ESD.77

Multidisciplinary System Design Optimization

Spring 2010

Barge Design Optimization

Anonymous MIT Students

What is a barge?

Flat bottomed vessel, typically non self-propelled, used to carry low value, heavy or bulky items.

Motivation

- Interest in marine environment disciplines.
- Opportunity to use and bring together previous academic experience.
- A common ship design problem would be extremely complex to handle in one semester.

Multi-disciplinary

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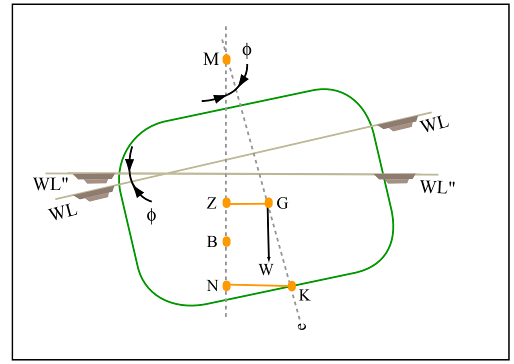
Hydrostatics



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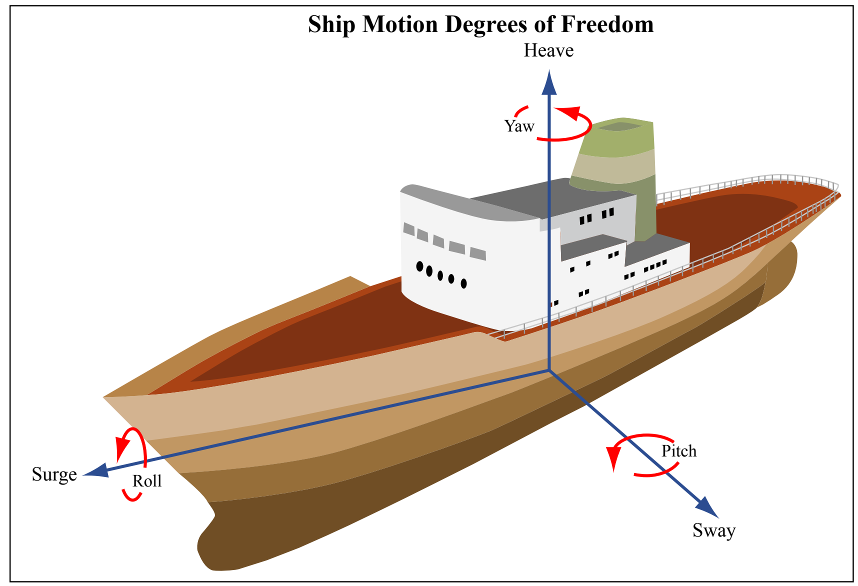
Hydrodynamics



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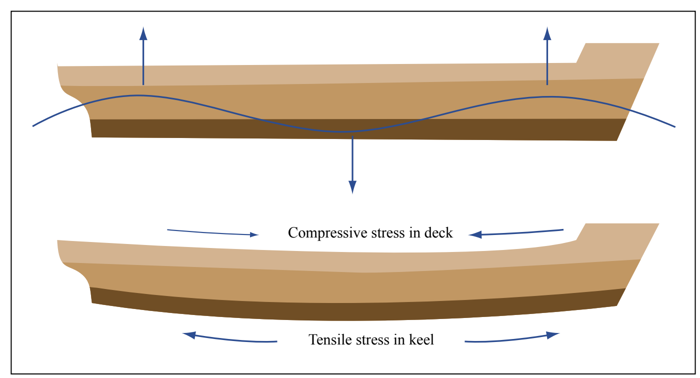
Structural Mechanics



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Problem Formulation

Design Variables		Lower Bound	Upper Bound	Unit
L	Length	90	140	m
B	Beam	20	35	m
D	Depth	4	9	m
t	Plate Thickness	12	28	mm

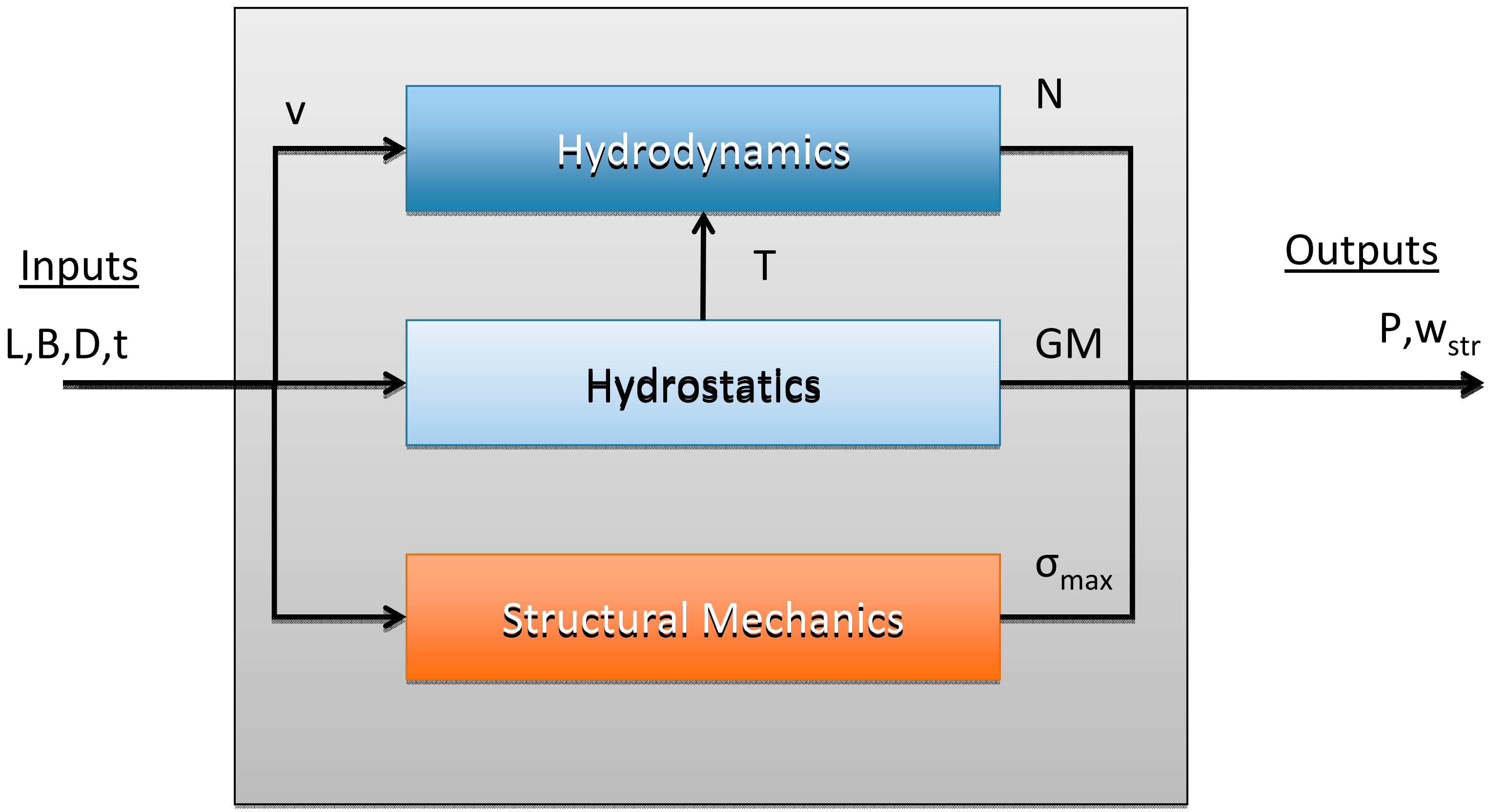
Design Parameters		Value	Unit
v	Speed	10	knots
kg	Payload vertical center of gravity	1.2D	
lcg	Payload longitudinal center of gravity	0.5L	
ω	Peak spectral frequency	0.7	rad/sec
H	Significant wave height	2.5	m
ρ	Sea water density	1025	kg/m^3
ρ_{str}	Material thickness	7850	kg/m^3

Barge cross-section

Design Objective is to maximize payload (P) s.t.

Inequality Constraints	
N<60	Number of occurences of green water on deck per hour
T<6m	Draft
GM>0.15m	Metacentric height
$\sigma_{k,sag}$<250MPa	Keel stress at sagging wave
$\sigma_{k,hog}$<250MPa	Keel stress at hogging wave
$\sigma_{d,sag}$<250MPa	Deck stress at sagging wave
$\sigma_{d,hog}$<250MPa	Deck stress at hogging wave

Input/Output Diagram

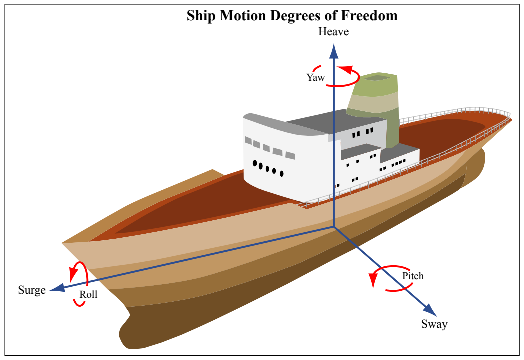


Modeling in MATLAB Multidisciplinary Feasible (MDF) Model

- Payload, the objective function, is also required as input by all modules.
- Feasibility is enforced at each optimization iteration.

Modeling in MATLAB Hydrodynamics

- Curve fitting of experimental local hydrodynamics properties from Lewis theory to allow for a continuous design space exploration.
- Seakeeping analysis for coupled heave and pitch motions using 2D strip theory.



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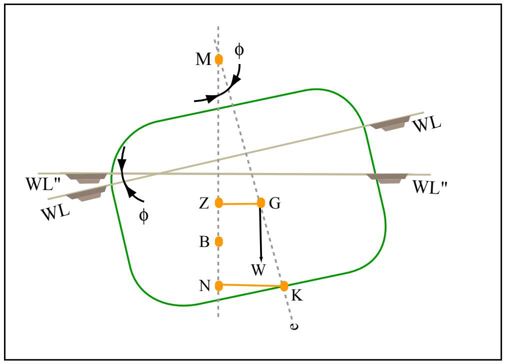
Assumption:

•Bretschneider spectrum with significant wave height of 2.5m and peak spectral frequency of 0.7rad/sec

Modeling in MATLAB Hydrostatics

- Determines the vertical metacentric height which is evaluated against American Bureau of Shipping (ABS) rules.



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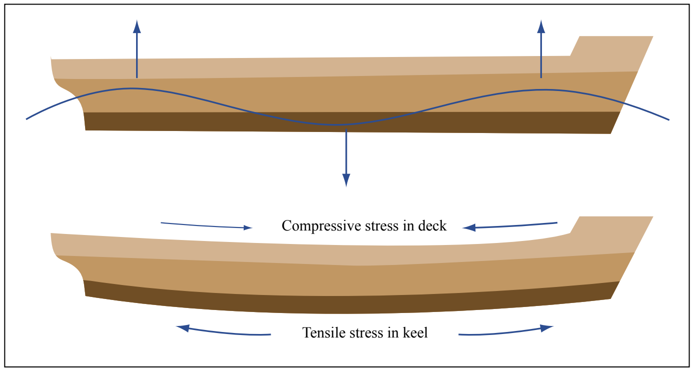
Assumption:
•Vertical position of payload's center of gravity at 1.2*D

Modeling in MATLAB
Structural Mechanics

- Uses ABS parametric equations to determine maximum keel and deck stresses in sagging and hogging wave conditions.



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Assumptions:

•Uniform longitudinal weight distribution.

Simulation and Benchmarking

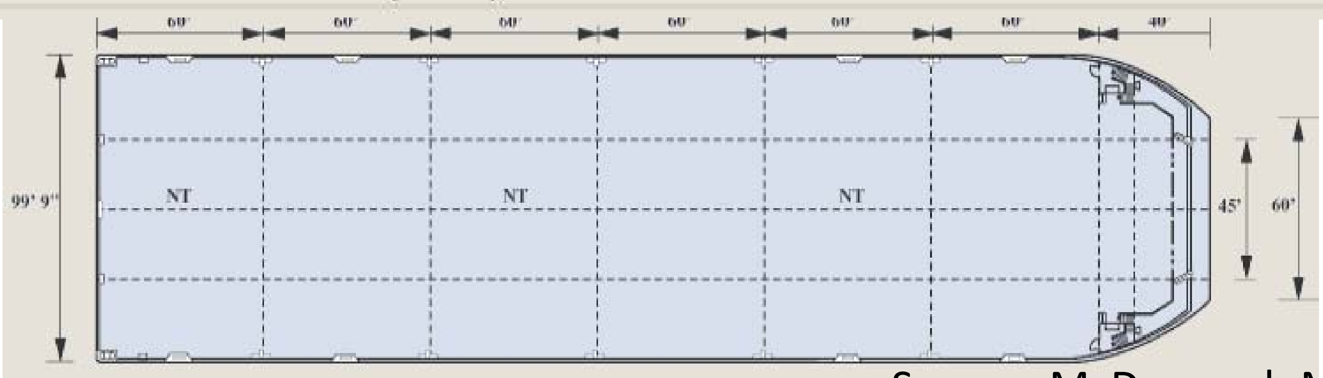
$$x = \begin{bmatrix} L \\ B \\ D \\ t \end{bmatrix} = \begin{bmatrix} 122 \\ 30 \\ 6.1 \\ 16 \end{bmatrix}$$

P=14,670tons

T=4.35m

N is the active constraint

Specifications - Marmac 400					
Length	400'	(121.92m)	Uniform Deck Load	4500 lbs/ft^2	(21,971 kg/m^2)
Width	99'9"	(30.4m)	Cargo Capacity at Loadline	12,625.8 s. tons	(11,453.9m tons)
Depth	20'	(6.10m)	Gross Tonnage	5781	
Loadline Draft	14'3"	(4.34m)	Net Tonnage	1741	
Light Draft	3'3"	(0.75m)			



Source: McDonough Marine Service

Initial Design Space Exploration

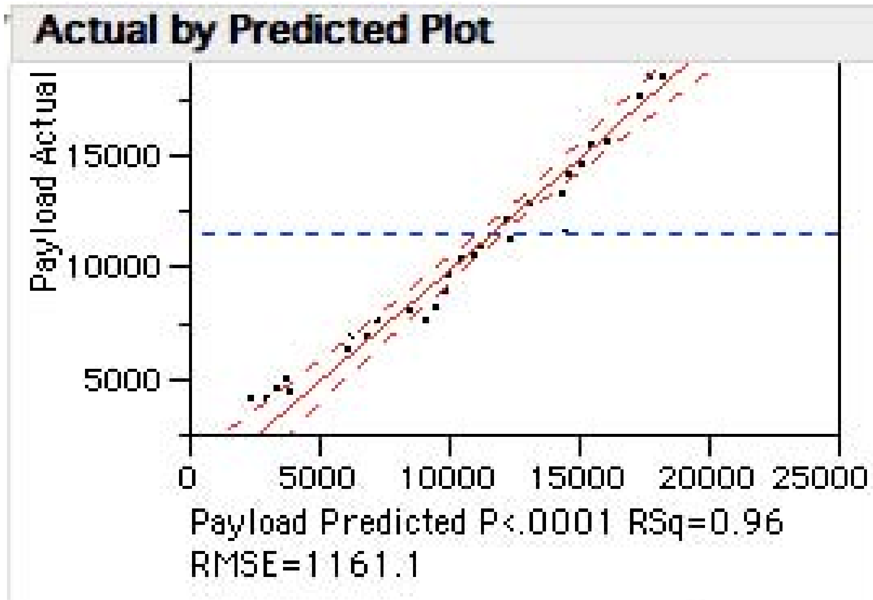
- 4 Design variables
- 3 Level (lower bound, mid, higher bound)
- JMP Statistical Software
- Generate DOE to capture main effect and two-way interactions
- 48 runs (16 were unfeasible)

Initial Design Space Exploration

Analysis of 32 feasible designs:

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-25816.74	1781.269	-14.49	<.0001
L	220.82255	11.14172	19.82	<.0001
B	444.69651	34.35048	12.95	<.0001
D	218.94769	126.6491	1.73	0.0953
t	-50.15281	39.0948	-1.28	0.2104



Recommended starting point for numerical optimization:

$$x = \begin{bmatrix} 140 \\ 35 \\ 9 \\ 20 \end{bmatrix}$$

Gradient-Based Optimization

SQP-MATLAB's "fmincon":

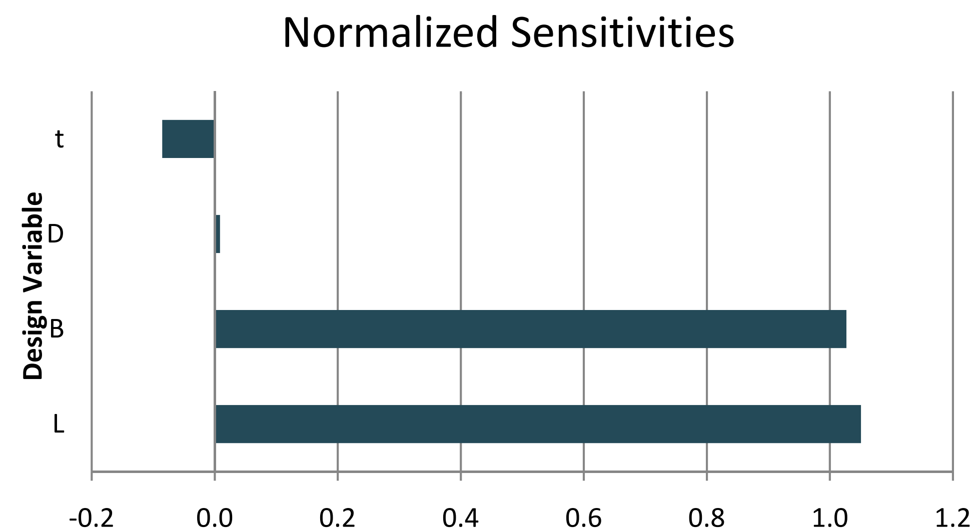
- Ability to handle multiple variables
- Ability to handle design variables' bounds

Results: P=23,530tons:

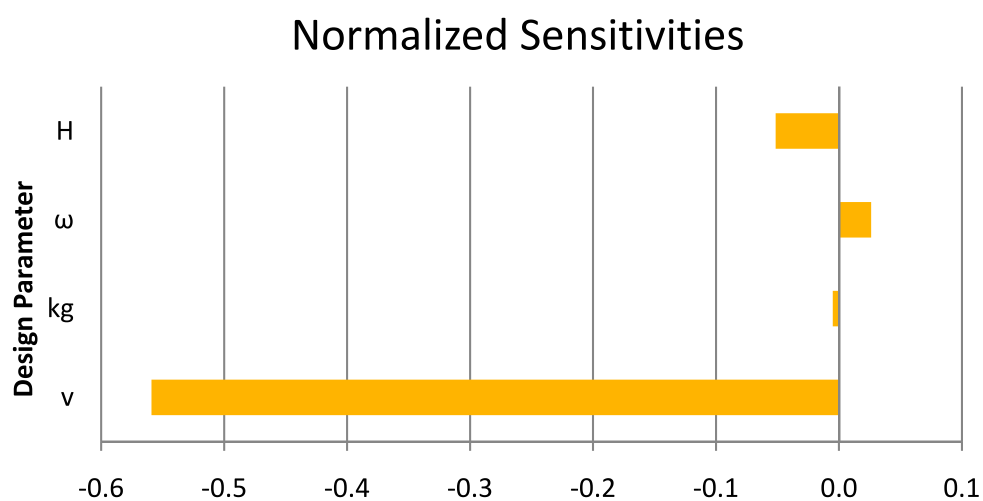
$$x^* = \begin{bmatrix} 137.8 \\ 34.2 \\ 8.7 \\ 14.2 \end{bmatrix} \quad \text{vs.} \quad x = \begin{bmatrix} 140 \\ 35 \\ 9 \\ 20 \end{bmatrix}$$

Sensitivity Analysis

Variables:



Parameters:

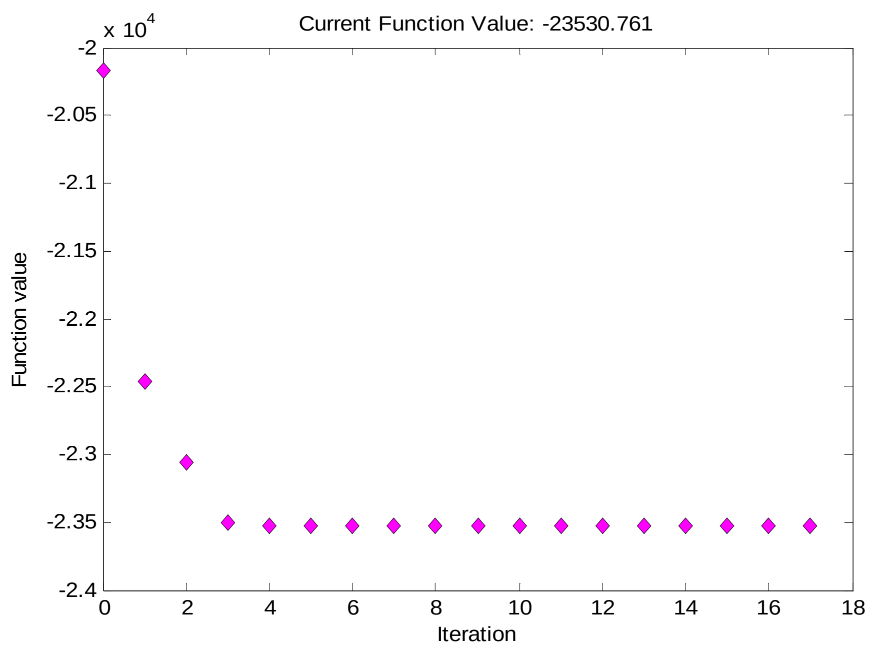


Active constraints:

- N
- $\sigma_{d,hog}$

Post-Optimality Analysis

- Hessian diagonal entries close to *O*(1)
- No improvement was achieved by trying to scale the design variables



Heuristic Optimization

Genetic Algorithm:

- Easy implementation of fitness function
- Close to the optimum

Results: P=22,468tons at $x = \begin{bmatrix} 138.7 \\ 34.6 \\ 8.9 \\ 25.1 \end{bmatrix}$ vs. $x^* = \begin{bmatrix} 137.8 \\ 34.2 \\ 8.7 \\ 14.2 \end{bmatrix}$

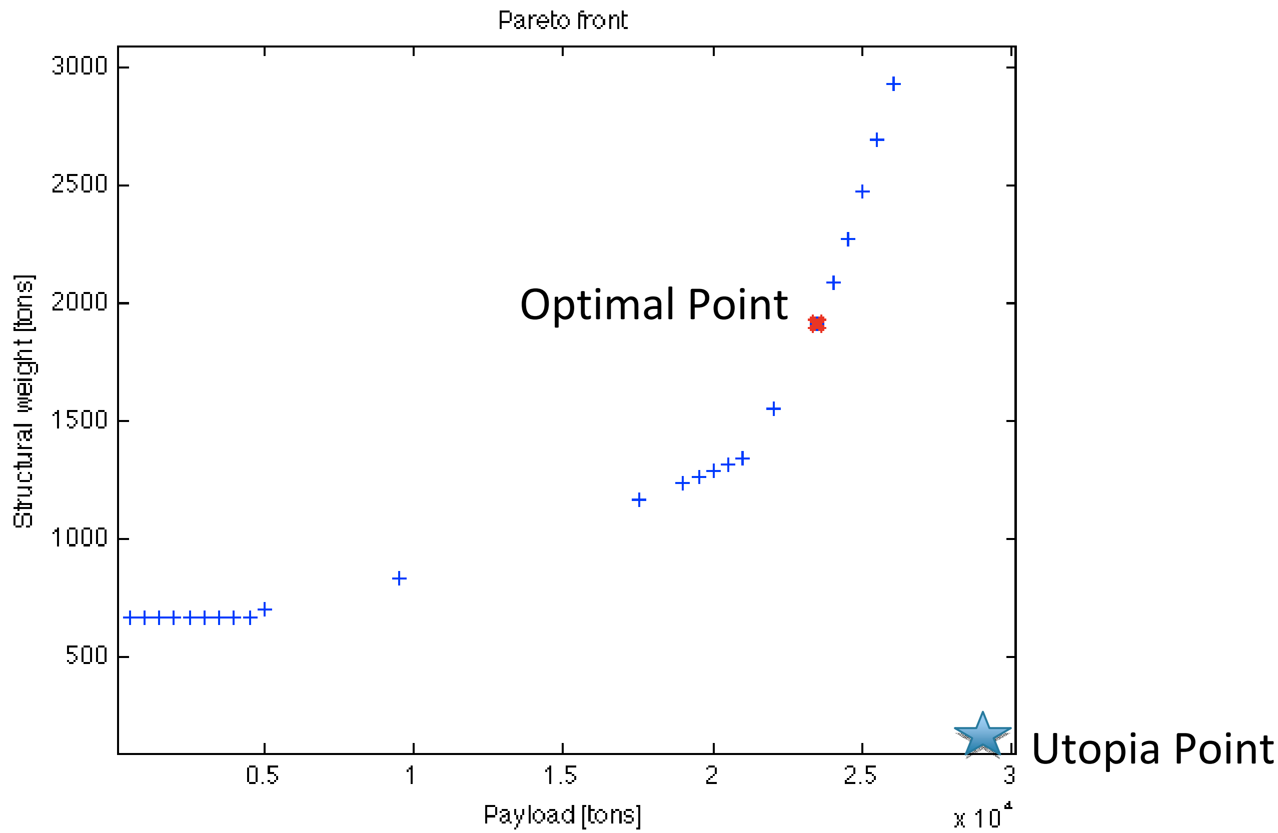
Global Optimum

Leveraging:

- DOE
- Gradient-based optimization
- GA

Maximum Payload of P=23,530tons at $x^* = \begin{bmatrix} 137.8 \\ 34.2 \\ 8.7 \\ 14.2 \end{bmatrix}$

Multi-Objective Optimization



Trade-off analysis at optimal payload solution:
For an extra ton of payload we need to add 244kg of structural weight

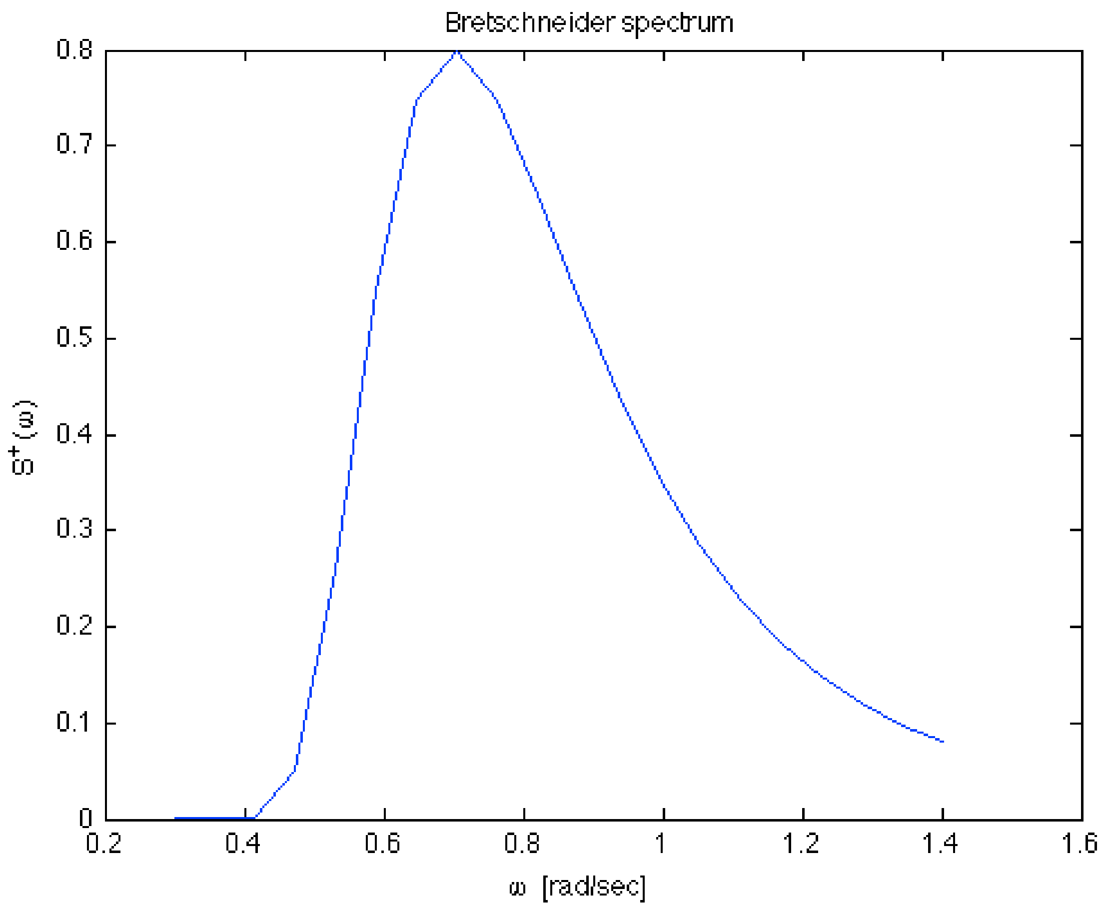
Conclusions

Model fidelity can be improved:

- Cross-section, scantlings, non-uniform plate thickness
- Consider most appropriate sea spectrum
- Evaluate all 6 degree of freedom motions and most importantly roll.

But will make optimization more challenging.

Back-up


Bretschneider spectrum
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
ω [rad/sec]
S⁺(ω)

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