High Fidelity Performance Behavior Models Development for Combat Ship in Model Based Environment

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Overview

Design space exploration process for combat ship hull forms with the use of high fidelity performance behavior models.

Tools used in process:

- **Rhino 5 | Orca3D**: 3D modeler for rapid, parametric hull form generation
- **Simerics**: High fidelity CFD
- **SMP**: Seakeeping analysis tool
- **ModelCenter**: Platform for integration, behavior models, and exploration

Agenda

1. Hull Form Development and Hydrostatics
2. Propulsion Power CFD and Seakeeping Calculations Integrated in ModelCenter
3. Relationships of Performance Characteristics and Hull Form Parameters
4. Response Surface Models
5. Sensitivity Analysis and Hull Form Performance Derivatives
6. Hull Form Performance Optimization Results
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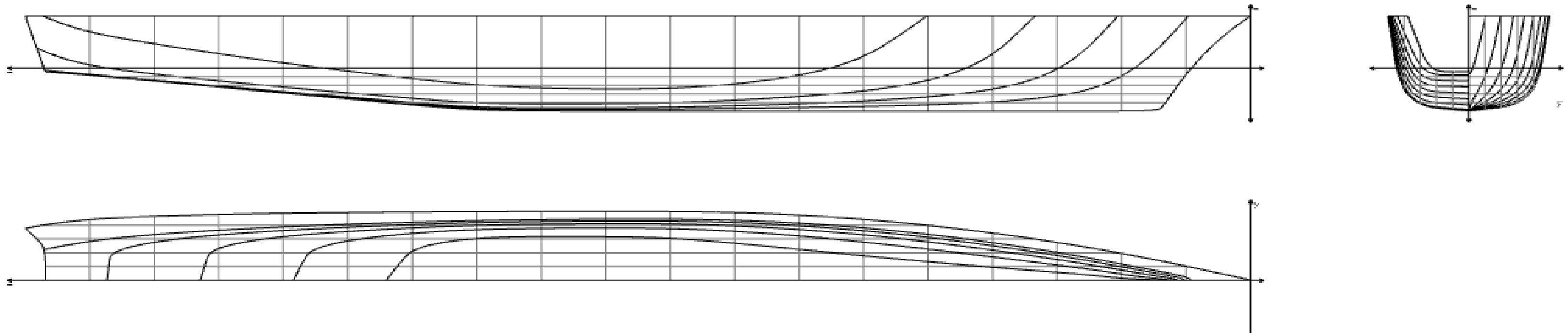
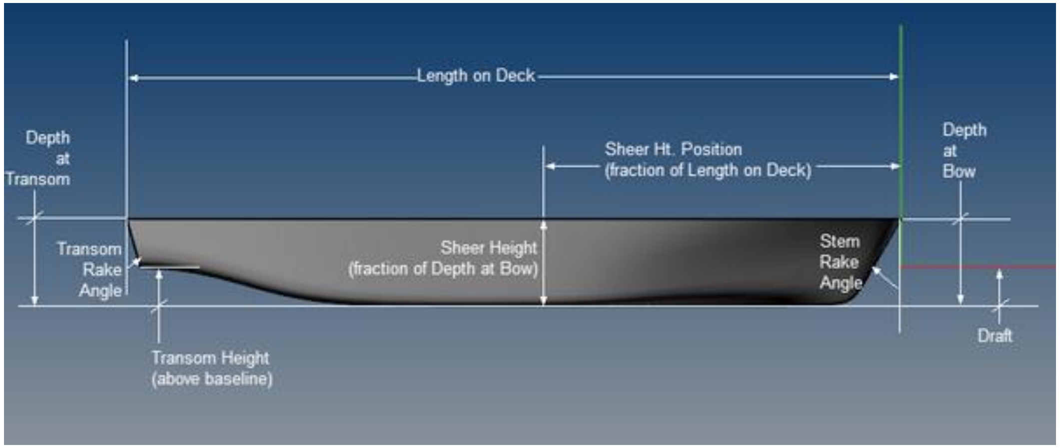
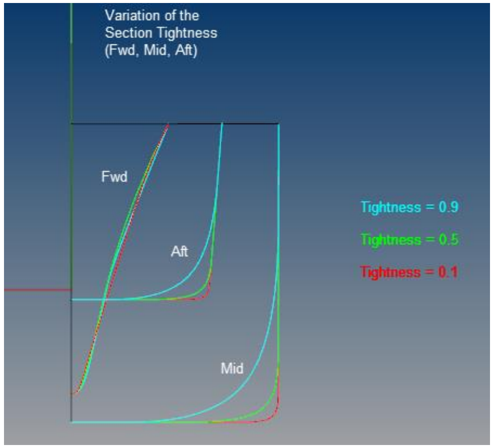
Baseline Hull Form



- 3D modeling tool utilizes input parameters for hull forms generation called "Control Parameters" which allow geometrical transformation
- Iterate until satisfied with input parameter ranges



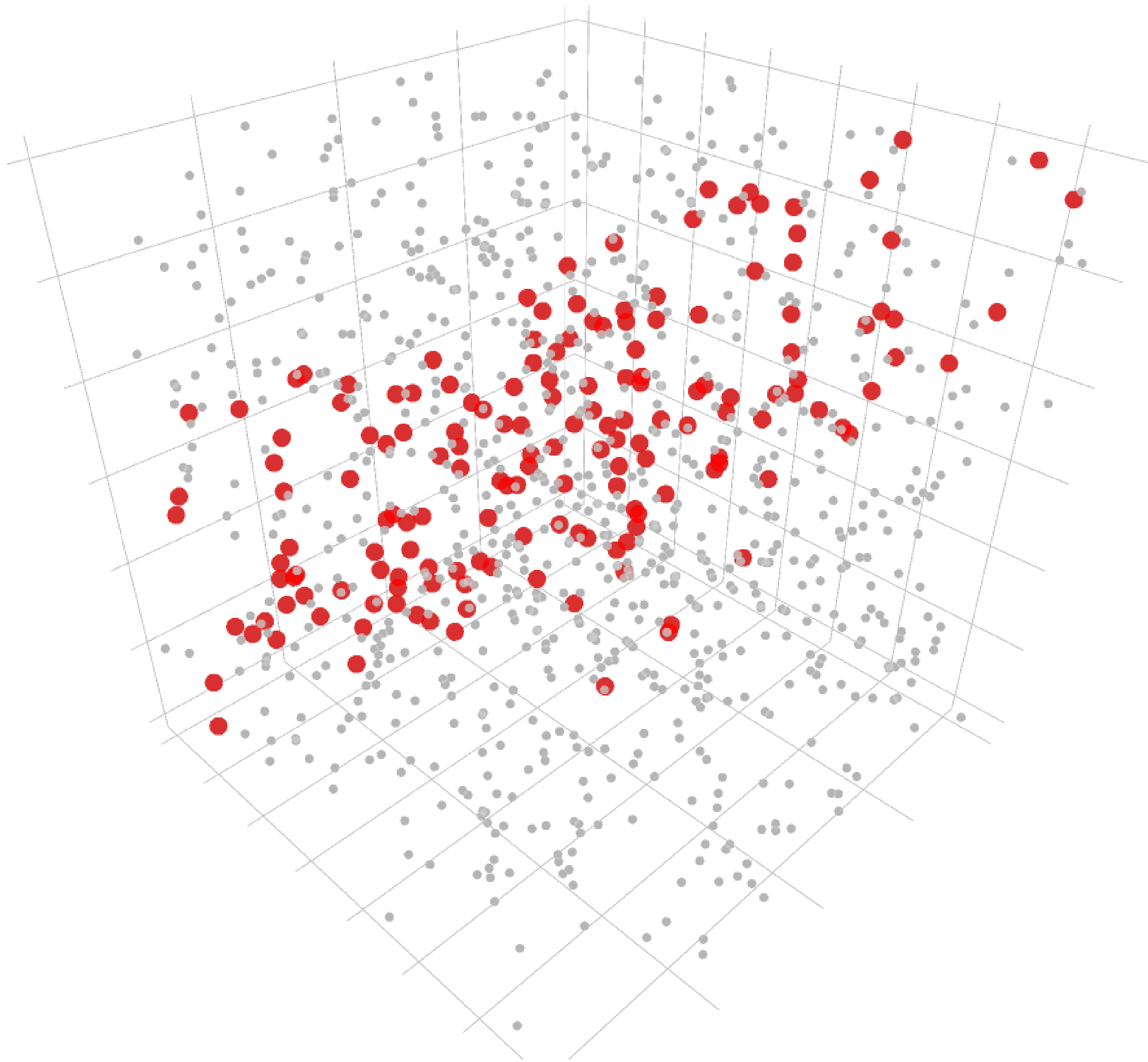


Hull Form Series

- Integrated with ModelCenter for DOE Latin Hypercube Sampling of 1000 runs
- Hydrostatics calculated for each hull
- 143 hulls are feasible as a result of the following hydrostatic constraints:

Variable	Minimum	Maximum
$Beam_{WL}$ to Draft	2.7	3.2
GM to $Beam_{WL}$	0.04	0.16
Slenderness	7	8.5
Prismatic Coefficient	0.56	1
Midship Coefficient	0.8	0.98
Block Coefficient	0.5	1

Feasible Hull Forms in the Design Space Domain



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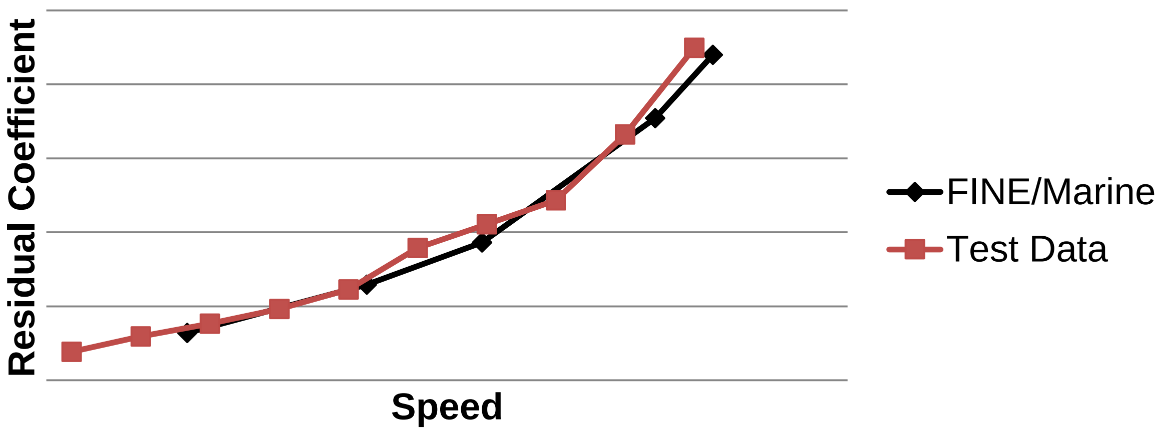
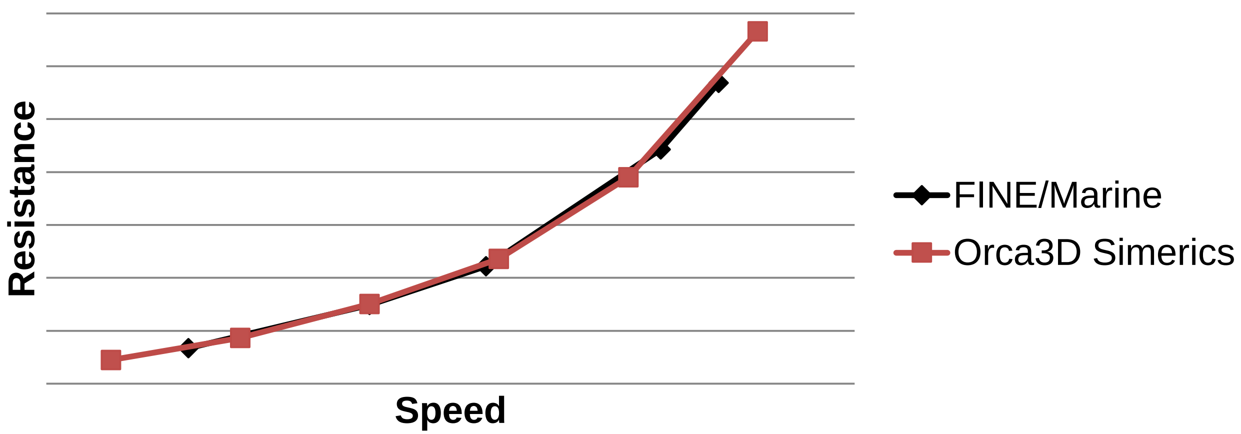
Propulsion Power CFD

- FINE/Marine CFD verification with comparative Navy test data

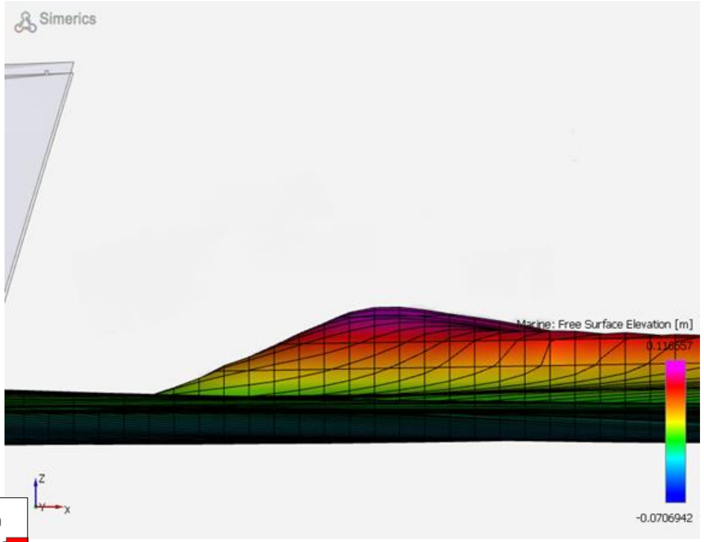


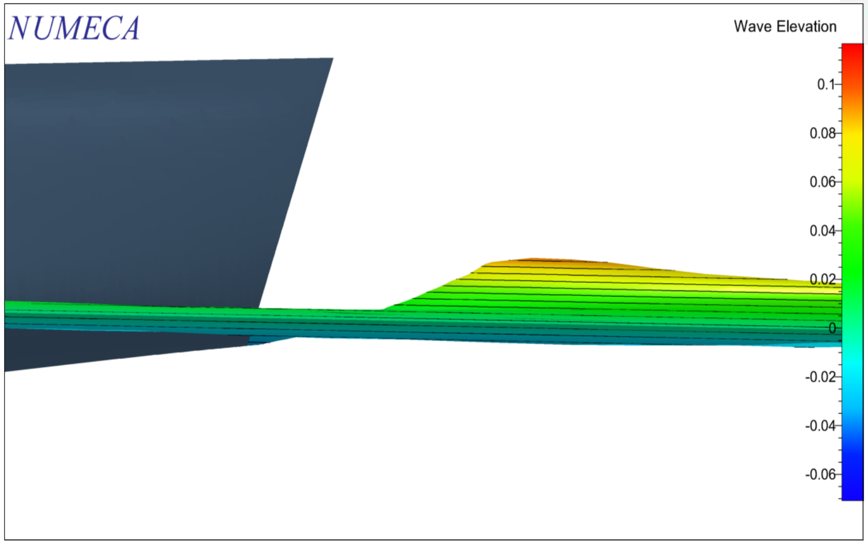
- CFD Comparison of FINE/Marine and Orca3D Simerics



Comparative Stern Waves

Orca3D Simerics
Stern Waves





FINE/Marine
Stern Waves

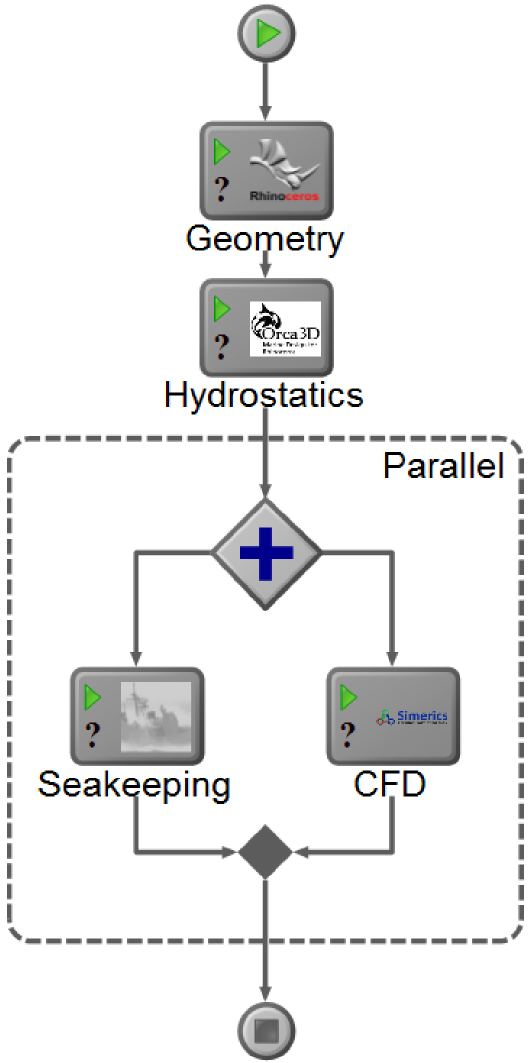
Seakeeping Calculations

- Percent Time of Operability (PTO) using NATO flight deck operability criteria in winter of the North Pacific Ocean at 16 knots
- The operability criteria are set to the following Significant Amplitude (SA) limits:

Motion	Limit
Roll	5°
Pitch	3°
Vertical Velocity	2 m/s

- Integration and automation process from the 3D modeler and analysis code was accomplished through a combination of Python and ModelCenter

ModelCenter Integration



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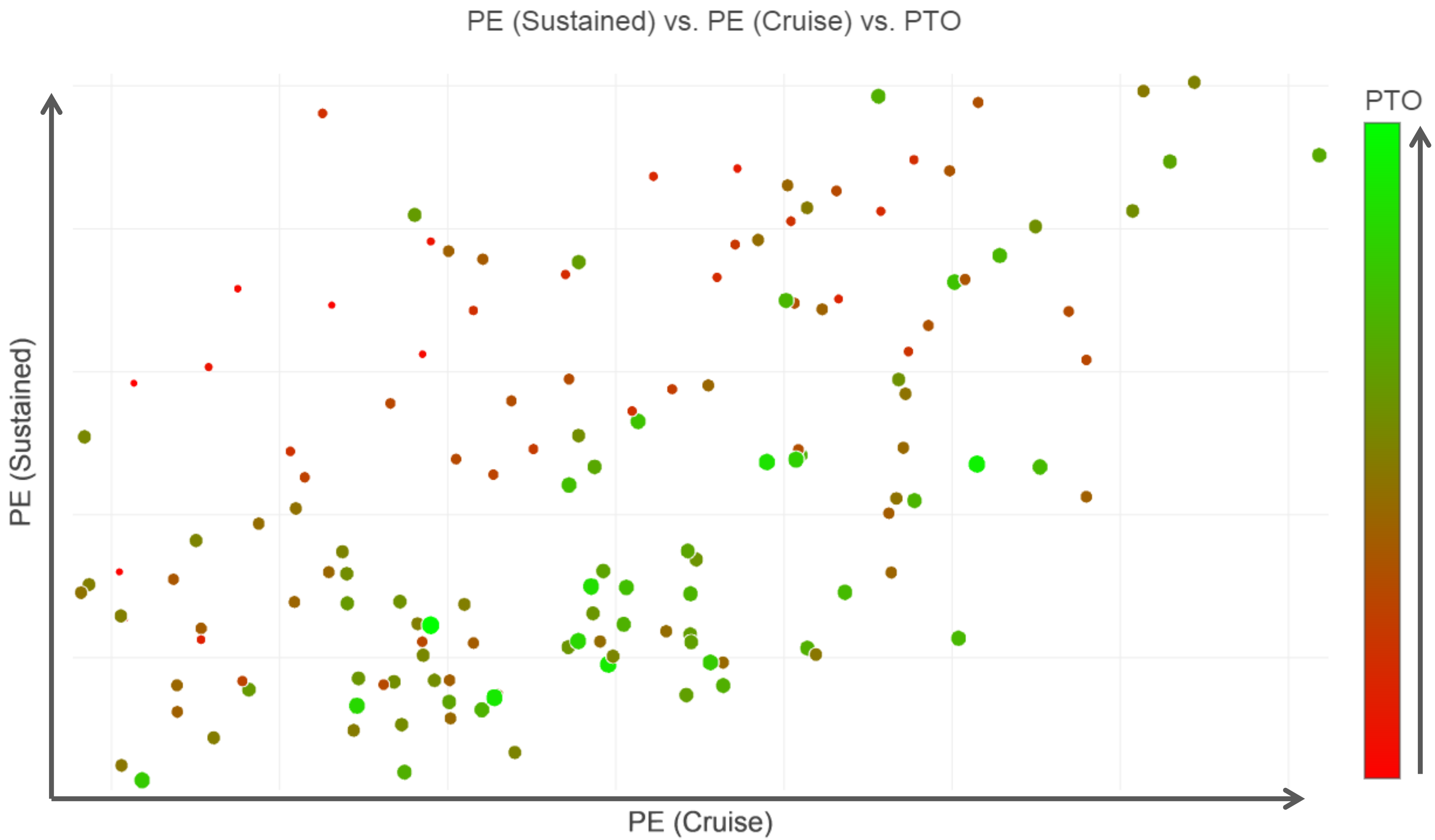
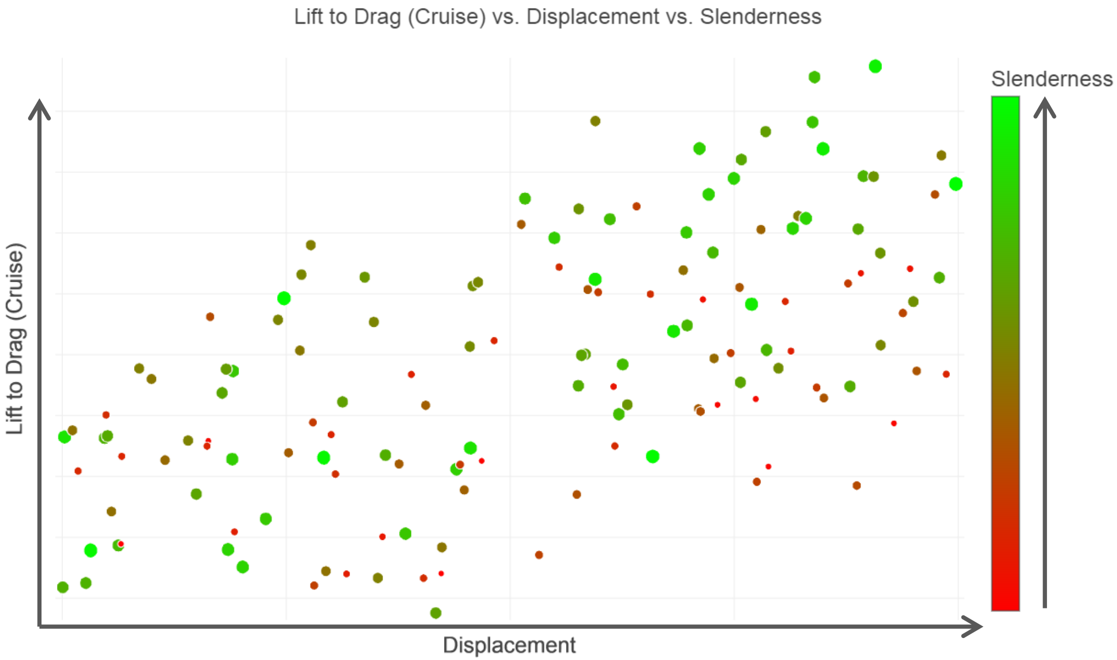
Design Space General View

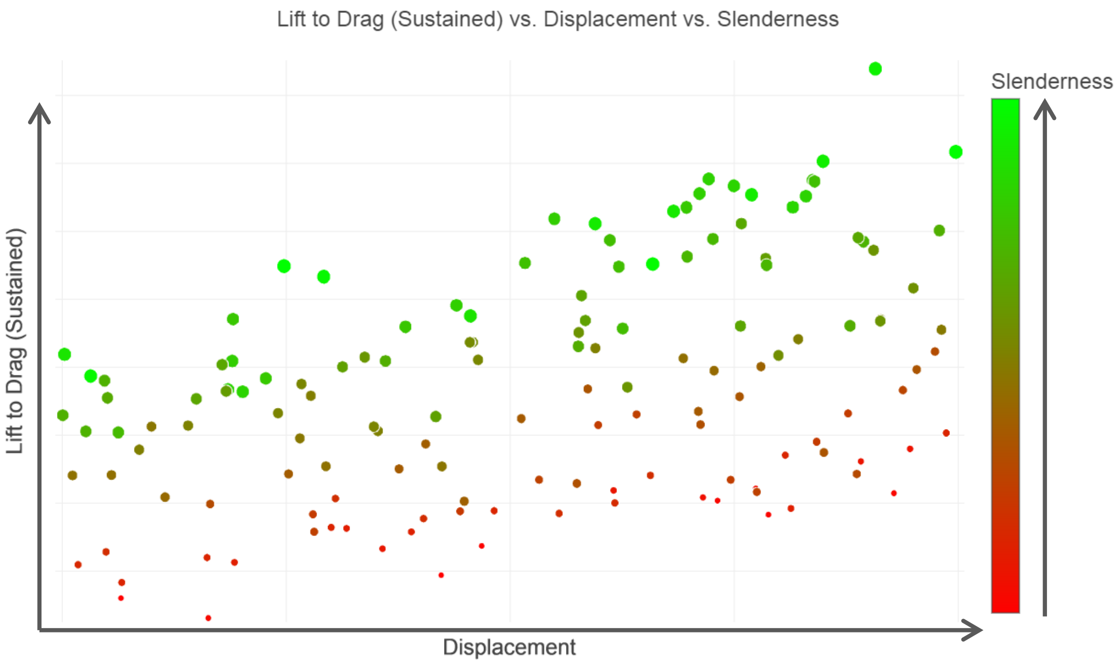
in PE 2D (Domain) with PTO (Size/Color)



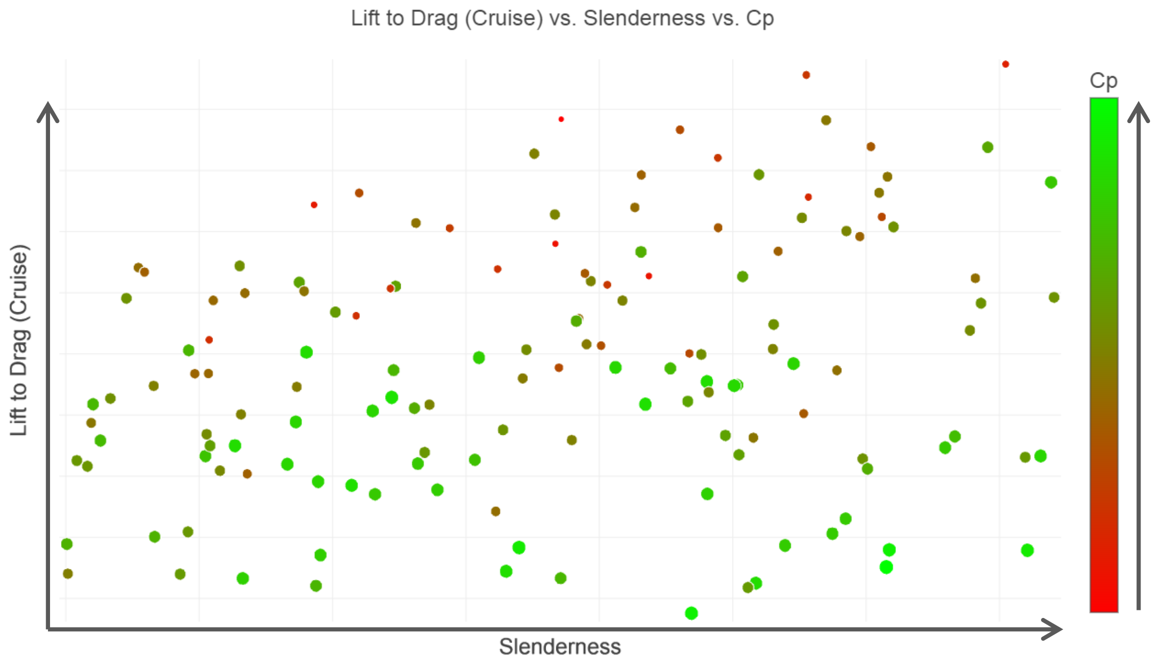
- PE Domain demonstrates considerable spread of PE at all Displacements
- Designs with different PTO are evenly distributed in the Powering domain



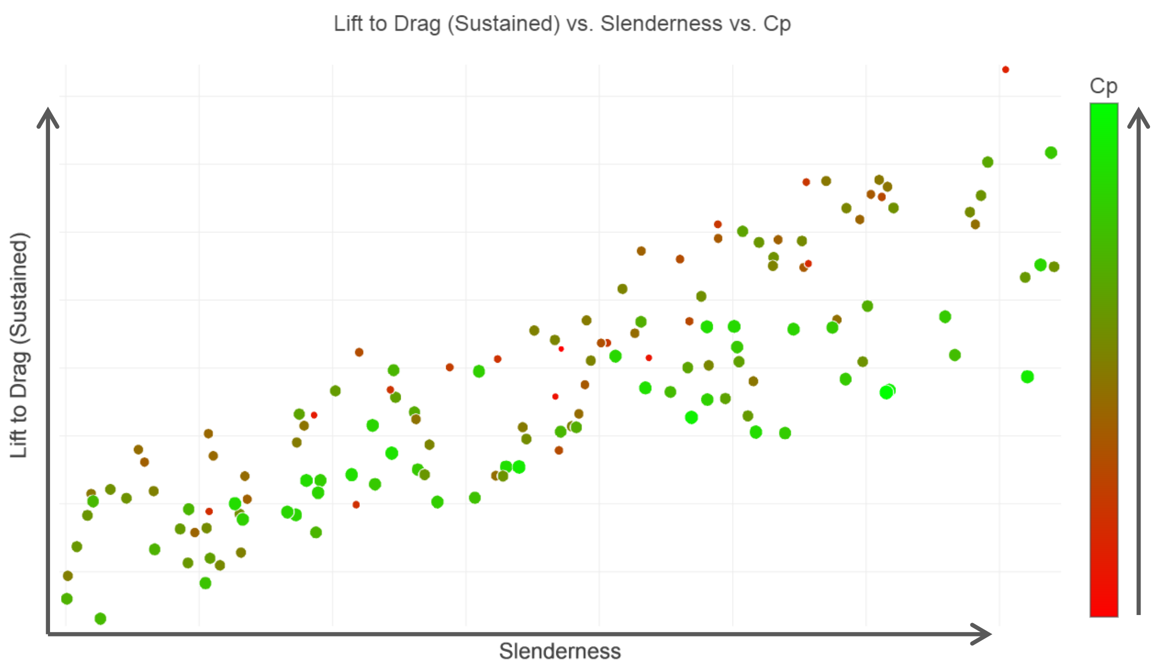
- **Cruise Speed** - high Slenderness points are distributed evenly in the Lift to Drag domain
- High Slenderness does not necessarily correlate to optimal designs (high Lift to Drag ratio) at all displacements



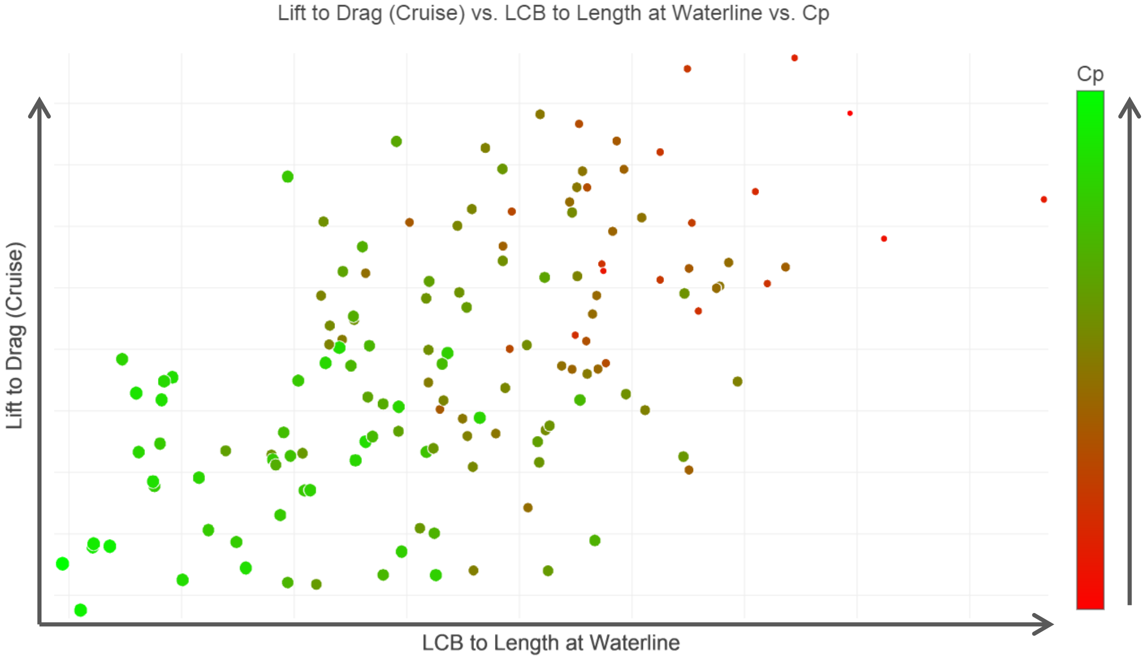
- **Sustained Speed** - highest Lift to Drag values are mostly achieved at highest Slenderness at all Displacements



- **Cruise Speed** - designs with different Cp are distributed almost evenly in the Lift to Drag domain at all displacements

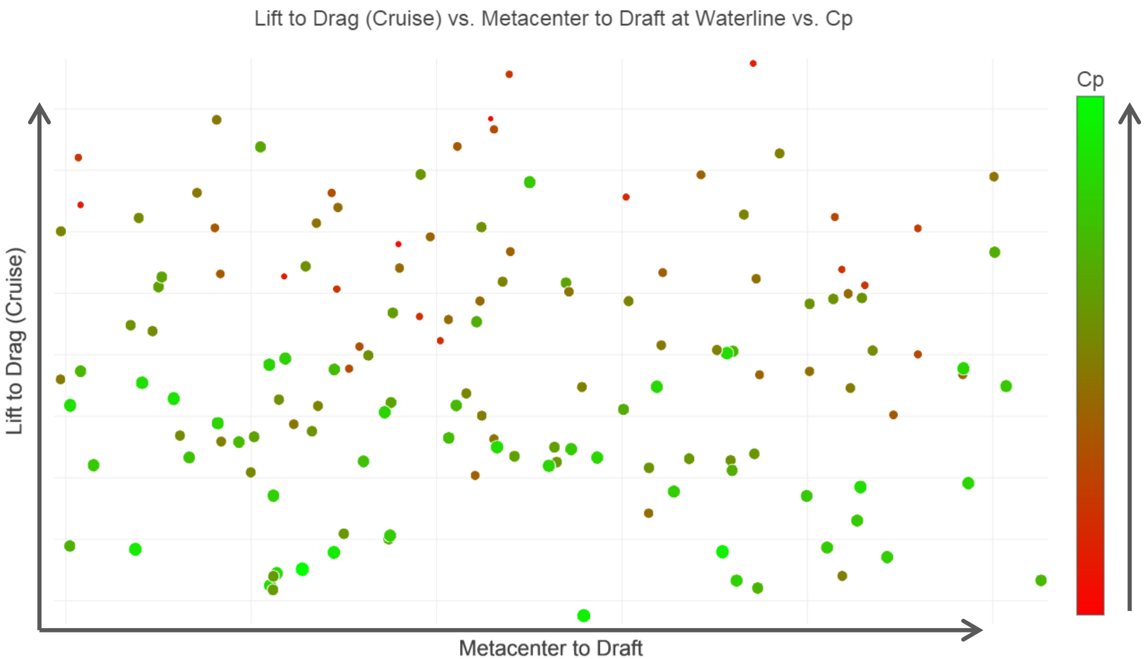


- **Sustained Speed** - The highest Lift to Drag is achieved at low values of Cp



General Trends:

- Higher LCB/Lwl (aft), Lift to Drag → Higher
- Higher LCB/Lwl (aft), Cp → Lower



General Trends:

- No correlations between Lift to Drag (Cruise) and Metacenter Height
- Higher Lift to Drag (Cruise), Cp → Lower

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Response Surface Models in ModelCenter

Sample RSM using
Kriging and Polynomial fitting:

Name	Type	Status	R^2 Adj.
Model.SMP95.Delta_PTO_LC1	Polynomial	Done	99.17%
Design Explorer Kriging	Design Expl...	Done	82.3962%
Polynomial	Polynomial	Done	99.17%
Model.SMP95.Delta_PTO_LC2	Polynomial	Done	99.36%
Design Explorer Kriging	Design Expl...	Done	81.5652%
Polynomial	Polynomial	Done	99.36%
Model.SMP95.Delta_PTO_LC3	Polynomial	Done	99.04%
Design Explorer Kriging	Design Expl...	Done	84.5744%
Polynomial	Polynomial	Done	99.04%
Model.SMP95.Delta_PTO_LC4	Polynomial	Done	96.78%
Design Explorer Kriging	Design Expl...	Done	79.6725%
Polynomial	Polynomial	Done	96.78%
Model.SMP95.Delta_PTO_LC5	Polynomial	Done	98.79%
Design Explorer Kriging	Design Expl...	Done	93.0498%
Polynomial	Polynomial	Done	98.79%
Model.SMP95.Delta_PTO_LC6	Polynomial	Done	99.39%
Design Explorer Kriging	Design Expl...	Done	93.5956%
Polynomial	Polynomial	Done	99.39%

All variables resulted in R^2 of 95% or higher

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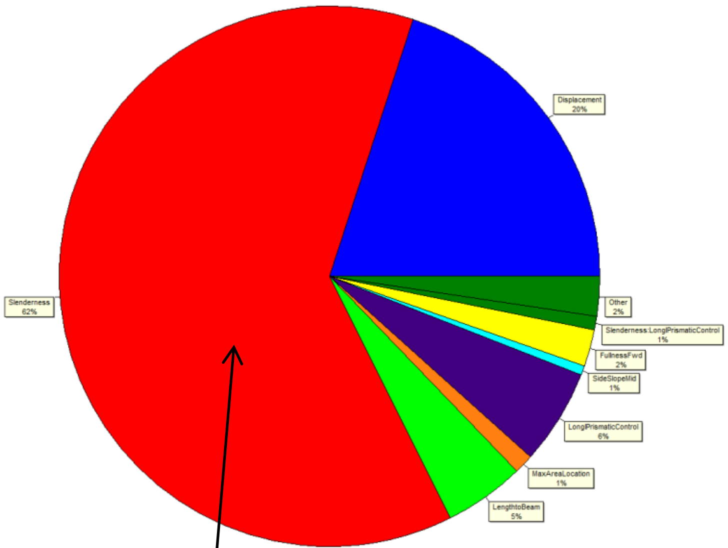
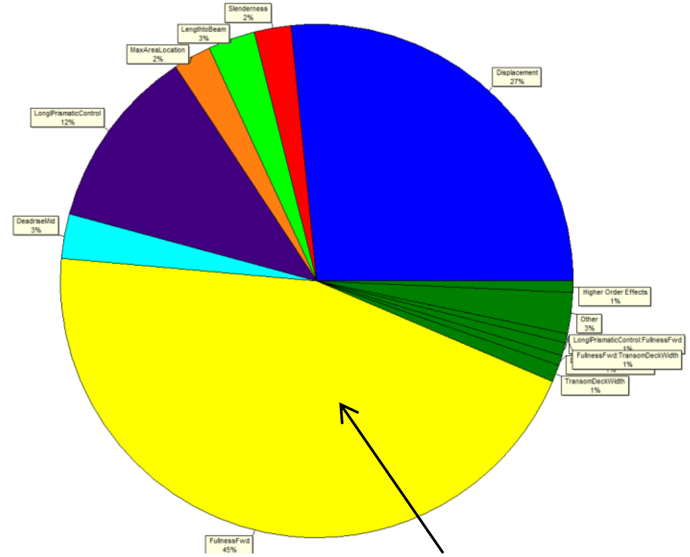
Design Parameters Influence on Propulsion Criteria: PE Powering (L/D) and PTO

L/D at Sustained Speed



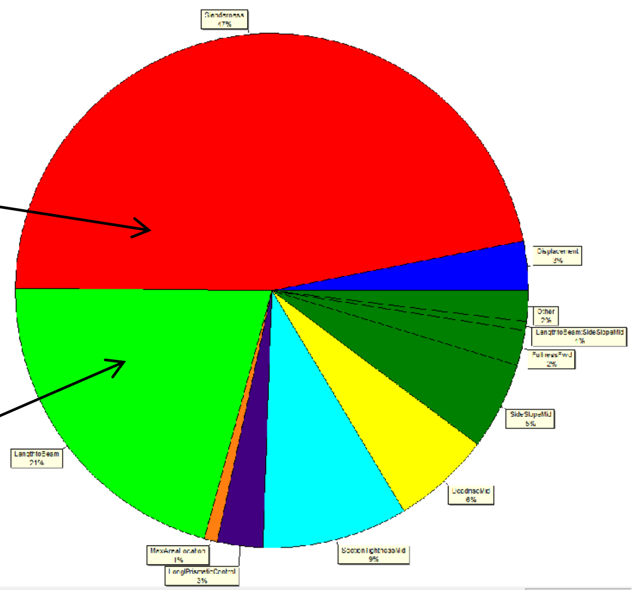
L/D at Cruise Speed



Fullness FWD

Slenderness

PTO



L/B

Design Costs of Hull Form parameters on Performance Criteria at Full Range of Displacements

Design Costs $\lambda_j = \partial(\Delta F)/\partial X_j$ are mostly consistent at various groups of displacements, however their numeric values are different. For example, for Slenderness parameter Design Costs are the following:

Displacement Group	**Small**	**Medium**	**Large**
$\lambda_{SI}^{\Delta PTO}$	0.1	0.12	0.12
$\lambda_{SI}^{\Delta PE}{}_{Cruise}$	0.03	0.01	0.02
$\lambda_{SI}^{\Delta PE}{}_{Sustained}$	0.23	0.27	0.27

The trend is fully consistent with all other sensitivity representative plots; Prediction Profiler allows us to estimate the design costs, which can be further used to coordinate hull forms selection in the course of design process among design subsystems and disciplines.

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Optimization Tasks

- For each displacement range of Small, Medium, and Large ship, two scenarios are optimized with Darwin Algorithm:

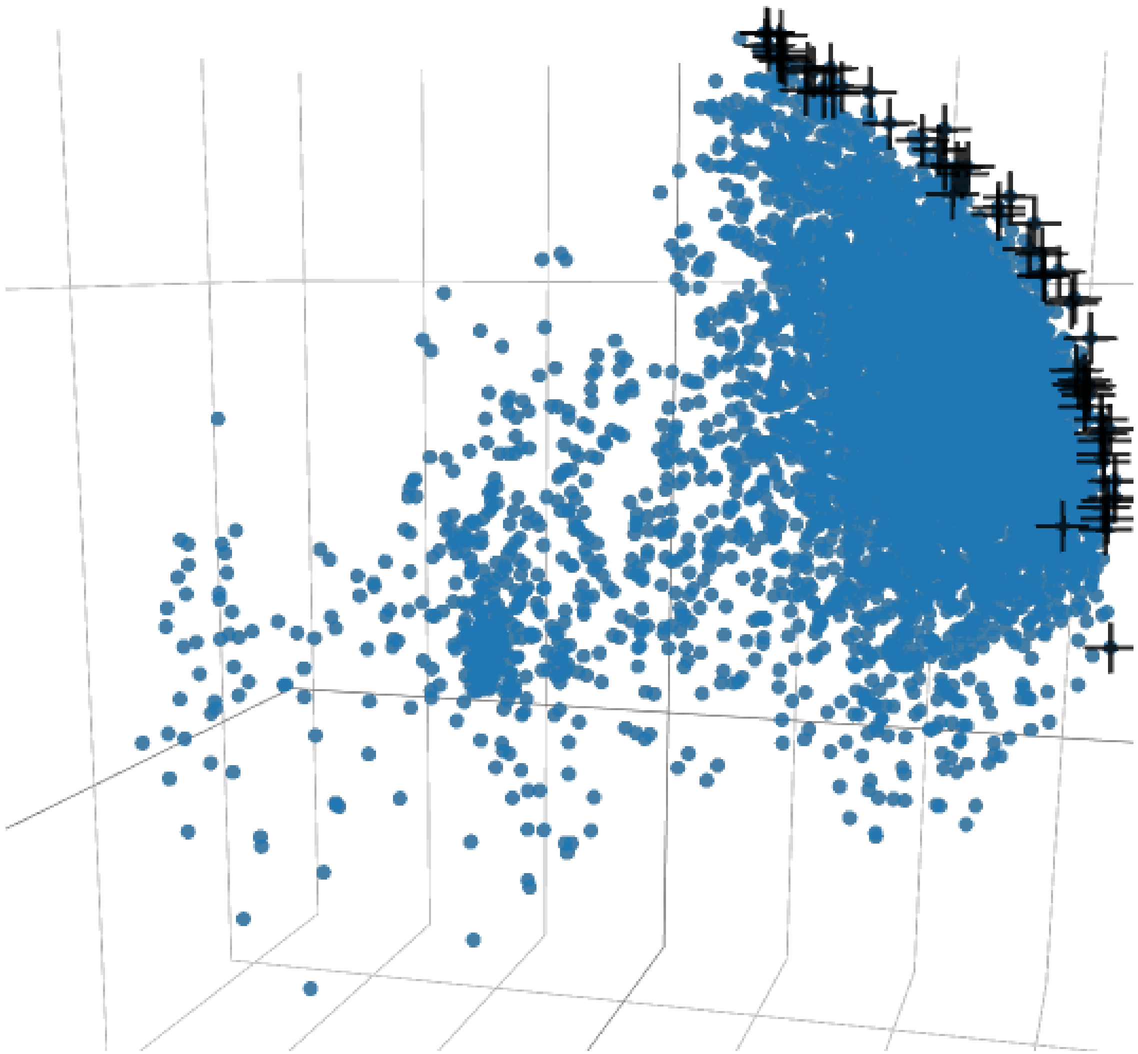
  1. Powering: $\Delta \frac{L}{D}_{cruise}$ vs. $\Delta \frac{L}{D}_{sustained}$

  2. Performance: $\Delta \frac{L}{D}_{cruise}$ vs. $\Delta \frac{L}{D}_{sustained}$ vs PTO

- Constraints are applied for the following hydrostatic variables:

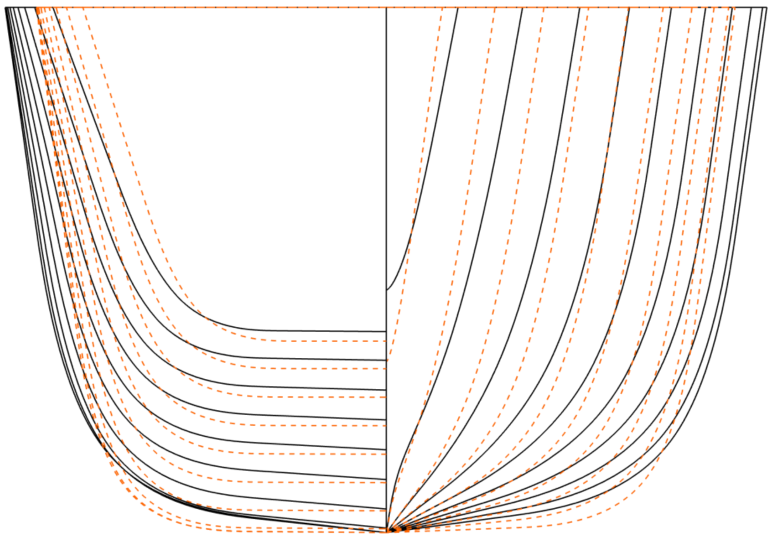
Variable	Minimum	Maximum
$Beam_{WL}$ to Draft	2.7	3.2
GM to $Beam_{WL}$	0.04	0.16
Prismatic Coefficient	0.56	1
Midship Coefficient	0.8	0.98
Block Coefficient	0.5	1

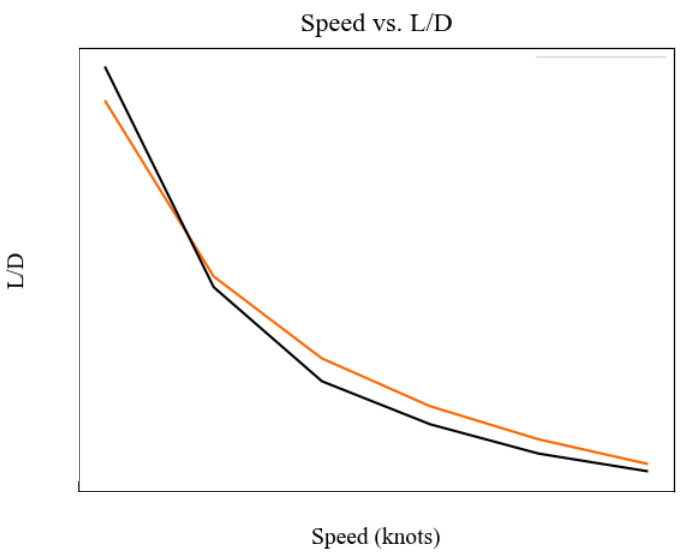
Pareto Front



1. Powering Optimization:
Pareto Point Example Snapshot

Optimized hull form (orange) versus baseline hull form (black)



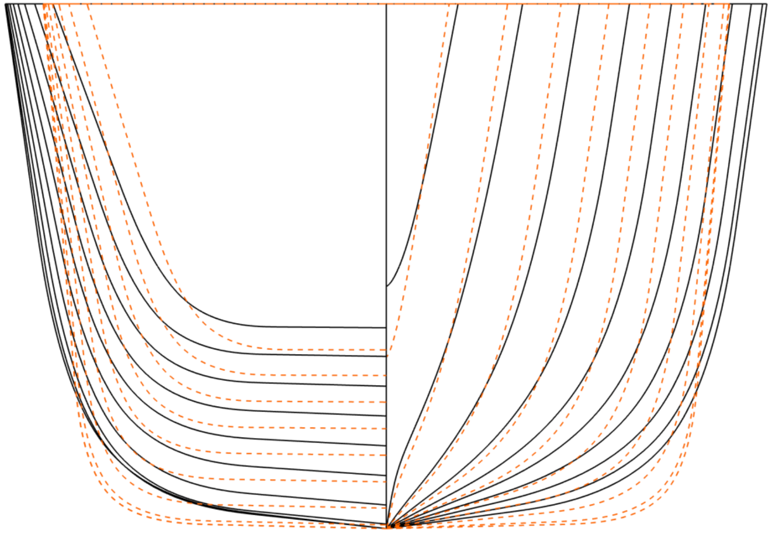


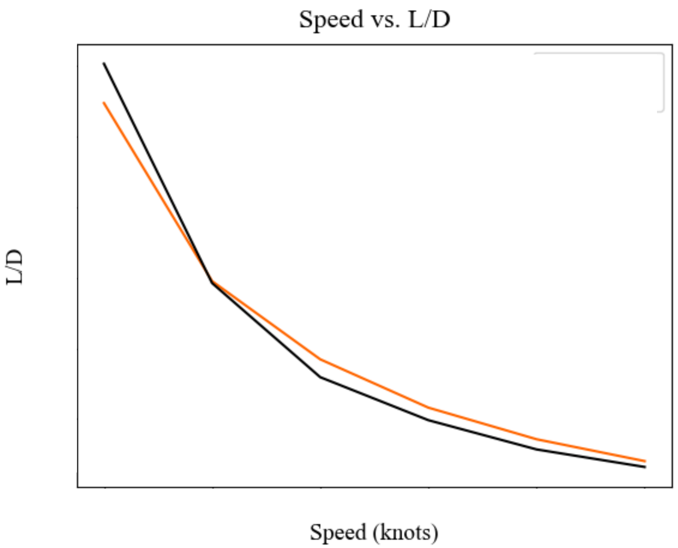
Performance Optimization Characteristics	
Δ Lift to Drag (Cruise)	**5.2%**
Δ Lift to Drag (Sustained)	**35.6%**
Δ PTO	5.7%

Not Optimized → Δ PTO

2. Performance Optimization:
Pareto Point Example Snapshot

Optimized hull form (orange) versus baseline hull form (black)





Performance Optimization Characteristics	
Δ Lift to Drag (Cruise)	**0.9%**
Δ Lift to Drag (Sustained)	**25.4%**
Δ PTO	**12.2%**

Optimization Tasks Summary

The results of sample optimization tasks can be summarized in comparison with the baseline hull form with the following table:

	Small Displacement Group		**Large Displacement Group**	
Criteria	**Powering**	**Performance**	**Powering**	**Performance**
Δ Lift to Drag (Cruise)	-5.0%	-8.0%	5.2%	0.9%
Δ Lift to Drag (Sustained)	12.5%	7.1%	35.6%	25.4%
Δ PTO	1.7%	6.4%	5.7%	12.2%

It is necessary to note that in the Powering results are presented with designs, which are already the best compromise between Powering at two speeds. The table shows the effect of adding the Operability criterion.

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Summary and Recommendations

1. The Study resulted with:
   - Series of the Monohull forms of combatant-type between small and large displacements
   - Effective Power Database with all coefficients, running trim data and detailed flow characteristics, including Wave pattern, Pressure, Streamlines and Velocity Distributions
   - Seakeeping database with Percent Time Operability at long and short crested waves
   - Response Surface Models, which provide quick, easy solution to calculate all hull forms geometrical and performance characteristics.
   - Results of ModelCenter sensitivity analysis and sample optimization tasks
2. It is recommended that
   - Surrogate Model development would include more types of regression relationships, including Neural Nets
   - DOE would include Sobol algorithms or o called LPt sequence of points