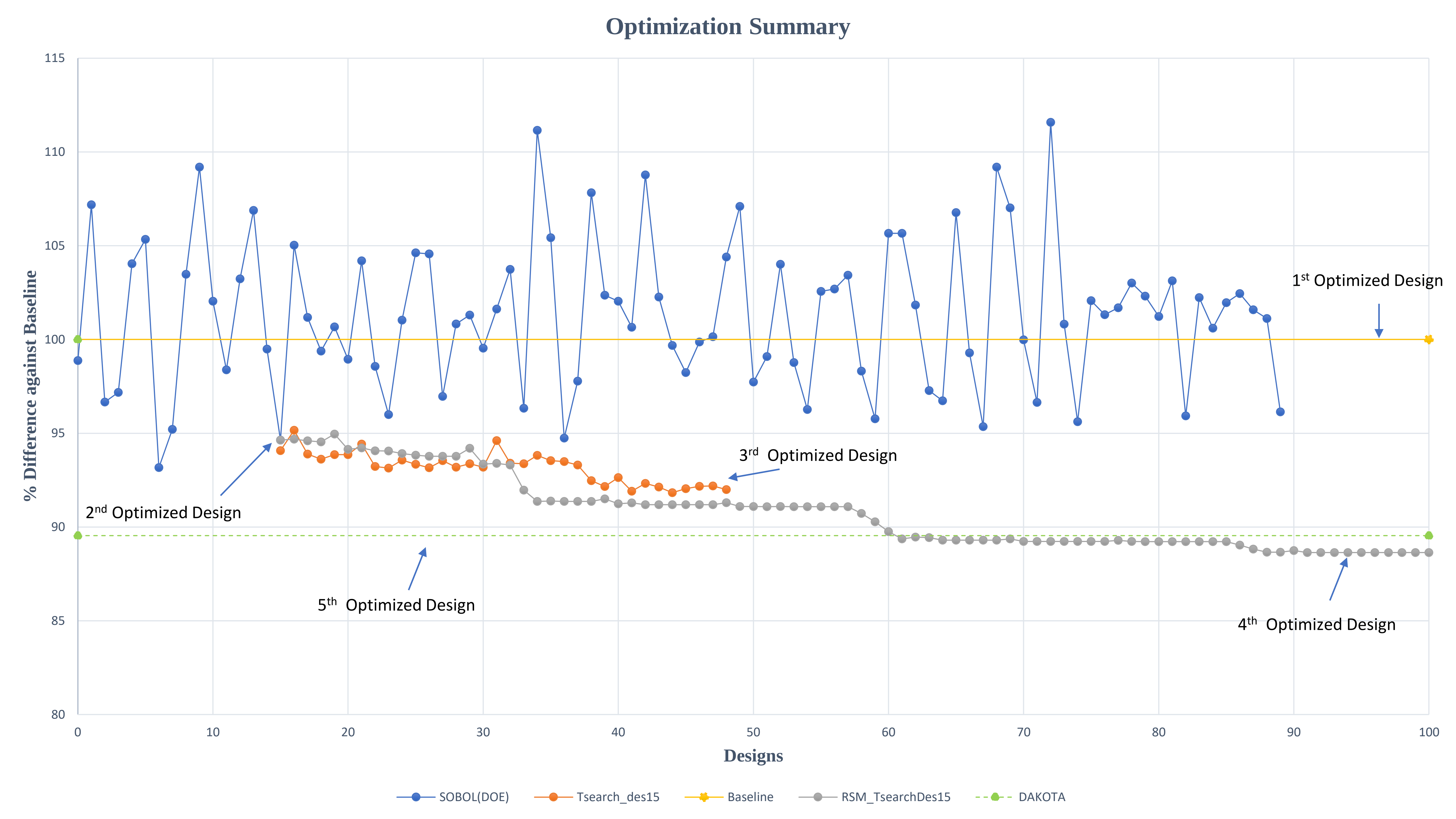
	CoP Value		Function Value	
# of Variants	**Kriging**	**ANN**	**Kriging**	**ANN**
40	0.8212	0.8034	218.42	219.5
50	0.8796	0.7902	218.42	220.39
60	0.8809	*0.9398*	218.42	214.13
70	0.8867	0.9095	218.42	217.56
80	*0.9446*	0.8014	218.42	220.95

Optimization Framework: 5th Optimized Design



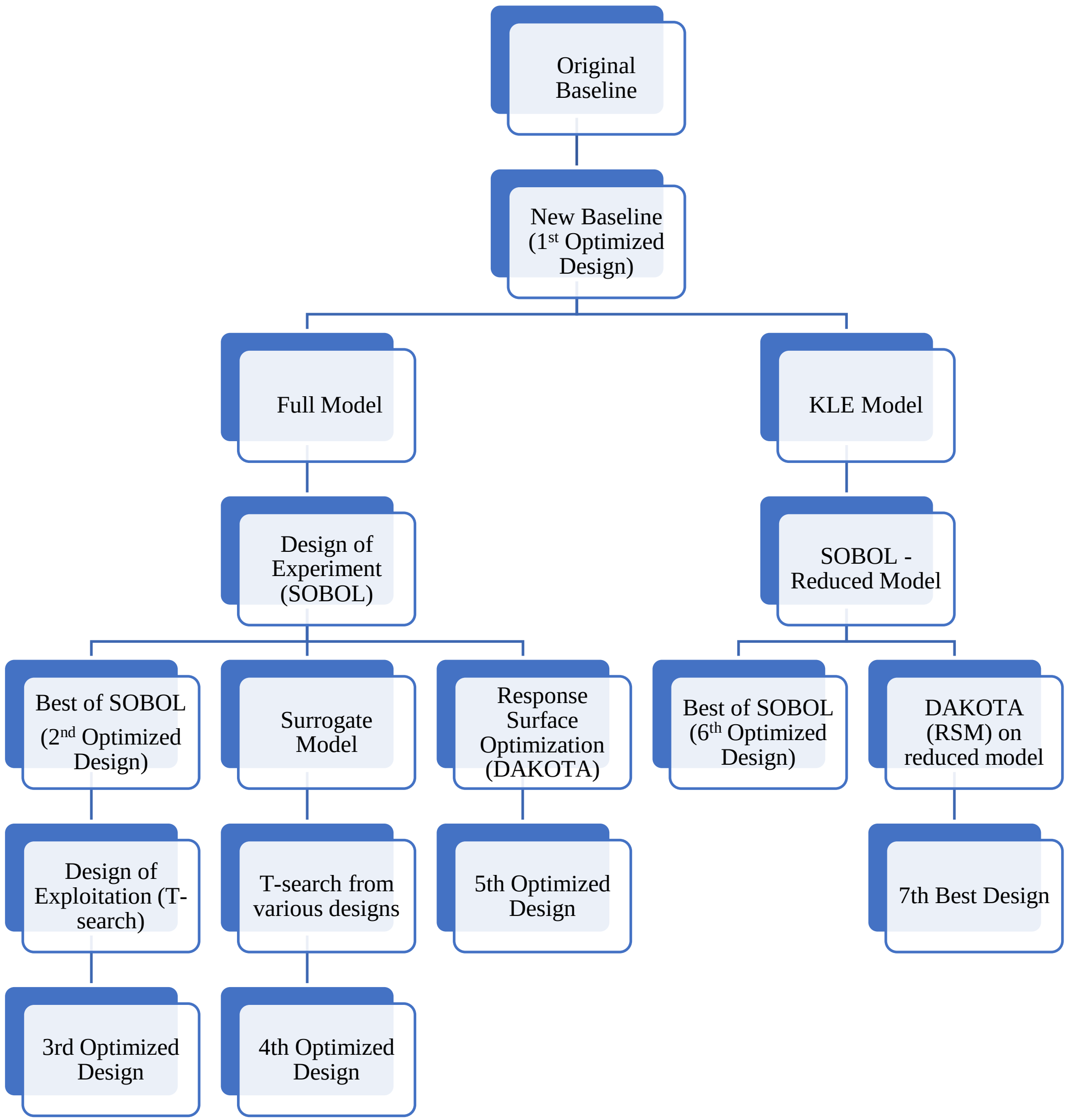
- 1st optimized design, is the new baseline for optimization
- Using Automated Software Connection of CAESES and STAR-CCM+ to run it in Batch Mode.
- Propeller thrust reduction as an objective function.


Optimization Summary
% Difference against New Baseline
115
110
105
100
95
90
85
80
0
10
20
30
40
50
60
70
80
90
100
Designs
Baseline
SOBOL(DOE)
Tsearch_des15
RSM_TsearchDes15
DAKOTA



Optimization Summary
% Difference against Baseline
115
110
105
100
95
90
85
80
0
10
20
30
40
50
60
70
80
90
100
Designs
1st Optimized Design
2nd Optimized Design
3rd Optimized Design
4th Optimized Design
5th Optimized Design
SOBOL(DOE)
Tsearch_des15
Baseline
RSM_TsearchDes15
DAKOTA

Optimization Framework: 6th & 7th Optimized Designs



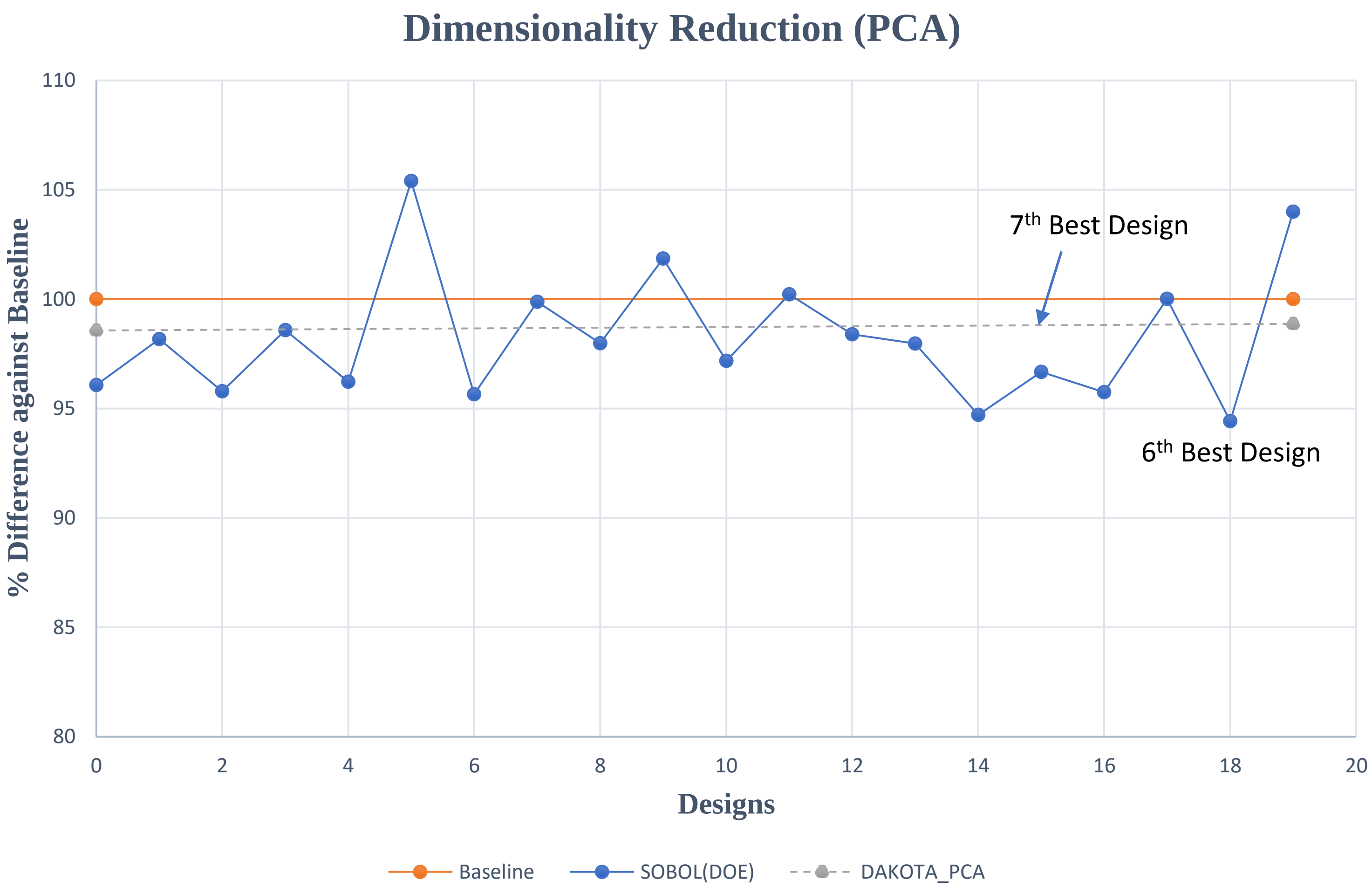
- 1st optimized design, is the new baseline for optimization
- Using Automated Software Connection of CAESES and STAR-CCM+ to run it in Batch Mode.
- Propeller thrust reduction as an objective function.

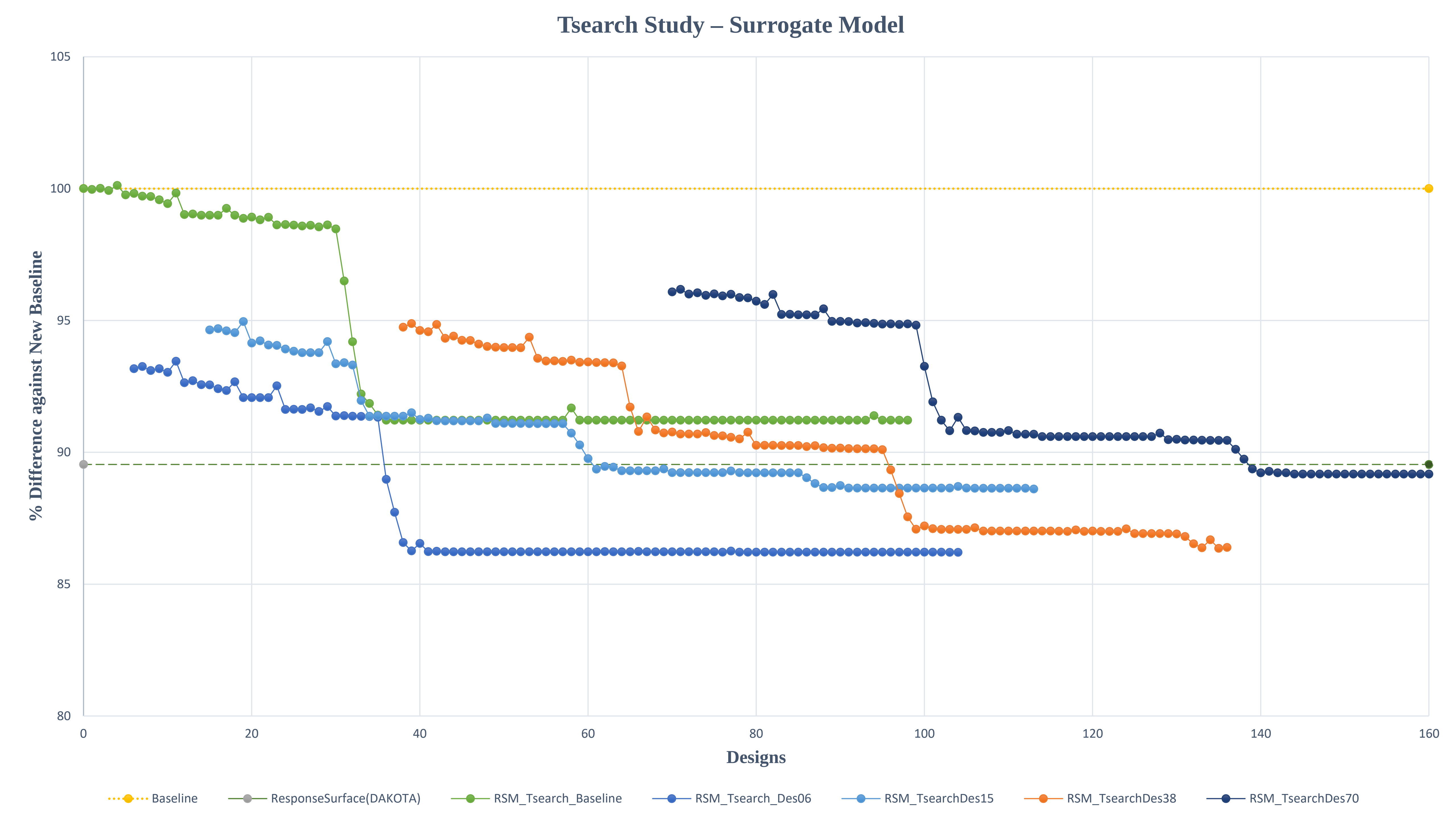
Dimensionality Reduction : KLE - Based Optimization

- Dimensionality Reduction with,
  - 2500 design samples
  - 10000 points per sample

- 4 Principal Parameters were recovered for DOE analysis

	Captured Variance		
Principal Parameter	**For Hull**	**For Tunnel**	**Combined**
1	56.78	77.58	51.00
2	82.04	92.56	81.54
3	98.03	97.56	97.10
4	**98.67**	**98.65**	**97.92**
5	99.1	99.16	98.41
6	99.34	99.52	98.76
7	99.46	99.77	98.96





Tsearch Study – Surrogate Model
105
100
95
90
85
80
% Difference against New Baseline
0
20
40
60
80
100
120
140
160
Designs
Baseline
ResponseSurface(DAKOTA)
RSM_Tsearch_Baseline
RSM_Tsearch_Des06
RSM_TsearchDes15
RSM_TsearchDes38
RSM_TsearchDes70

Optimization Summary : Simplified Setup

	% Improvement	
RSM Studies Results	**With Kriging Model**	**With CFD Model**
Starting from Baseline	91.21	93.13
Starting from Des0006	86.21	88.91
Starting from Des0015	88.11	90.05
Starting from Des0038	86.36	89.36
Starting from Des0070	89.13	90.39

- Cross-Validation of Surrogate Model with CFD
- T-search starting from Des0015 taken as optimized design # 5

Optimized Design	Optimization Methods	Propeller Thrust (N)	Difference (%)	Time Taken (Hrs)	Data set (Hrs)
1st	New Baseline for Optimization	436.84	100	2.3	-
2nd	Design of Exploration (SOBOL)	413.42	94.64	207	-
3rd	Tsearch from 2nd	401.88	92.00	80.5	-
4th	DAKOTA based on SOBOL	391.12	89.53	2.3	207
5th	Tsearch-RSM	393.36	90.05	2.3	207
6th	Design of Exploration (SOBOL) - KLE	415.56	95.13	46	-
7th	DAKOTA - based on KLE	424.32	97.13	2.3	46

Summary of Optimized Results

Optimization Summary : Full Appended Hull & Fine Mesh

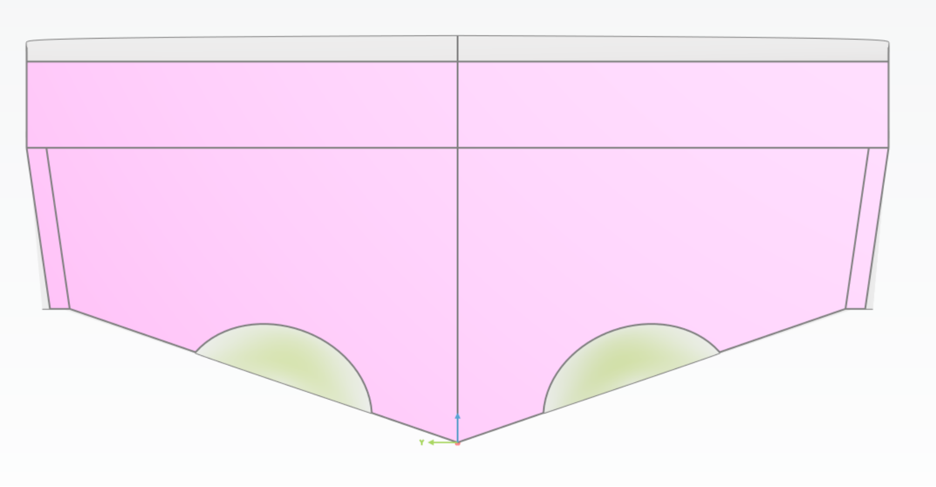
		Optimized Design							
	Original Baseline	1st	2nd	3rd	4th	5th	6th	7th	Units
Thrust	520.4	494.78	448.6	440.76	434.64	438.34	452.04	487.3	N
RPMs(one prop)	2280.29	2255.47	2204.2	2205.83	2205.12	2199.32	2206.72	2230.34	/s
Torque	24.44	23.46	21.42	21.196	20.9644	21.0506	21.54	22.84	N.m
Power(kW)	2.9180	2.7705	2.4721	2.4481	2.4205	2.4241	2.4888	2.667	kW/motor
Rtm-FD	519.17	494.31	441.55	434.63	428.1	432.24	445.37	479.99	N
Pitch	3.67	4.214	3.83	4.57	4.556	5.01	3.65	4.19	deg
Heave	0.0792	0.0975	0.09	0.1038	0.1047	0.1134	0.0871	0.1267	m
LCG	1.504	1.354	1.354	1.354	1.354	1.354	1.354	1.354	m
% Improvement	**0.00**	**4.92**	**13.80**	**15.30**	**16.48**	**15.77**	**13.14**	**6.36**	**%**

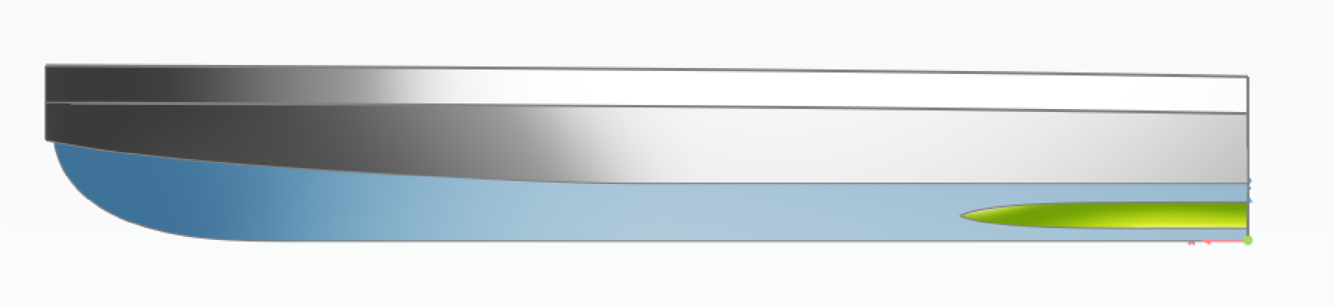
Conclusion and Final Remarks

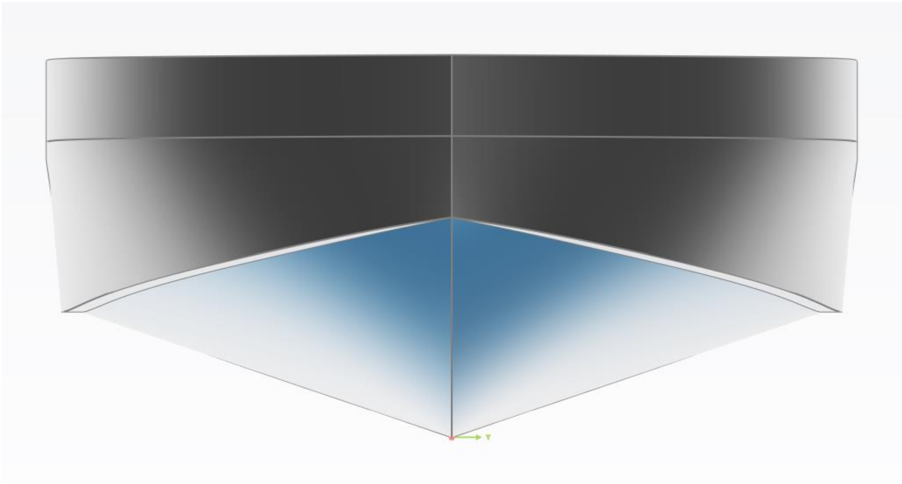
- Comprehensive studies for optimization of Planing Craft is presented with propeller thrust as the objective function.
- Fully Parametric model is built in CAESES, consisting 18 design variables.
- CFD simulations is carried out in STAR-CCM+ , results are verified and validated using grid convergence studies and experimental data, respectively.
- Automated software connection of CAESES and STAR-CCM+ is formed to perform optimization studies.
- Design of exploration is carried out to explore the design space. Exploitation is carried out using deterministic and stochastic methods.
- Using data-driven and dimensionality reduction of design space (KLE) to reduce the optimization time.
- Optimized designs shows 5-15% improvements, the obtained designs are compared with respect to quality of the design against the time taken to achieve it.

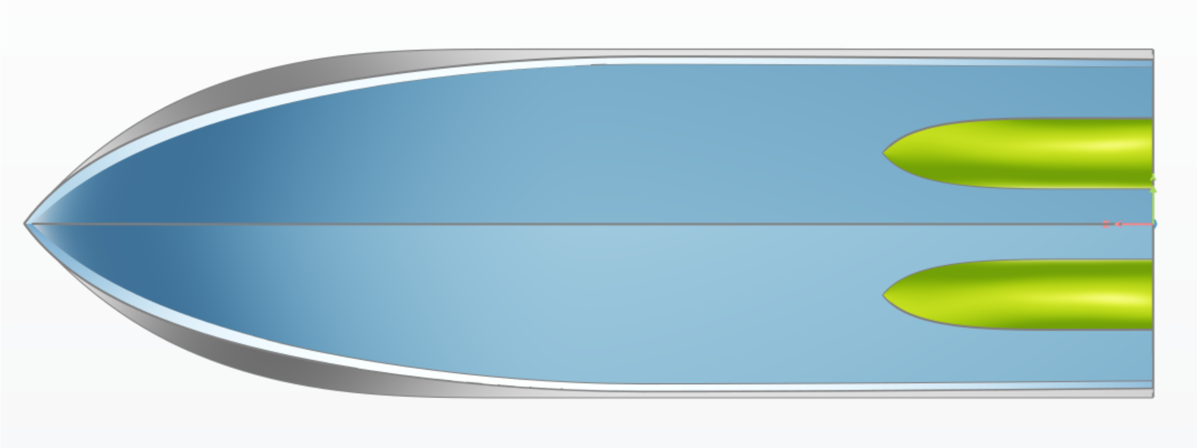
New Baseline: 1st Optimized Design

1st Design ------> 4% reduction in propeller thrust



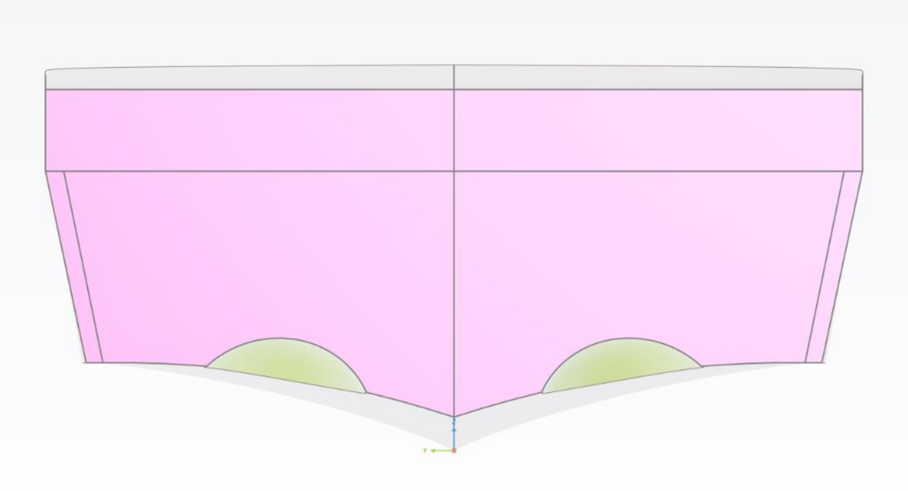


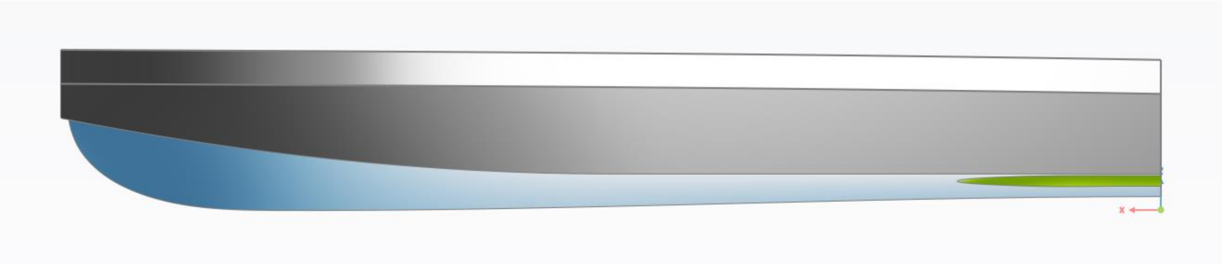


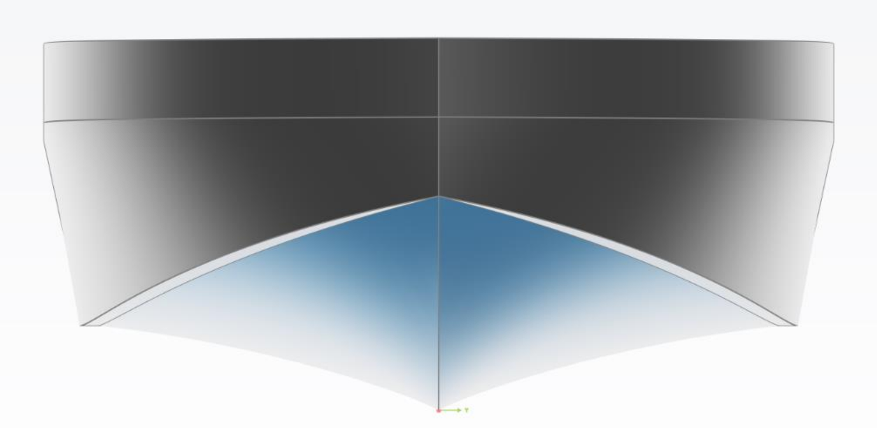


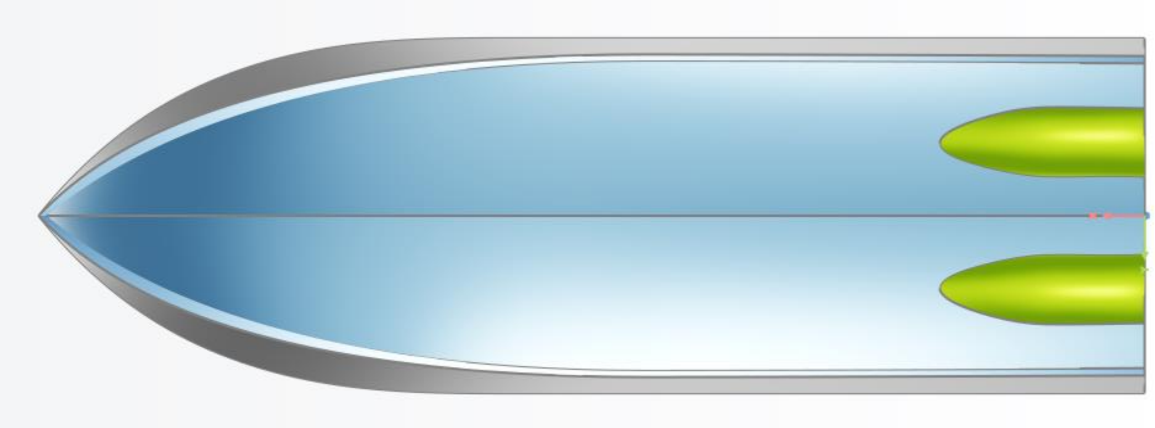
Optimized Designs : Different Views

3rd Design ------> 15.3% reduction in propeller thrust



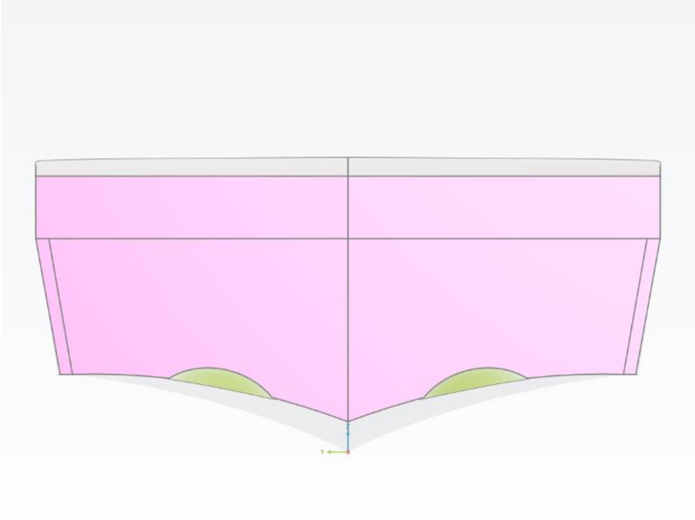


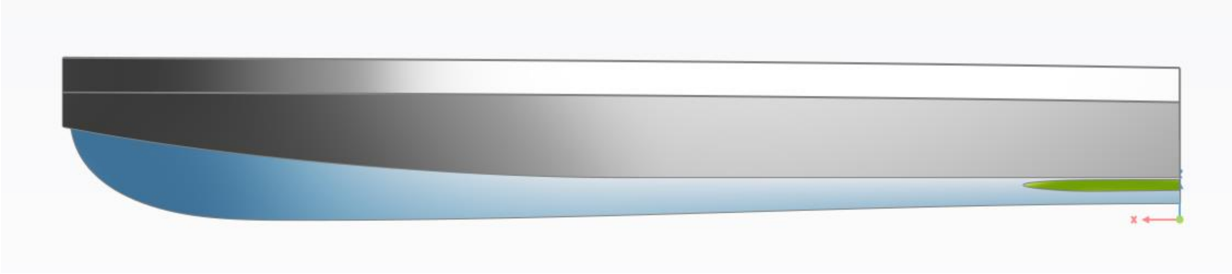


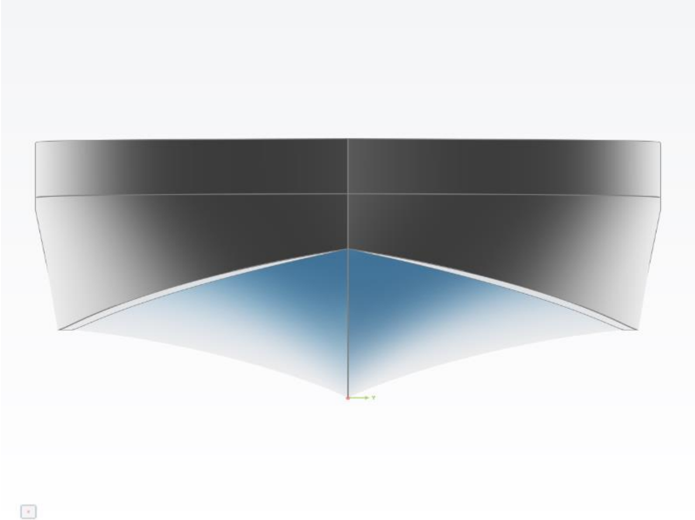


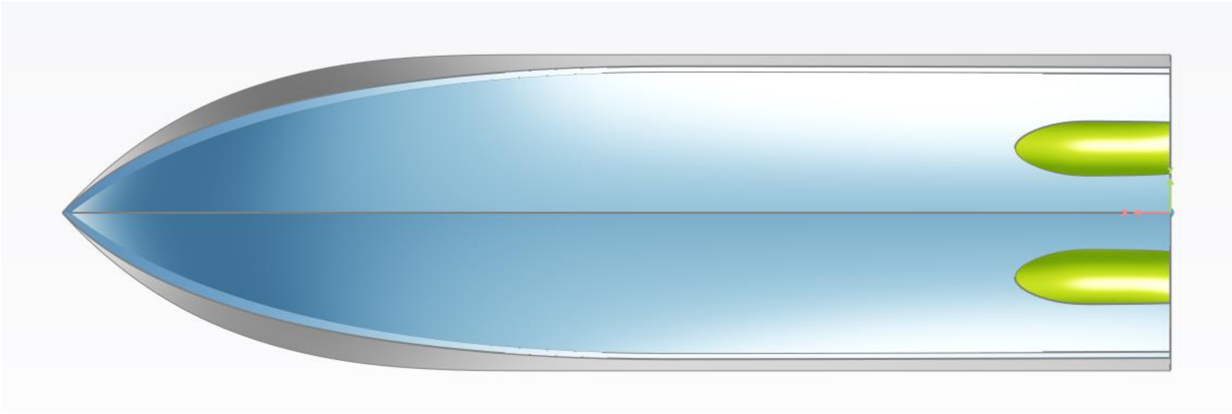
Optimized Designs : Different Views

6th Design ------> 15.77% reduction in propeller thrust









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