Implementation of Design Space Exploration and Optimization for Early Stage Ship Design

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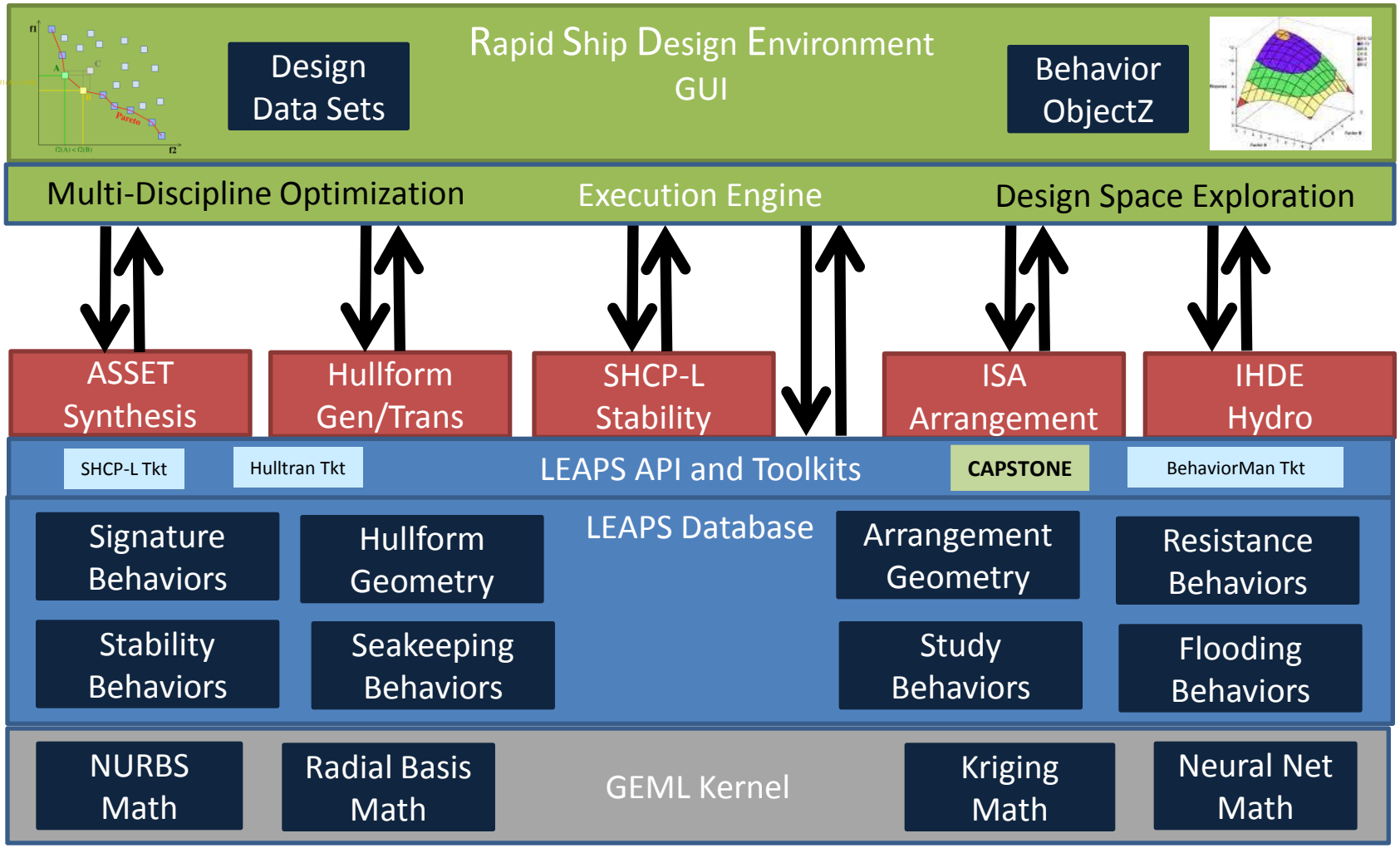
DOD HPC MODERNIZATION PROGRAM

Rapid Ship Design Environment



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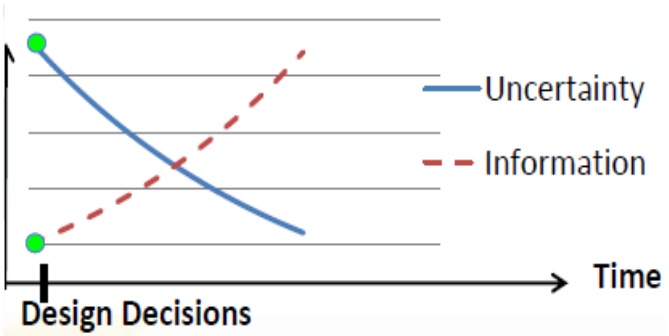
Problem Statement

Historically the Navy has used a point design methodology when designing a ship. During the early stages of design there is enormous pressure to "lock down" the ship design as early as possible. These design decisions are made at a time when the detail and fidelity of the design information is low, and the requirements of the design are not well known.

Later in the design process, the fidelity of the ship design is brought up to a point where physics based analysis can be performed. Analysis reveals deficiencies, and these deficiencies require relaxation of requirements or exotic solutions to retain an acceptable ship design.



The remainder of the design effort is a frantic race to keep the ship design feasible, and meet the requirements. By the end of the process, the ship design is at the edge of infeasibility, exotic, expensive, and has little or no capability to accept future growth. The resulting ship design is difficult to maintain, and is unable to keep pace with the rapidly changing security environment.

Example Design Problem

For the purposes of our design problem, let us assume Navy is designing a notional new cruiser. The design and engineering details of the ship and systems are fictitious

The primary mission of the cruiser is to provide protection to the aircraft carrier from enemy missiles and aircraft.

Two design teams are developing the design in parallel, each using a different design approach. This presentation provides a comparison of two different design approaches.

- Point-based design method
- Set-based design method

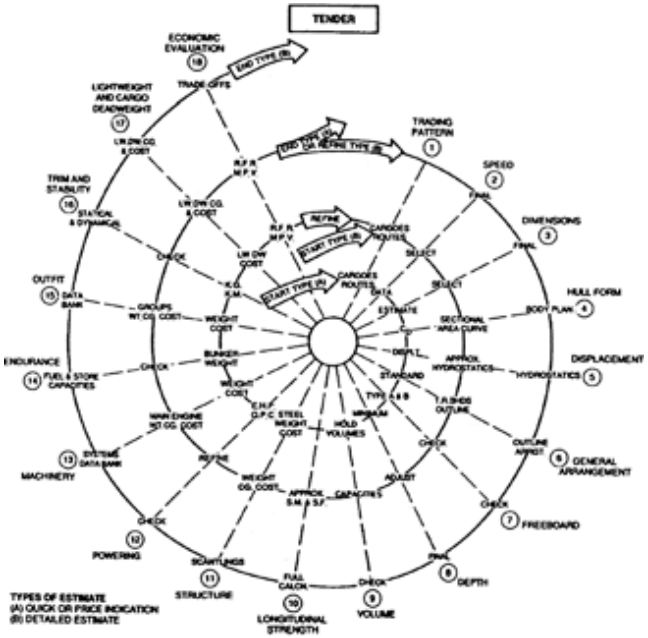
To facilitate the comparison, a design scenario has been developed to exercise both design approaches. This design scenario is a requirements change during the design process. This is a realistic example of the type of design challenges that occur during the ship design process.

Both teams will use the same Naval Architecture tools.

Point-Based Design

Point-based design is an approach to the design effort where:

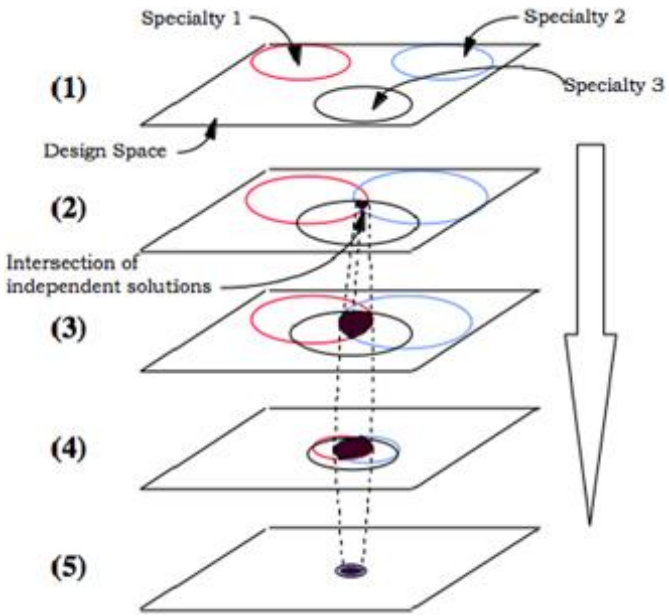
- Baseline Design is created, then configuration managed
- Design is iterated to achieve feasibility and ideally, optimality, during the design process.
- Typically one major design change is incorporated during each design iteration. The design iteration determines the full ship impact of the change.
- Design is typically worked by each engineering discipline in series, resulting in “over the wall” type engineering.
- Design is complete when you run out of time.



Set-Based Design

Set-based design is an approach to the design effort where:

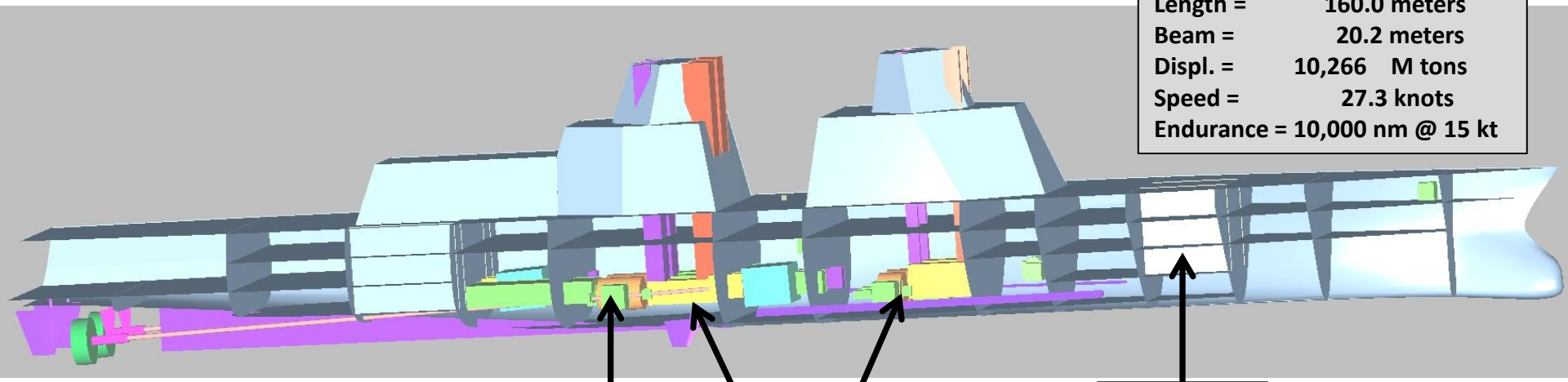
- broad sets of design parameters are defined
- these sets are kept open (no decision) until the tradeoff information is fully defined
- as the sets narrow, the level of detail (design fidelity) increases
- the sets are gradually narrowed until the best solution is evident*



*SINGER, D. J., DOERRY, N. and BUCKLEY, M. E. (2009), What Is Set-Based Design?. Naval Engineers Journal, 121: 31–43. doi: 10.1111/j.1559-3584.2009.00226.x

Notional Cruiser Baseline

(same baseline used for both teams)



- The Cruiser's power plant was designed with resiliency in mind – it is electric drive, where generators provide power to electric motors for propulsion as well as power for "hotel" loads and mission systems.

- The minimum required speed for the ship is 27 knots.

Design Scenario

Both Teams are in the middle of a new cruiser design effort. Due to a new threat development, the traditional missile based air warfare capability is deemed to be insufficient.

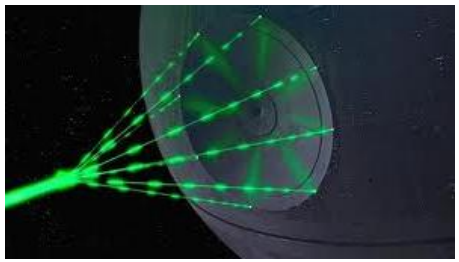
It is determined that Forward Missile Magazine will be replaced with a Laser Air Warfare (AAW) System to provide persistent air defense capability. The Laser AAW system has significantly more staying power in a conflict than a finite quantity of missiles, it is limited only by the fuel carried on the ship.

The Laser AAW system does have an increase in weight, space, power when compared to the conventional missile system–this it a significant change that will effect the entire ship design – and will require a major redesign effort.

Forward Missile Module

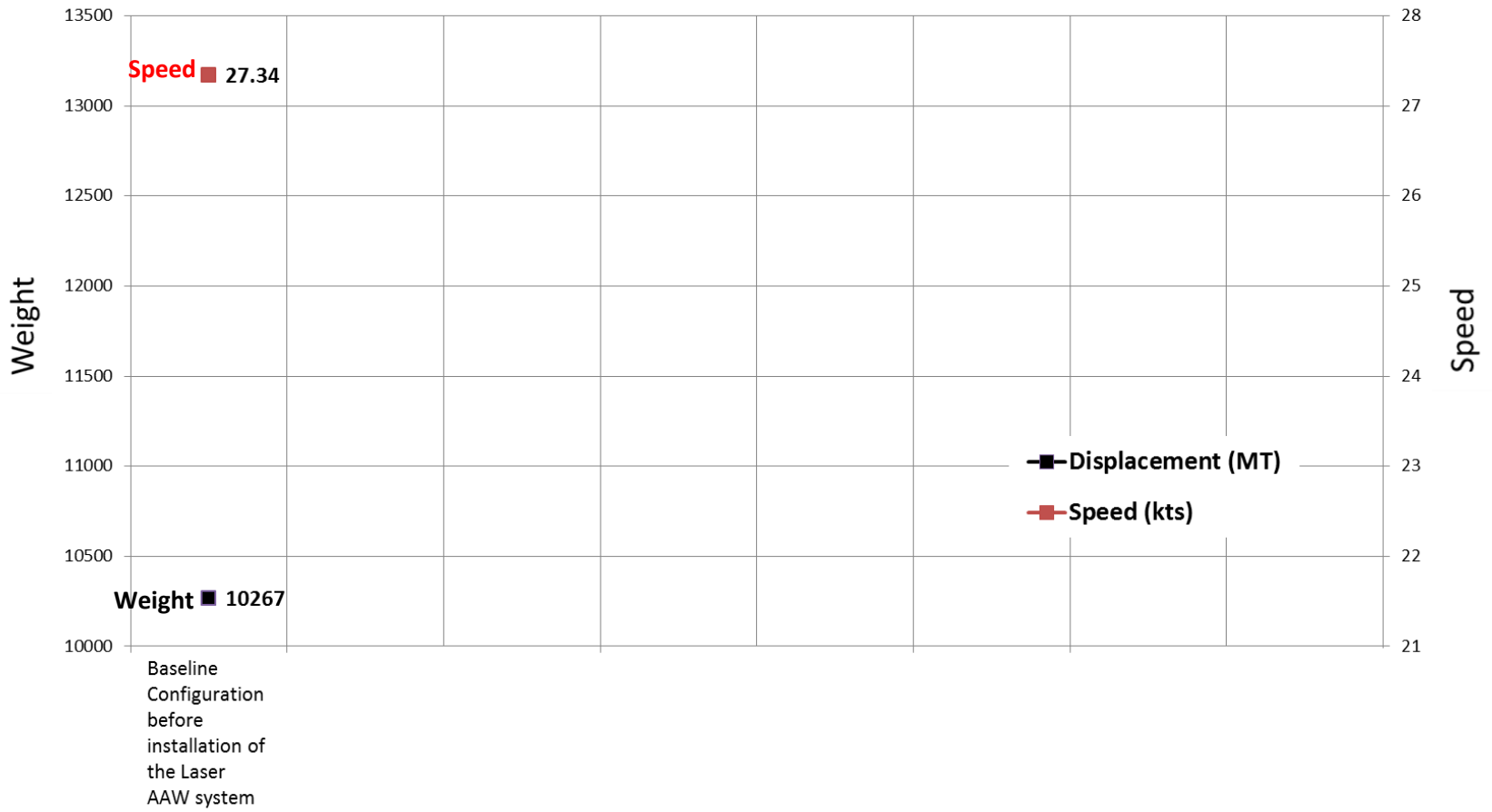
Weight = 210 metric tons
Power = 20 kW @ cruise
= 70 kW @ battle

Laser AAW System



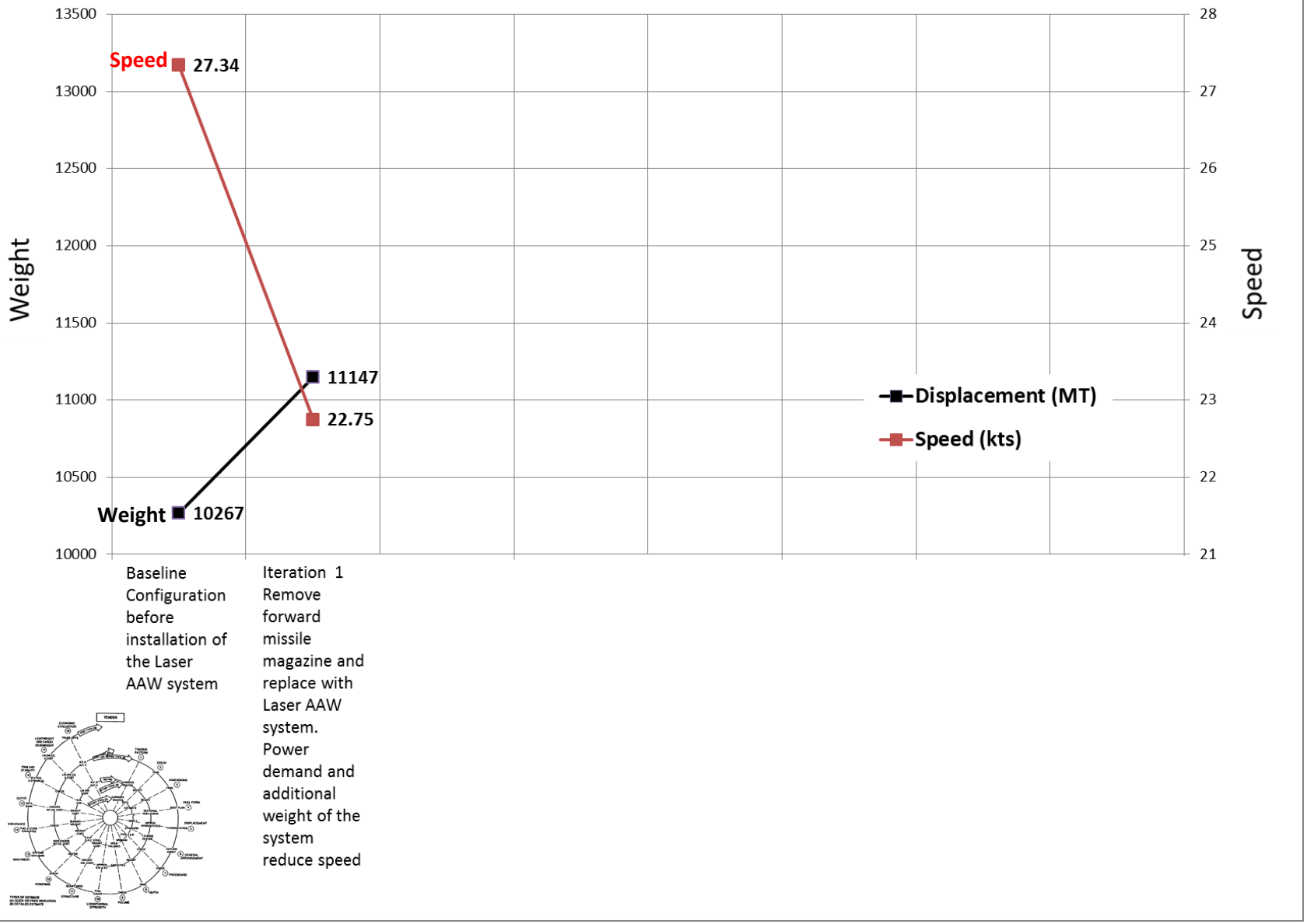
Weight = 450 metric tons
Power = 1,000 kW @ cruise
= 12,000 kW @ battle

Point Design



- Design philosophy is that the team will try to minimize changes to the ship
- The team decides that with the addition of the Laser AAW system, more electrical power will the key change to the ship design.
- The team decides to focus on changing the power and cooling plants. The beam will be changed as necessary, and length will fixed at 160 meters to minimize the growth of the ship.

Point Design



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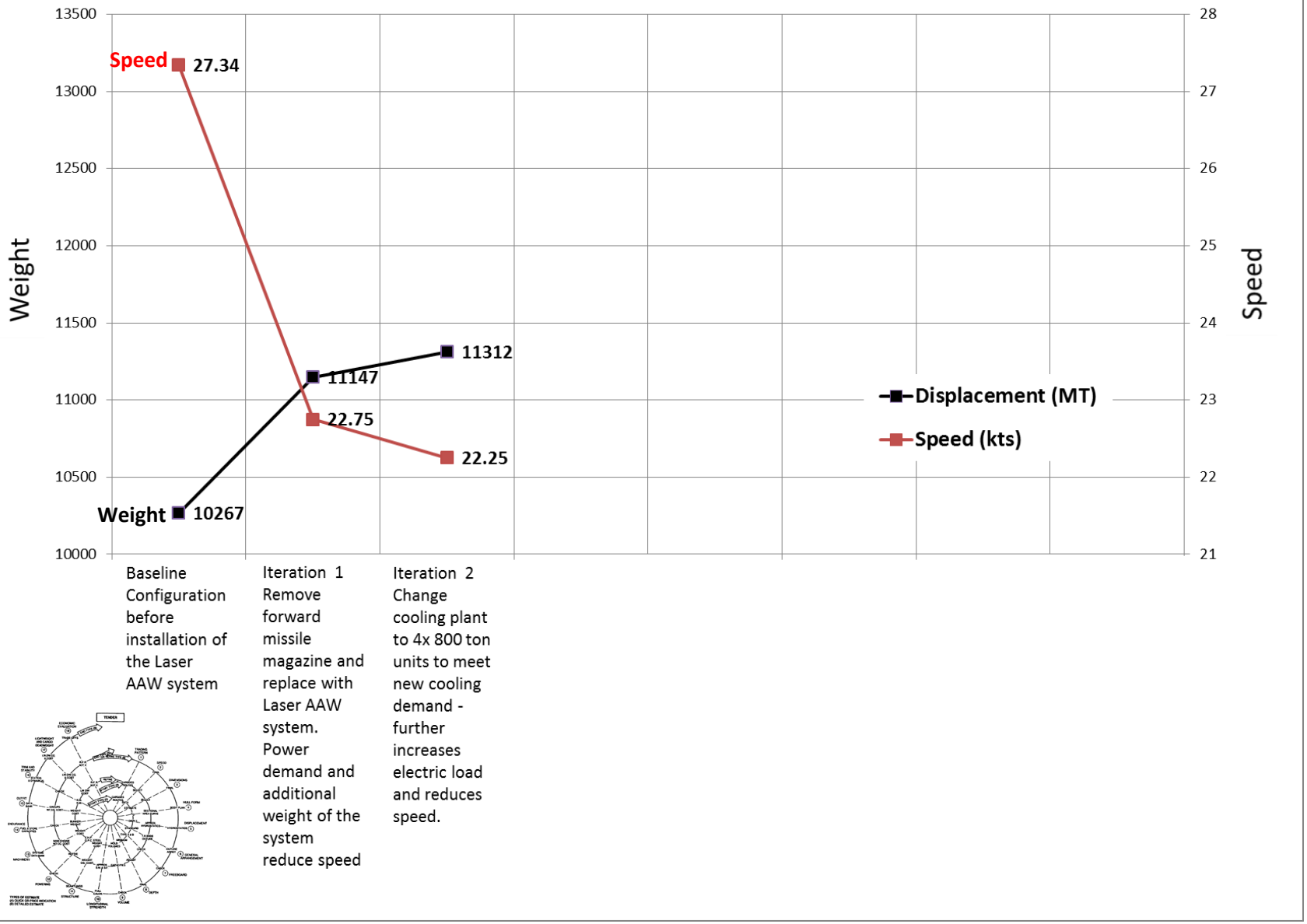

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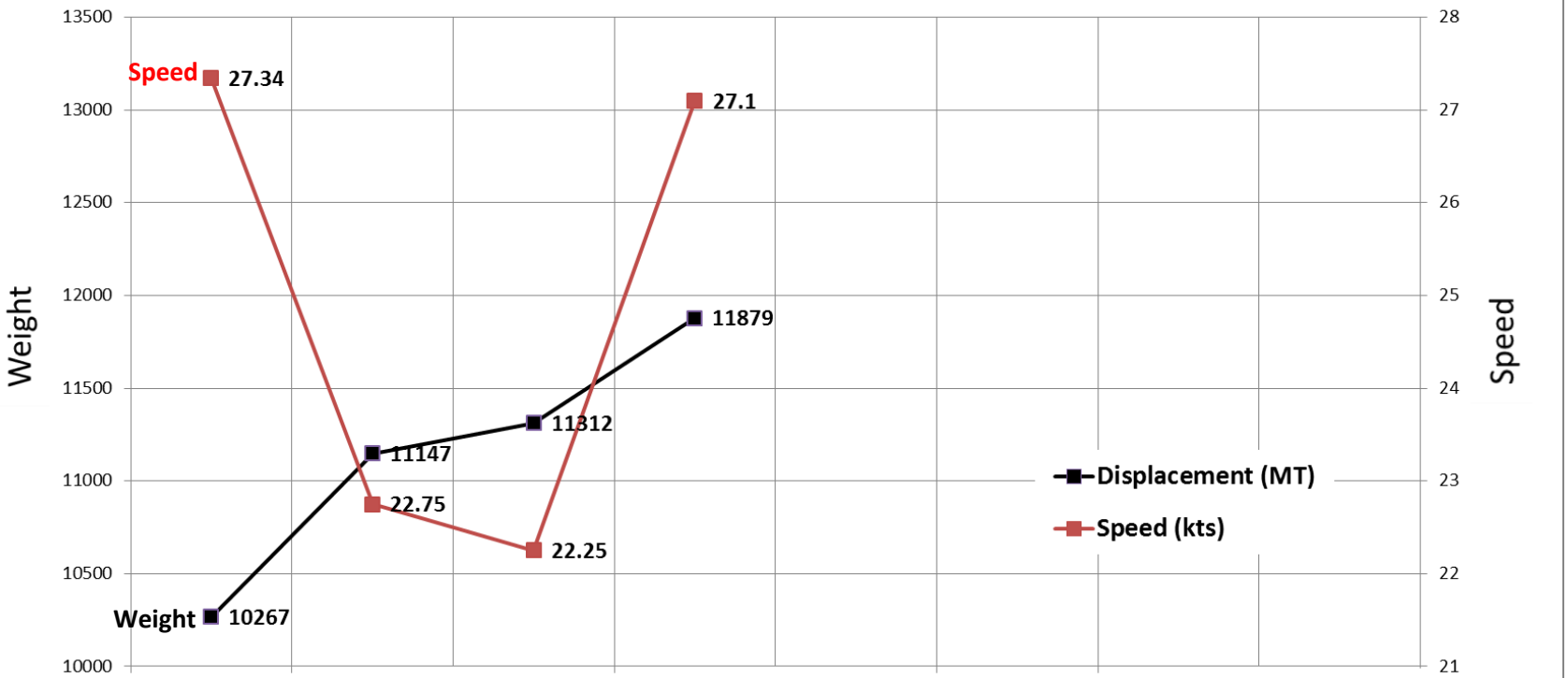
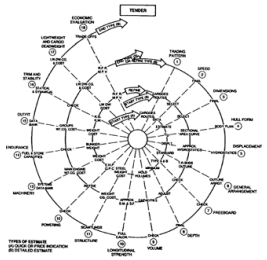


Baseline Configuration before installation of the Laser AAW system

Iteration 1 Remove forward missile magazine and replace with Laser AAW system. Power demand and additional weight of the system reduce speed

Iteration 2 Change cooling plant to 4x 800 ton units to meet new cooling demand - further increases electric load and reduces speed.

Iteration 3 Change main generators from 2x 22 MW gas turbines to 2x 35 MW gas turbines. - restores 27 knot required speed.



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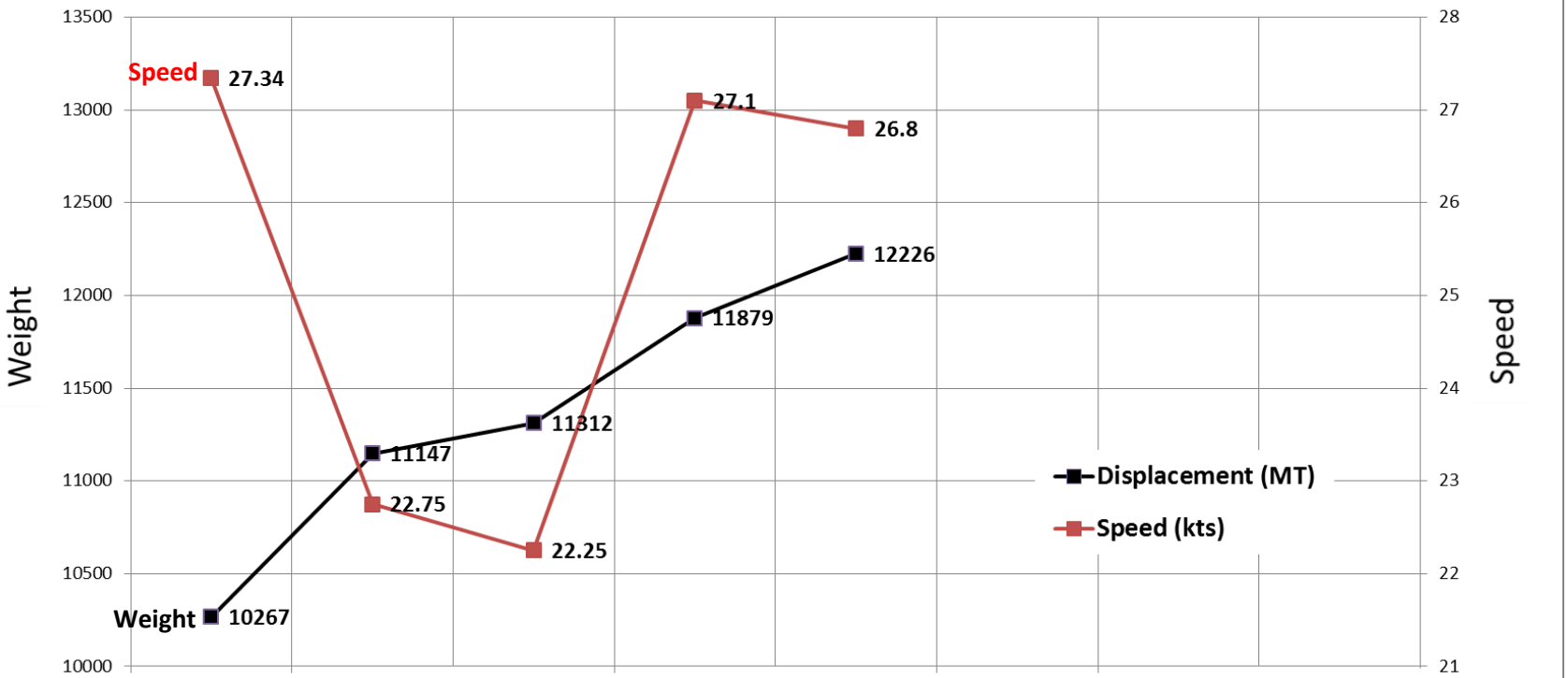

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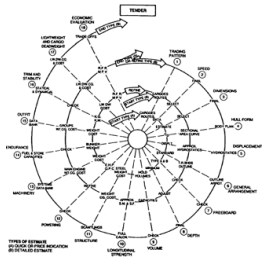
Iteration 4 Change beam of the ship to accomodate new area requirements of cooling and generating plant changes. Speed falls below required 27 knots



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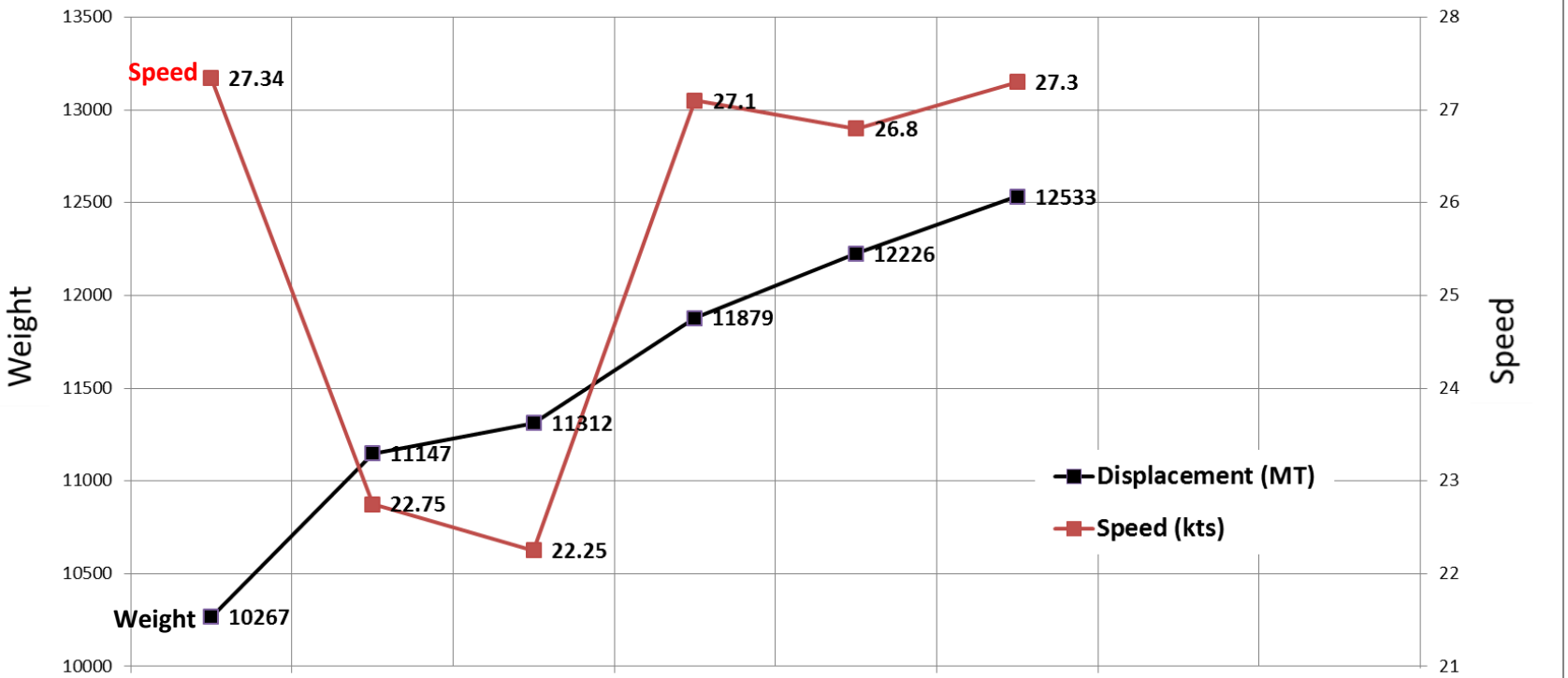

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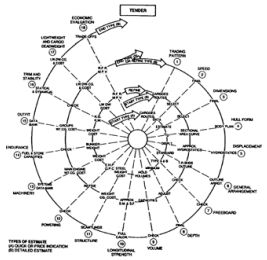

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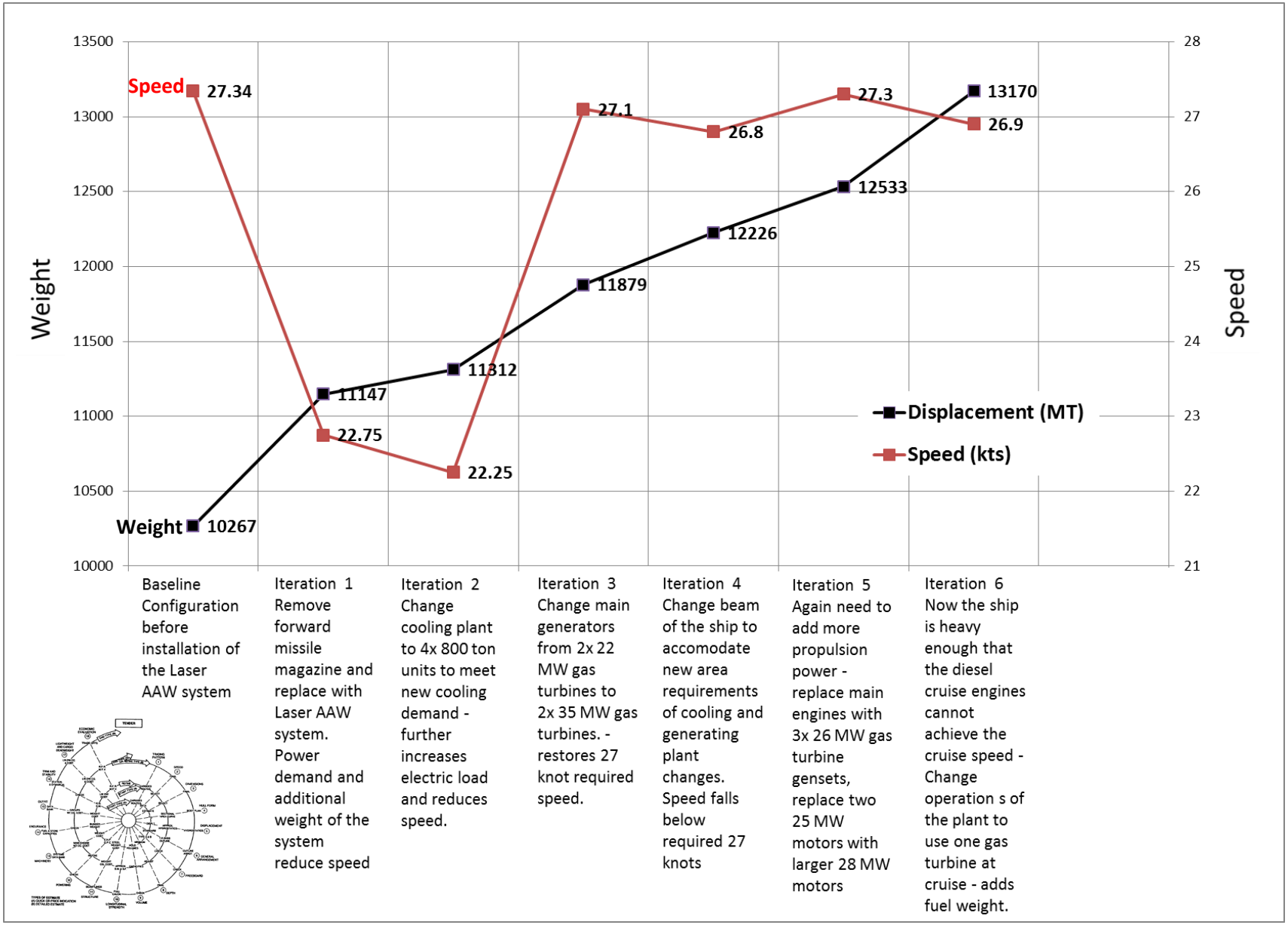

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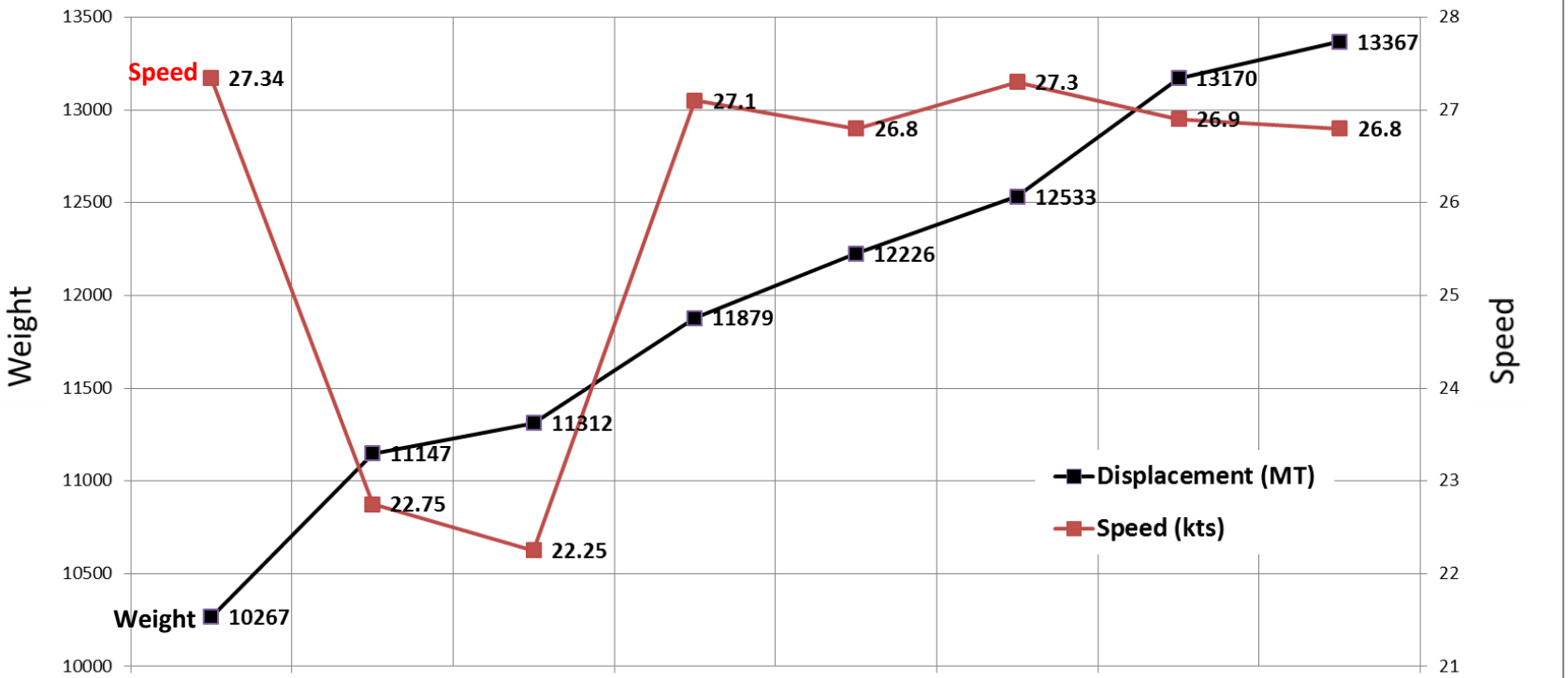
Iteration 6 Now the ship is heavy enough that the diesel cruise engines cannot achieve the cruise speed - Change operation s of the plant to use one gas turbine at cruise - adds fuel weight.

Point Design



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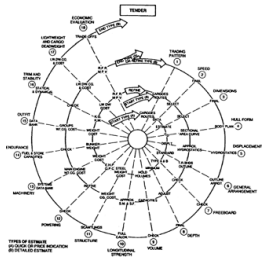
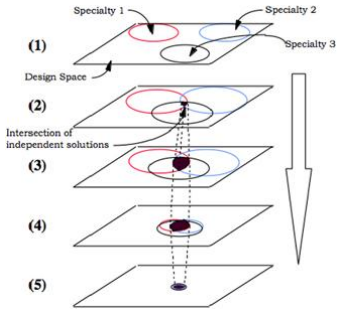
Iteration 7 Increase bean to accomodate additional fuel tankage required. Could upsize the entire power plant again, but this would continue make the ship heavier.



Sample Set-Based Design Parameters

Parameter	Low value	High value
• Length	140 meters	180 meters
• Beam	18 meters	24 meters
• FWD Armament weight	210 metric tons	600 metric tons
• FWD Armament Elec Load	70 kW	16,000 kW



- Main Engine Options:
  - 2x 12 MW Diesel Generators
  - 2x 22 MW Gas Turbine Generators
  - 2x 24 MW Gas Turbine Generators
  - 2x 35 MW Gas Turbine Generators
  - 2x 37 MW Gas Turbine Generators

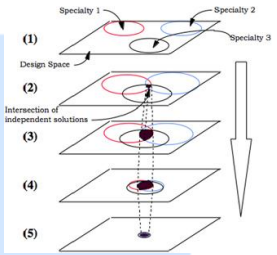
- Cruise (Secondary) Engine Options:
  - 2x 6 MW Diesel Generators
  - 2x 9 MW Diesel Generators
  - 2x 12 MW Diesel Generators

- Cooling Plant Discrete Options:
  - 4x 500 ton Cooling Plants
  - 4x 800 ton Cooling Plants
  - 4x 1100 ton Cooling Plants

- Propulsion motor size
  - 2x 25 MW
  - 2x 28 MW
  - 2x 32 MW

Set-Based design team is exploring ship designs in this "space". The final values have not been decided, this will occur at the end of the process.

2x 6 MW DE, 2x 22 MW GT, 25 MW Motor



Plot of power required for Laser vs. Ship Length – for Baseline Power Plant

White areas indicate feasible space (none for this power plant)

Blue area indicates space where the ship does not meet speed

Green area indicates space where the ship does not have enough electrical power.

Baseline Design

Maximum Margined Electric Load

Armament Mission KWAddition(1_10)

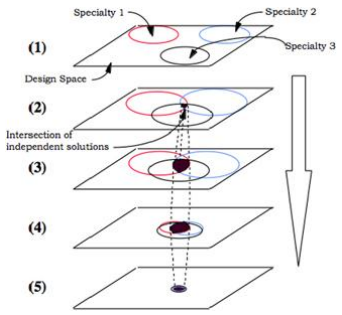
16000
15000
14000
13000
12000
11000
10000

145 150 155 160 165 170 175

Hull Length Between Perpendiculars(1)

Initial Set Reduction – Eliminate Unacceptable Designs

Parameter	Low value	High value
• Length	140 meters	180 meters
• Beam	18 meters	24 meters
• FWD Armament weight	~~210~~ 450 metric tons	600 metric tons
• FWD Armament Elec Load	~~70~~ 12,000 kW	16,000 kW



- Main Engine Options:
  1. ~~2x 12 MW Diesel Generators~~
  2. ~~2x 22 MW Gas Turbine Generators~~
  3. ~~2x 24 MW Gas Turbine Generators~~

  Insufficient Power (no feasible space)
  4. 2x 35 MW Gas Turbine Generators
  5. 2x 37 MW Gas Turbine Generators

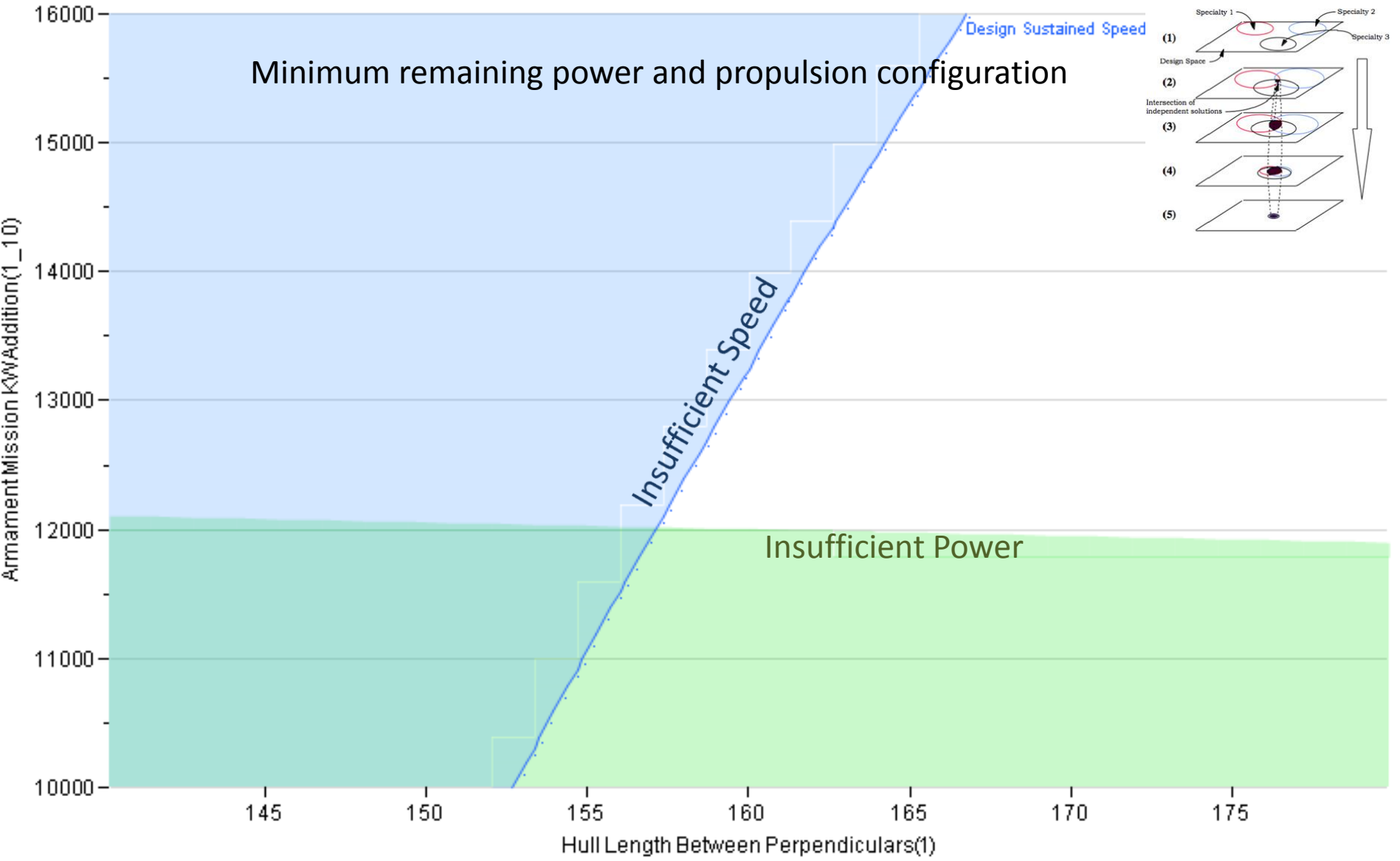
- Cruise (Secondary) Engine Options:
  1. ~~2x 6 MW Diesel Generators~~ Insufficient power for cruise
  2. 2x 9 MW Diesel Generators
  3. 2x 12 MW Diesel Generators

- Cooling Plant Discrete Options:
  1. ~~4x 500 ton Cooling Plants~~ Insufficient Cooling
  2. 4x 800 ton Cooling Plants
  3. 4x 1100 ton Cooling Plants

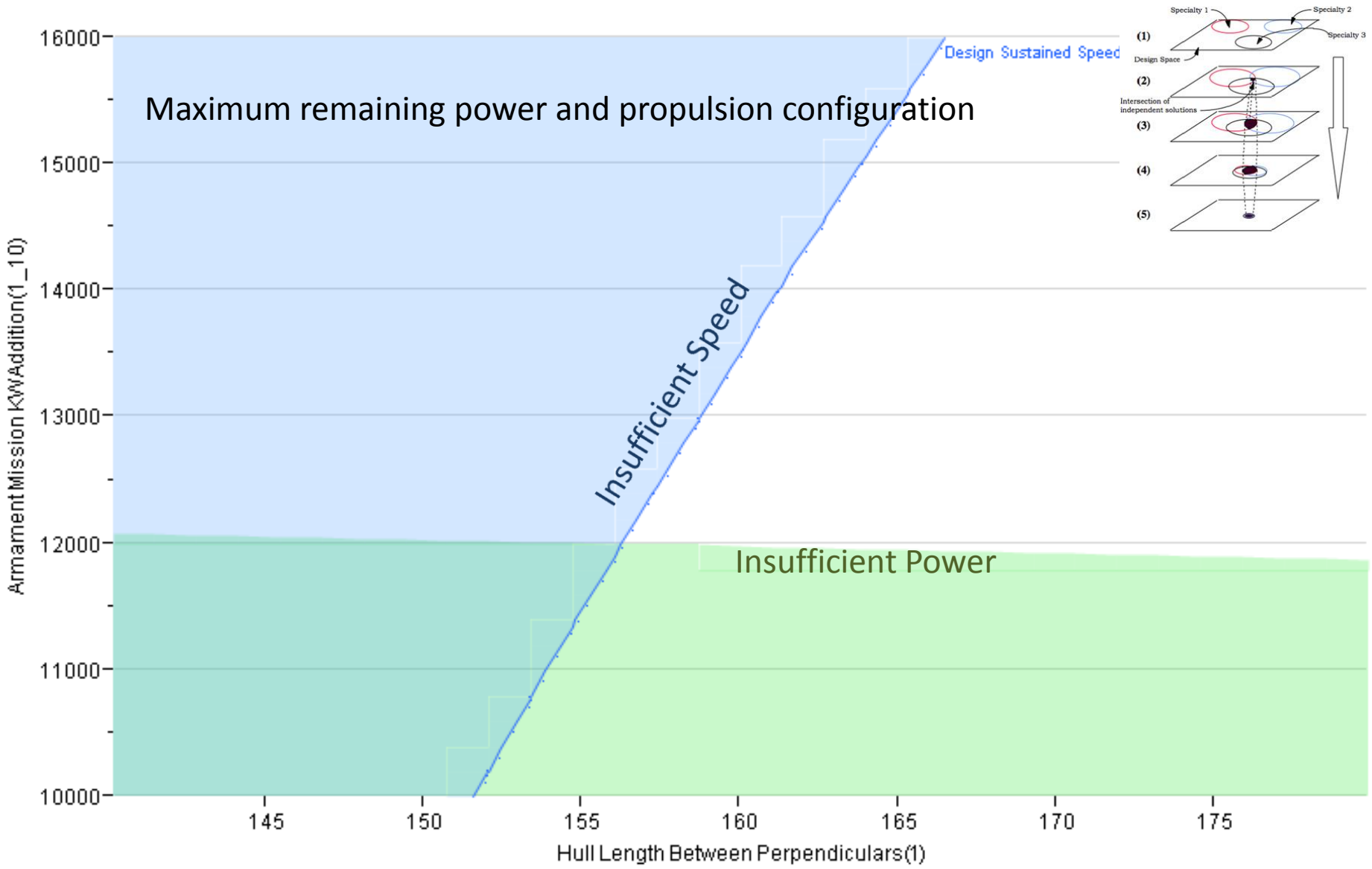
- Propulsion motor size
  1. 2x 25 MW
  2. 2x 28 MW
  3. 2x 32 MW

Set-Based design team is exploring ship designs in this "space". The final values have not been decided, this will occur at the end of the process.

2x 9 MW DE, 2x 35 MW GT, 25 MW Motor

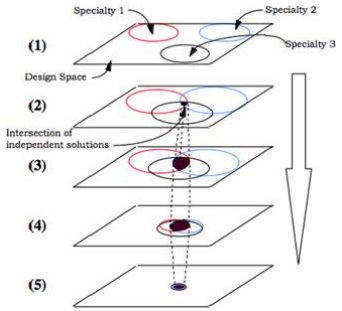


2x 12 MW DE, 2x 37 MW GT, 34 MW Motor



Second Set Reduction – Eliminate Unacceptable Designs

Parameter	Low value	High value
• Length	140 meters	180 meters
• Beam	18 meters	24 meters
• FWD Armament weight	~~210~~ 450 metric tons	600 metric tons
• FWD Armament Elec Load	~~70~~ 12,000 kW	16,000 kW



- Main Engine Options:
  1. ~~2x 12 MW Diesel Generators~~
  2. ~~2x 22 MW Gas Turbine Generators~~
  3. ~~2x 24 MW Gas Turbine Generators~~

  } Insufficient Power

  4. 2x 35 MW Gas Turbine Generators
  5. ~~2x 37 MW Gas Turbine Generators~~ More Power not a discriminator

- Cruise (Secondary) Engine Options:
  1. ~~2x 6 MW Diesel Generators~~ Insufficient Power
  2. 2x 9 MW Diesel Generators
  3. ~~2x 12 MW Diesel Generators~~ More Power not a discriminator

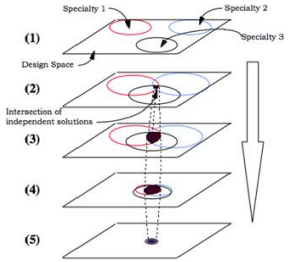
- Cooling Plant Discrete Options:
  1. ~~4x 500 ton Cooling Plants~~ Insufficient Cooling
  2. 4x 800 ton Cooling Plants
  3. 4x 1100 ton Cooling Plants

- Propulsion motor size
  1. 1.2x 25 MW
  2. ~~2.2x 28 MW~~
  3. ~~3.2x 32 MW~~

  } More Power not a dscriminator

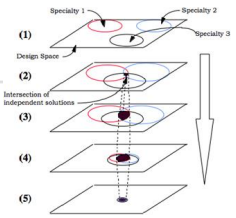
Set-Based design team is exploring ship designs in this "space". The final values have not been decided, this will occur at the end of the process.

- **Next step will be to check the resiliency of the remaining design space and pick a final design that is not at the edge of feasibility**



- **The way to do this is to develop a what if scenario, and test to see what designs are still valid. Assume that the Laser AAW system experiences a 25% growth in weight, and a 25% growth in required power – since it is a developmental system, there is a high degree of risk.**

2x 9 MW DE, 2x 35 MW GT, 25 MW Motor

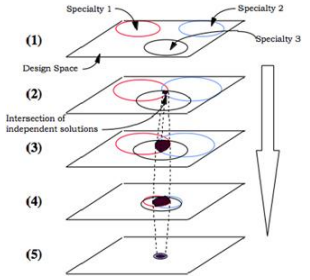


The power plant is sufficient to accept a 25% increase in the Laser AAW system power. Minimally, the hull needs to be 165 meters long in order to maintain the required speed. The cooling plant would have to be upgraded to the 1100 ton unit to accept the 25% increase.
Down select to 170 meter length (backed off from minimum)
Down select to 1100 ton cooling units

25% increase in weight and power for the Laser AAW system.

Third Set Reduction – Final Design

Parameter	Low value	High value
• Length	170 meters	
• Beam	21.5 meters	
• FWD Armament weight	450 metric tons	563+ metric tons (25%)
• FWD Armament Elec Load	12,000 kW	15,000+ kW (25%)



- Main Engine Options:
  1. ~~2x 12 MW Diesel Generators~~
  2. ~~2x 22 MW Gas Turbine Generators~~
  3. ~~2x 24 MW Gas Turbine Generators~~
  4. 2x 35 MW Gas Turbine Generators
  5. ~~2x 37 MW Gas Turbine Generators~~

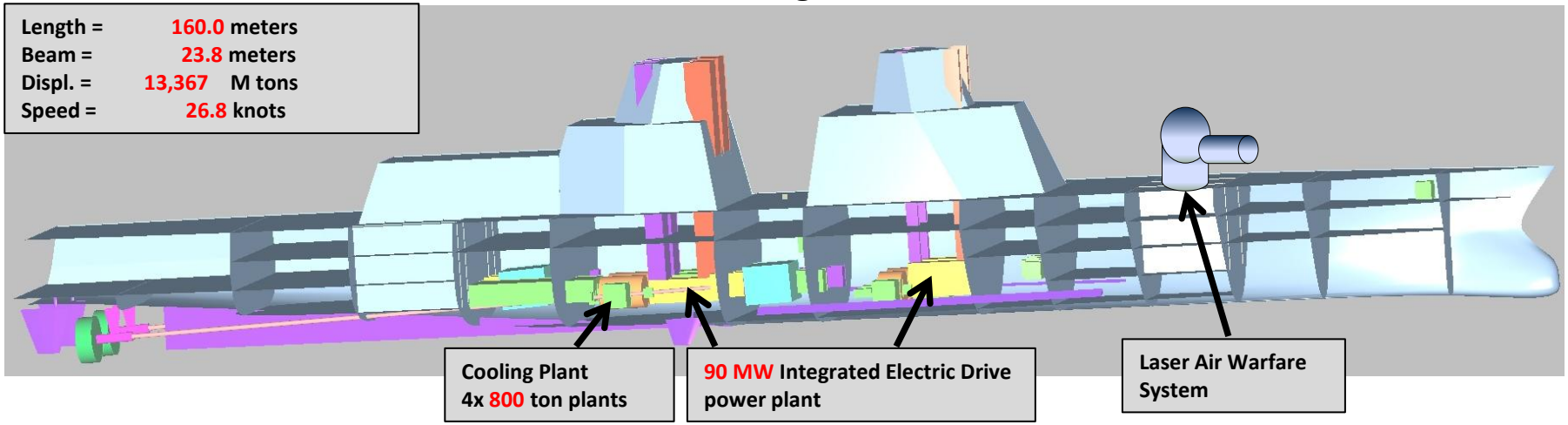
- Cruise (Secondary) Engine Options:
  1. ~~2x 6 MW Diesel Generators~~
  2. 2x 9 MW Diesel Generators
  3. ~~2x 12 MW Diesel Generators~~

- Cooling Plant Discrete Options:
  1. ~~4x 500 ton Cooling Plants~~
  2. ~~4x 800 ton Cooling Plants~~
  3. 4x 1100 ton Cooling Plants

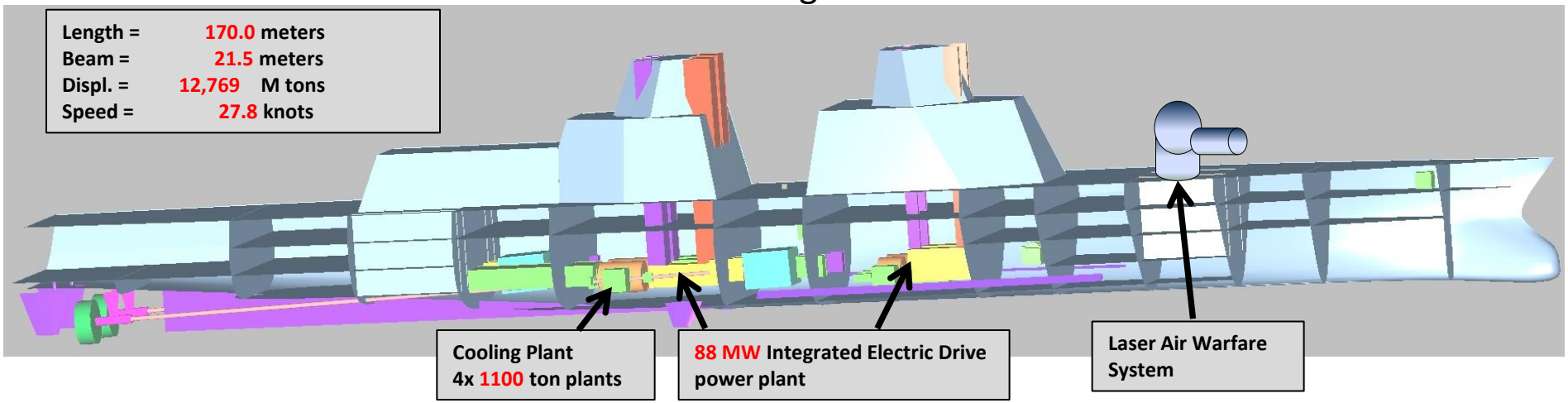
- Propulsion motor size
  - 1.2x 25 MW
  - ~~2.2x 28 MW~~
  - ~~3.2x 32 MW~~

Final Designs

Point-Based Design Result



Set-Based Design Result



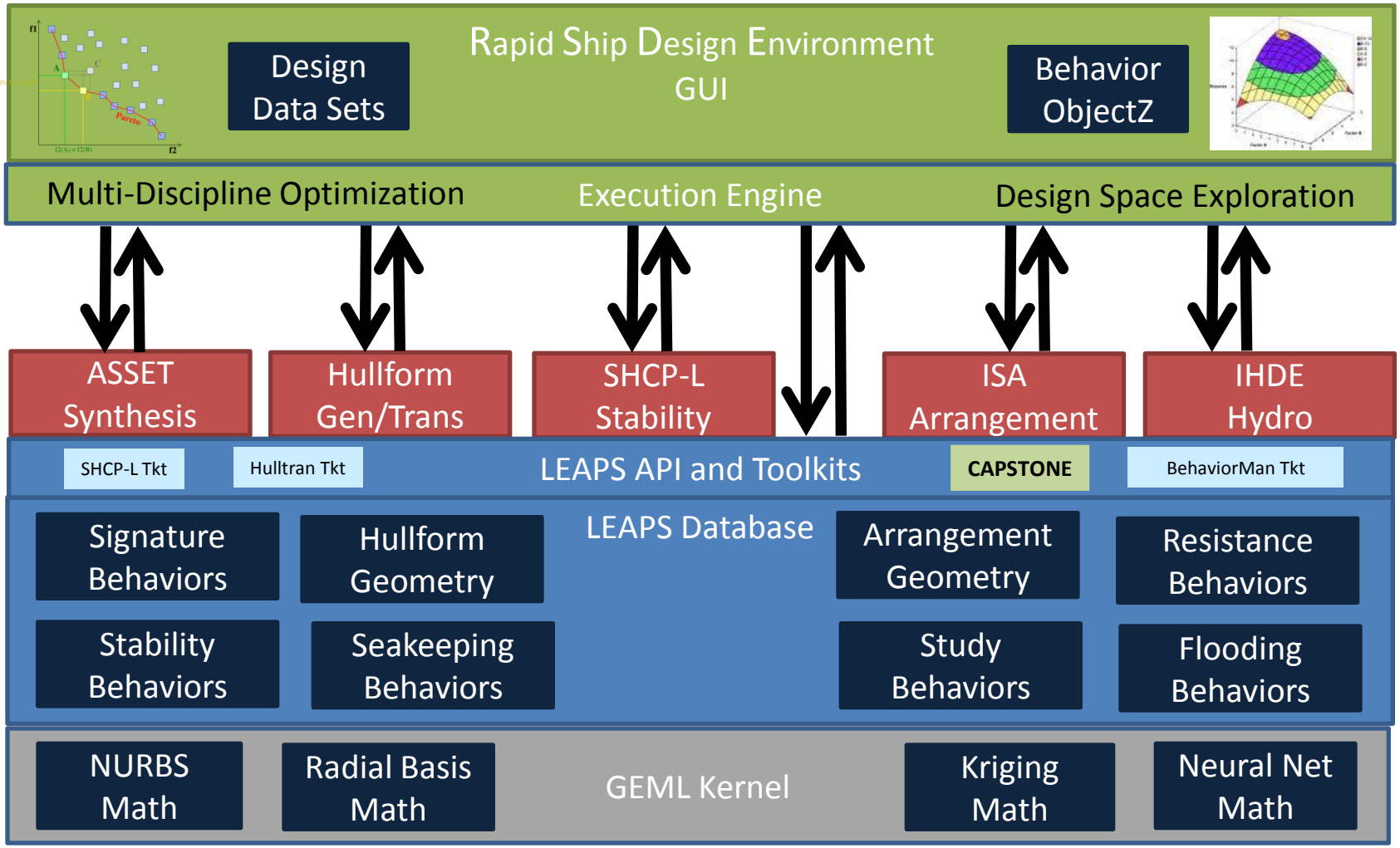
Conclusions

- **The Point-based design ship does not make the required speed, and is unable to accept additional weight and power without further degrading speed.**
  - Redesign would again be required if the Laser AAW system were to require more power or get heavier. The power plant, cooling plant, and beam would again have to be resized.
  - The Point Design used 7 design iterations to achieve this result.

- **Set Based Design ship was able to make speed with significant margin, it has a lower weight, and employs a smaller power plant than the Point-Based Design.**
  - This was achieved by keeping the design space open for length, beam, weapons system characteristics, power plant, and cooling plant until later in the process.
  - The Set-based solution can also tolerate a 25% increase in weight and power to the Laser AAW system with no impact to the ship design.
  - The Set-Based Design used 3 ‘iterations’ to achieve this result.

- **Both design efforts required the same amount of time to develop the ship design.**

Rapid Ship Design Environment



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