Naval Set-Based Design

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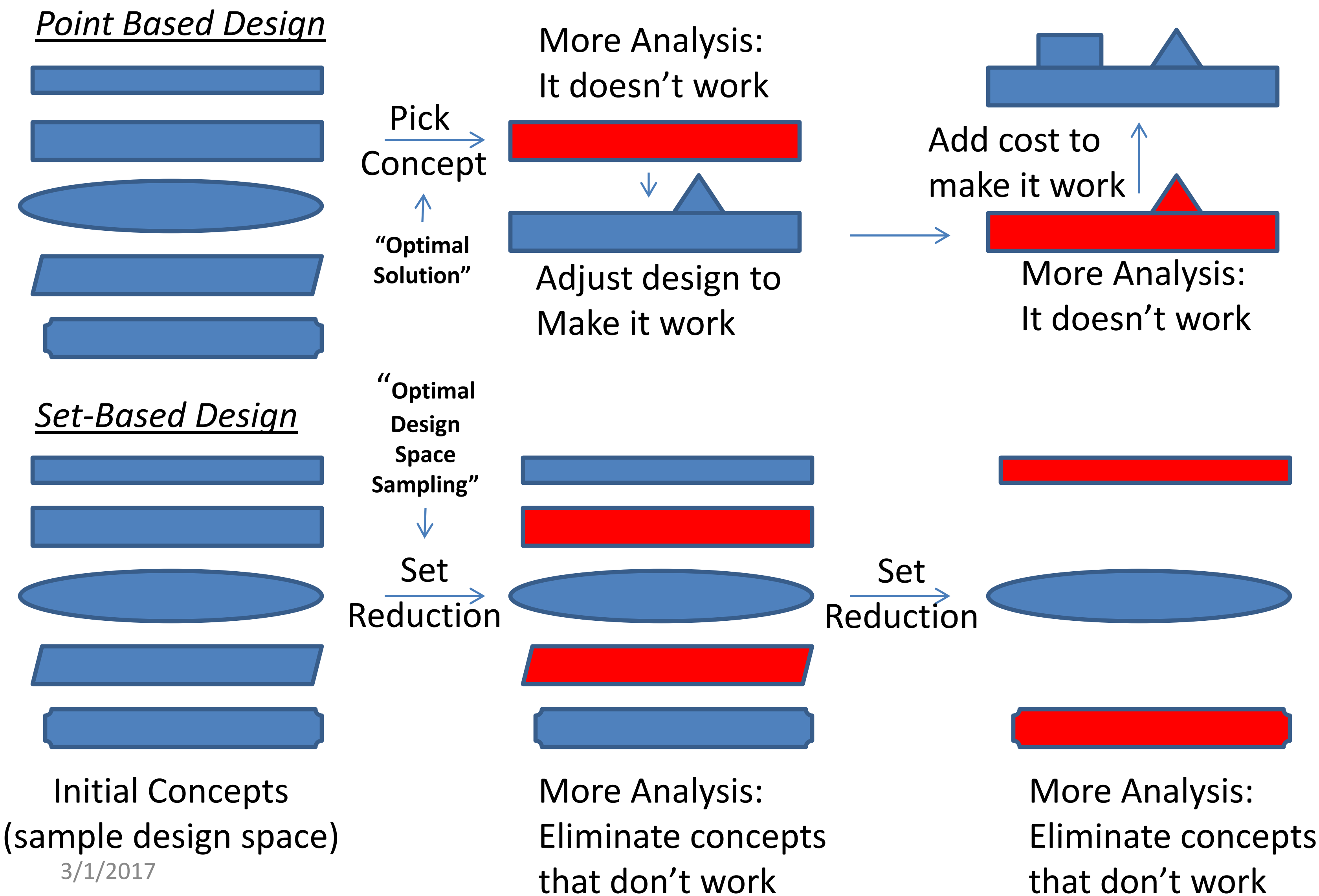
See http://doerry.org/norbert/papers/papers.htm
for more papers and presentations

Point Based vs Set-Based Design



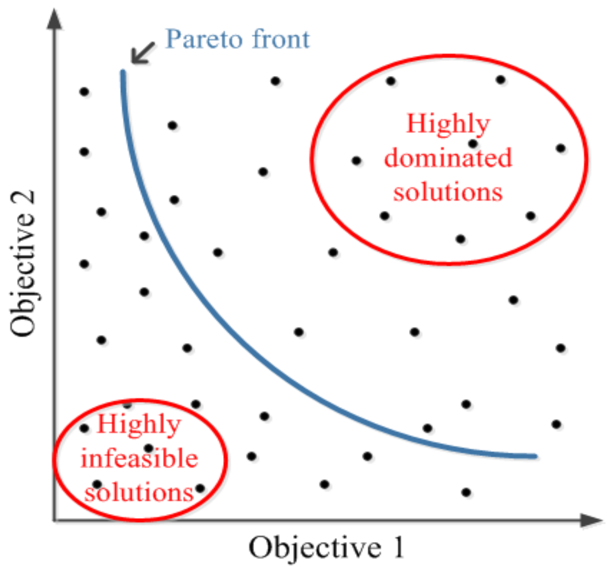
Principles of Set-Based Design (SBD)

- Understand the design space
  - Identify feasible regions within a wide set of boundaries
  - Explore tradeoffs by designing and analyzing multiple alternatives
  - Communicate sets of possibilities
- Integrate by intersection
  - Have specialists consider a design from their own perspective
    - Work in parallel asynchronously
  - Look for intersections of feasible sets – Eliminate infeasible
  - Impose minimum (maximum) constraint – Eliminate dominated
  - Seek conceptual robustness – Diversity
- Establish feasibility before commitment
  - Narrow sets gradually while increasing detail or scope of analysis
  - Stay within set once committed (Unless new knowledge indicates otherwise)
  - Control by managing uncertainty
  - DOCUMENT ALL SET REDUCTIONS

Make robust data-driven decisions

Set-Based Design Feasibility and Viability

- Feasible:
  - Configuration achieves objectives based on current fidelity of modeling and analysis
- Viable:
  - Configuration achieves objectives based on future more detailed modeling, analysis, and testing
- A feasible configuration may not be viable
  - Should not choose a specific configuration as representative or optimal
  - Decisions should be made at capability concept level, not the configuration level
- Cost for a given capability concept should be based on a diverse set of feasible configurations
  - Avoid common mode failures
  - Reflect undecided requirements



McKenney, Thomas, and David Singer, "Set-Based Design," SNAME (mt) Marine Technology, July 2014, pp. 51-55.

Systematically Eliminate
- Highly Dominated Solutions
- Not Feasible Solutions

SBD as a Design Method

- A **Design Method** is the way design alternatives are understood, analyzed, and selected.
- A **Design Process** is a series of structured steps to implement the design approach.
  - Concept Exploration (Pre-milestone A)
  - Preliminary – Contract Design (Milestone A to B)
- **Design Tools** provide information and knowledge as part of the Design Process to enable the Design Method.
  - Often part of a Model Based Systems Engineering (MBSE) Environment
  - Can also include prototyping and physical testing

What method to use:

- Set-Based Design (Convergent)
  - A large number of design variables
  - Tight coupling among design variables
  - Conflicting requirements
  - Flexibility in requirements allowing for trades
  - Technologies and design problems not well understood – learning required for a solution
- Point-Based Design (Iterative)
  - Specific technologies required
  - Design optimization based along only one or two design variables
  - Well-understood technologies and design problems

Set-Based Design Examples

- Past
  - (1980’s to present) Toyota Product Development
  - (2008) SSC: Ship to Shore Connector (Preliminary Design)
  - (circa 2009) planned to use for CG(X) (Preliminary Design)
  - (2013) ACV: Amphibious Combat Vehicle (Requirements)
  - (2014) SSCTF: Small Surface Combatant Task Force (Requirements)
  - (2016) SMI: Smart Mine Initiative (Requirements)
- Ongoing / Future
  - Future Surface Combatant (Requirements)
  - Force Architecture Studies (Requirements)
- When to use …
  - A large number of variables
  - Tight coupling among variables
  - Technologies and design problems not well understood – learning required for a solution

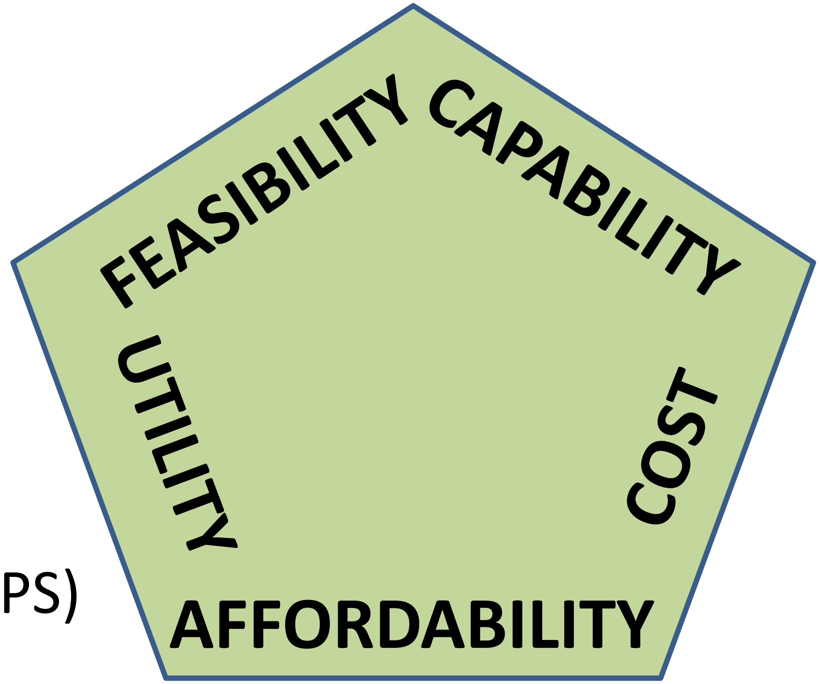
What is the Design Problem?

- Pre-Milestone A: Concept Exploration
  - What is the set of operational requirements for which a system can be built over a desired time period for a desired amount of funds to achieve a desired operational value?
  - Designing Requirements
  - Examples: ACV and SSCTF
- Milestone A to Milestone B: Preliminary & Contract Design
  - What is the best set of specifications for procuring a system to achieve the desired operational requirements within the desired time period and cost constraints?
  - Designing Specifications
  - Example: SSC

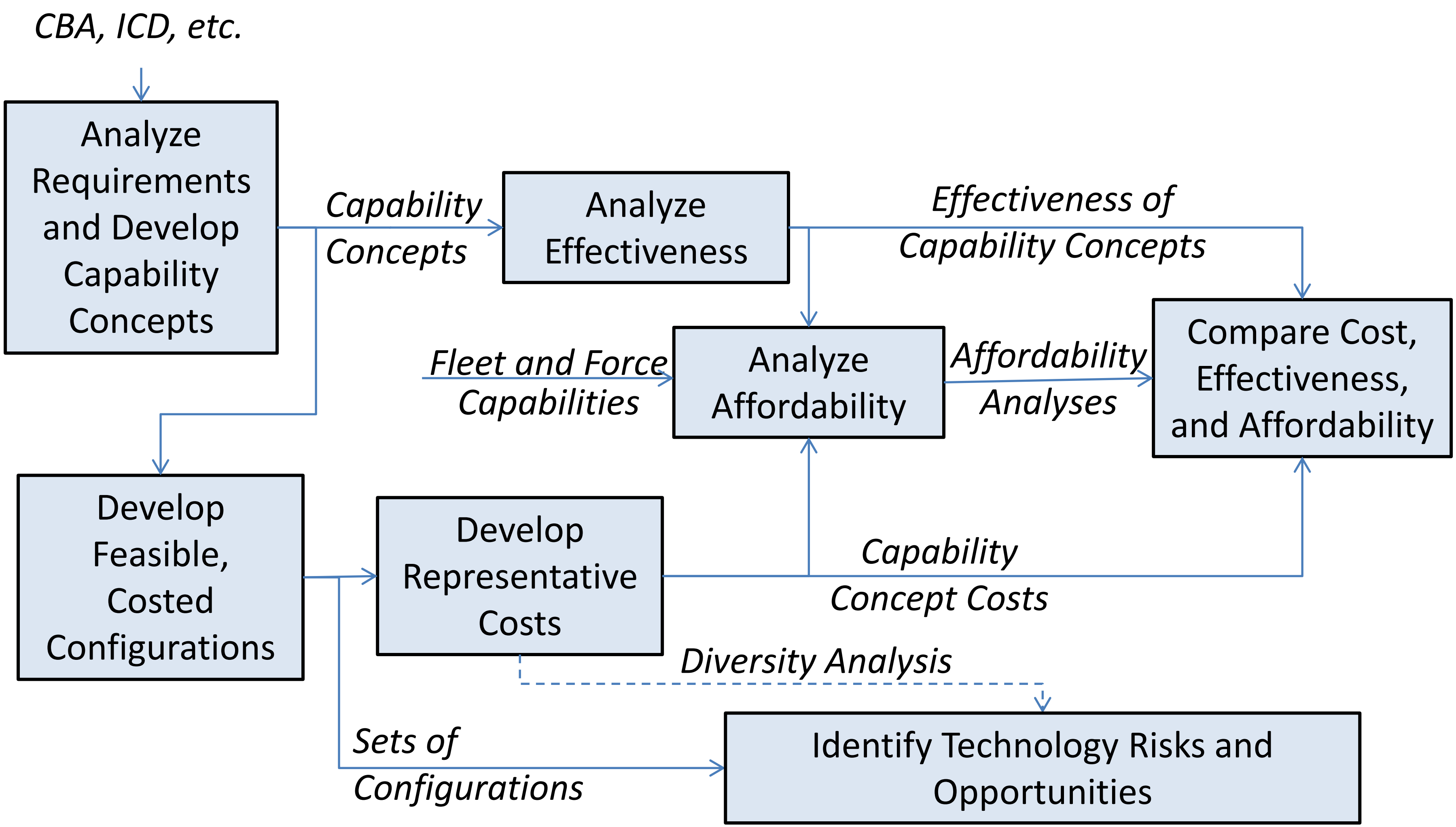
Both may use SBD as a “Design Method” but will have different “Design Processes”

Concept Exploration

- Understand the interaction of
  - Cost
  - Capability
  - Feasibility
  - Utility
  - Affordability
- Capability Concept
  - Set of requirements
  - Concept of Operations (CONOPS)
  - Employment strategy
  - Acquisition strategy
  - Support strategy

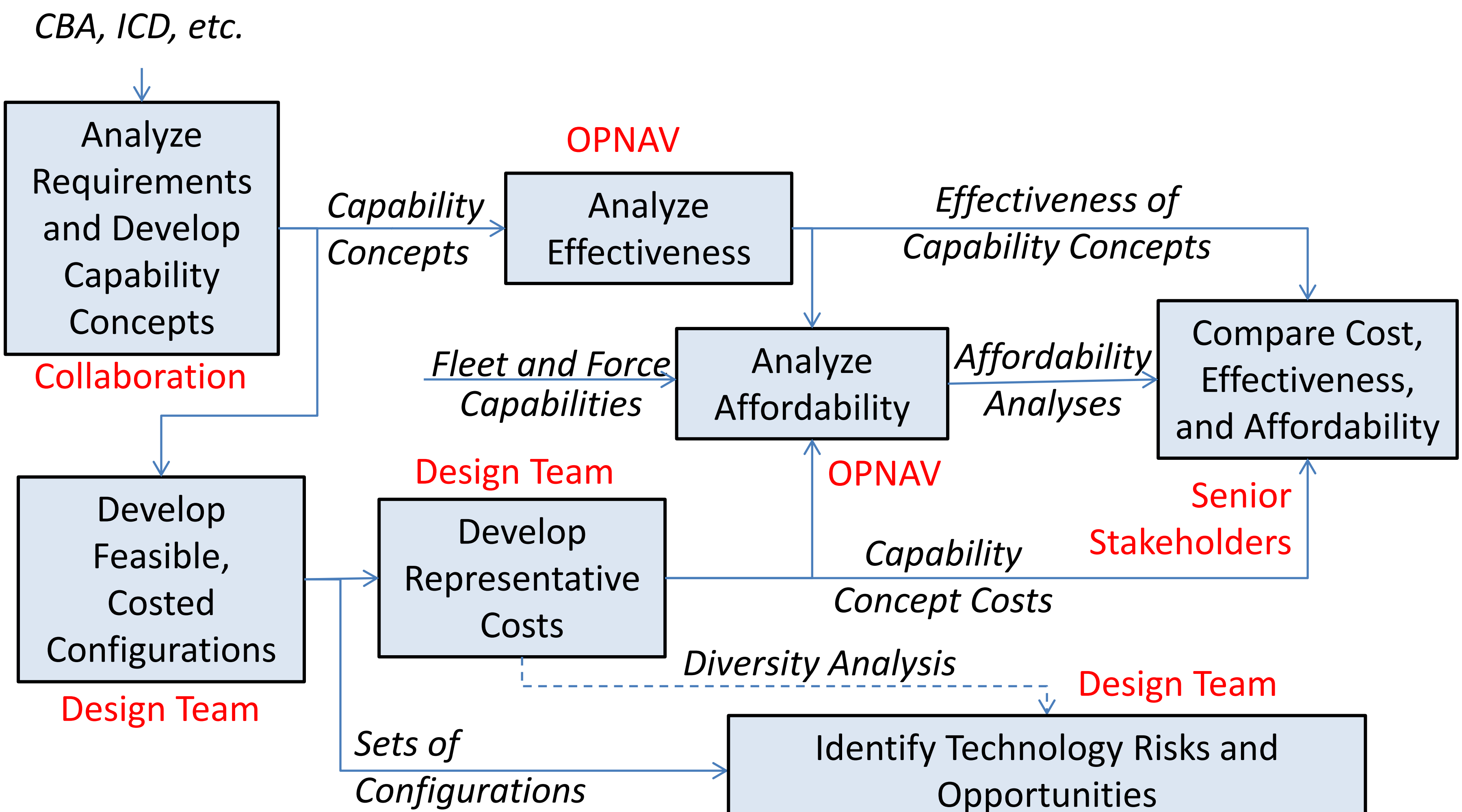


Reference Concept Exploration Process

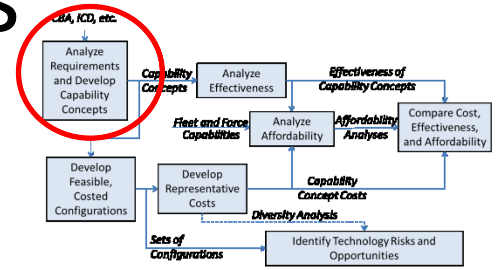


One of many possible processes for Implementing the Set-Based Design Method

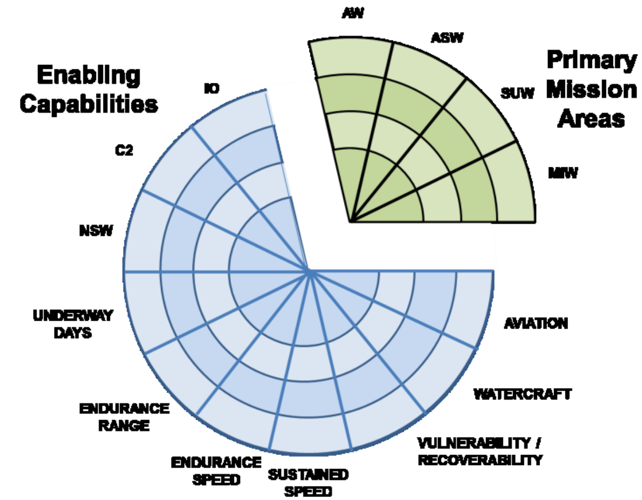
Distributed Execution



Analyze Requirements and Develop Capability Concepts

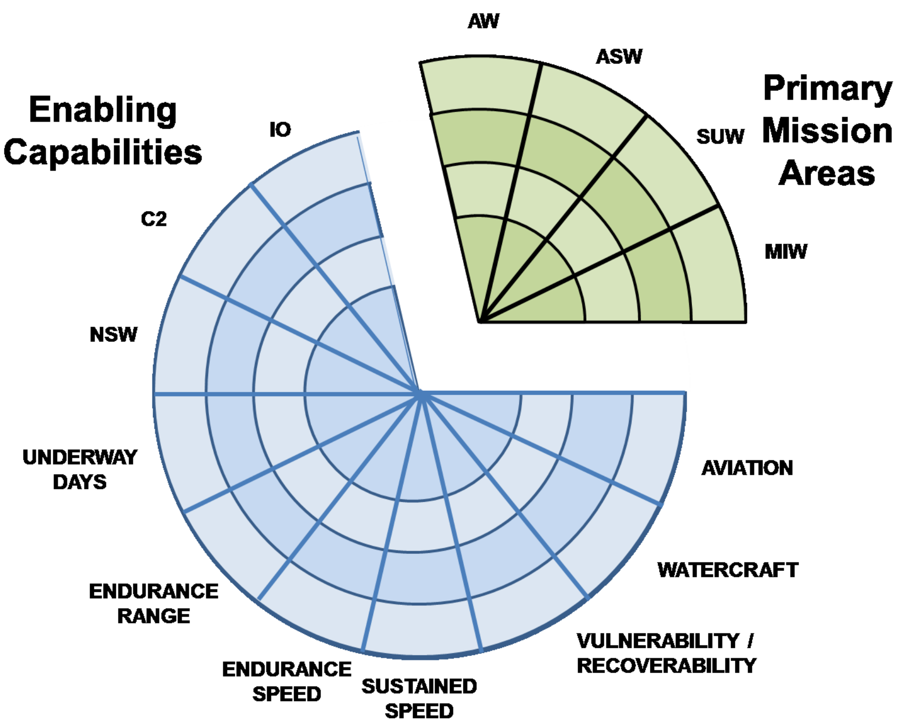


- **<u>Understand the Tasking (What are the QUESTIONS?)</u>**
- Develop a set of Capability Concepts
  - Primary Mission Areas (PMA)
    - Major drivers
  - Enabling Capabilities (EC)
    - Less major drivers
- Identify capability levels for each area
  - Discrete levels of performance
- PMAs and ECs should be sufficient to analyze effectiveness.
  - Enable parallel assessment of representative cost and effectiveness
- Restrict total number of Capability Concepts
  - Use SBD principles to minimize the set of Capability Concepts to study.
    - For Example: SSCTF reduced set from 192 to 8
  - Good range is between 8 and 50 capability concepts
- Define other requirements
  - Fixed value, or …
  - Provide range for the requirement
    - Representative cost and effectiveness analysis should consider the full range in assessing performance.
  - Document in Ground Rules and Assumptions
- Can conduct side studies for understanding impact of ECs.
  - May be deferred until Pre-Preliminary Design



SSCTF Capability Concept

- Primary Mission Areas
  - Air Warfare (AW)
  - Anti-Submarine Warfare (ASW)
  - Surface Warfare (SUW)
  - Mine Warfare (MIW)
- Enabling Capabilities



192 Different Combinations of Primary Mission Areas

Set-Based Design used to reduce number of Capability Concepts from 192 to 8

	Capability Concept							
Mission Area Capabilities	**CC 1**	**CC 2**	**CC 3**	**CC 4**	**CC 5**	**CC 6**	**CC 7**	**CC 8**
Self Defense against Air, Surface, Undersea Threats	X	X	X	X	X	X	X	X
Capability to detect and engage small craft within- the-horizon of own ship		X	X	X	X	X	X	X
Capability to achieve mission kill of over-the-horizon surface targets					X	X	X	X
Capability to detect and engage undersea threats in support of ASW operations	X		X	X			X	X
Limited capability to defend other ships against ASCMs	X	X		X		X		X

Logical reduction process based on
- Analysis of Force Architecture
- Little difference in physical systems for several Capability Concepts

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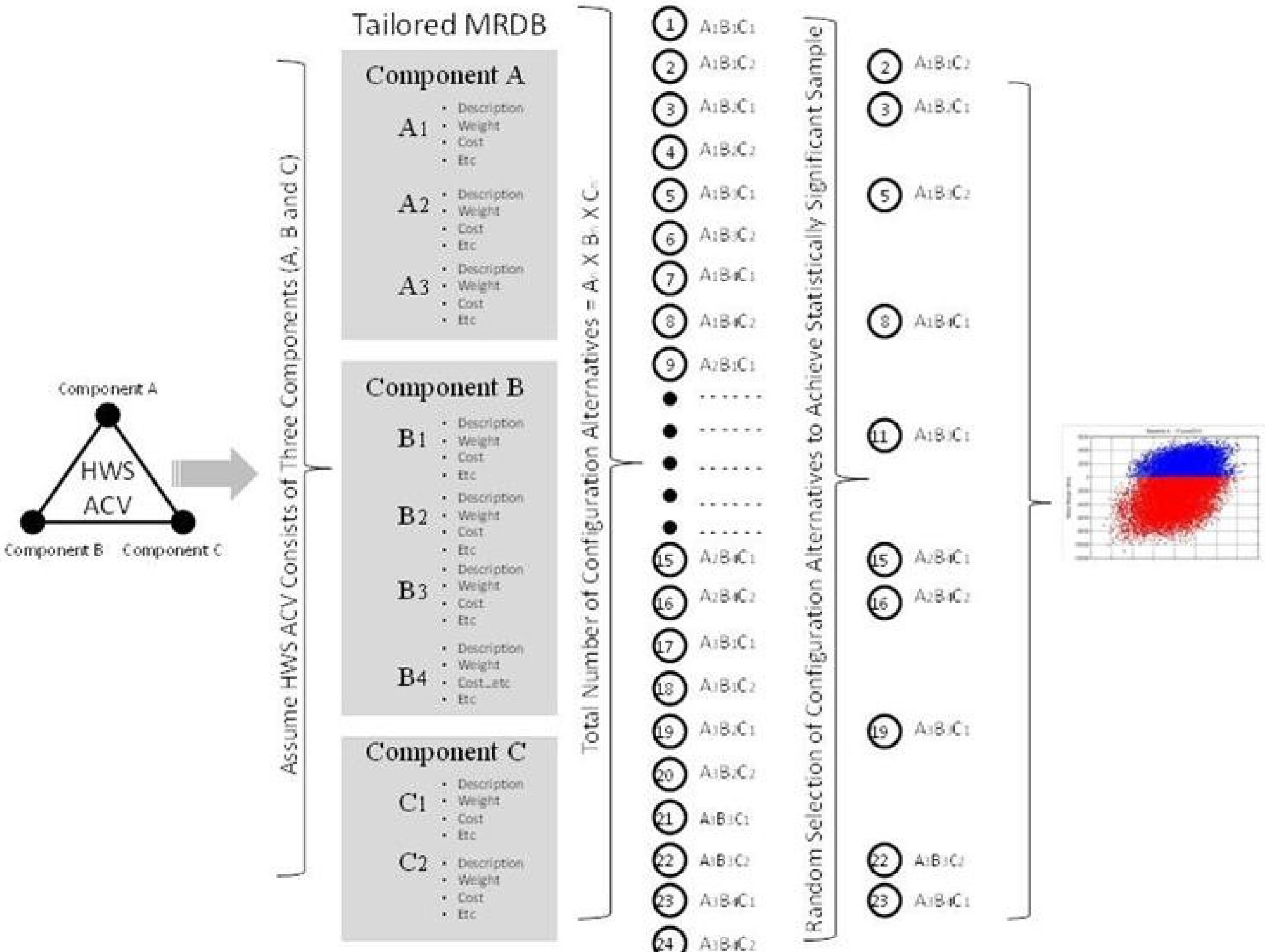
Configuration Modeling for Technical Feasibility Analysis and Cost Estimating

- Market Research
  - Document component cost and technical data
  - Use a well defined Work Breakdown Structure (WBS)
  - Base on information provided by Industry (if possible)
    - Data traceability retained
  - Trace capability concept requirements to component selection
- System Modeling Tool
  - Use data from the Market Research Database
  - Calculate parameters needed to establish feasibility
  - Other technical parameters needed by the Cost Model
  - Assumptions documented in a Ground Rules & Assumptions (GR&A)
    - Best Practice: Incorporate the GR&A into the Study Guide
- Cost Model
  - Calculate acquisition and lifecycle cost estimates
  - Assumptions documented in GR&A

Assembling a Configuration



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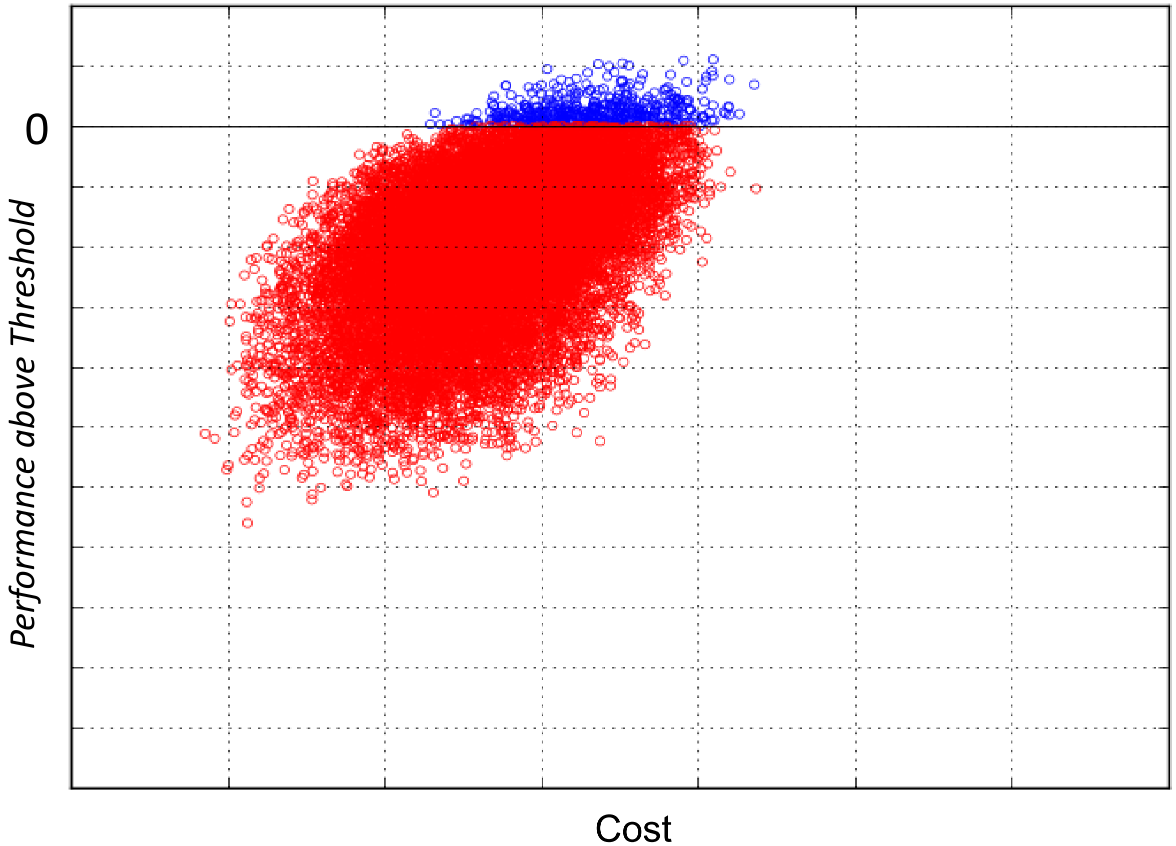
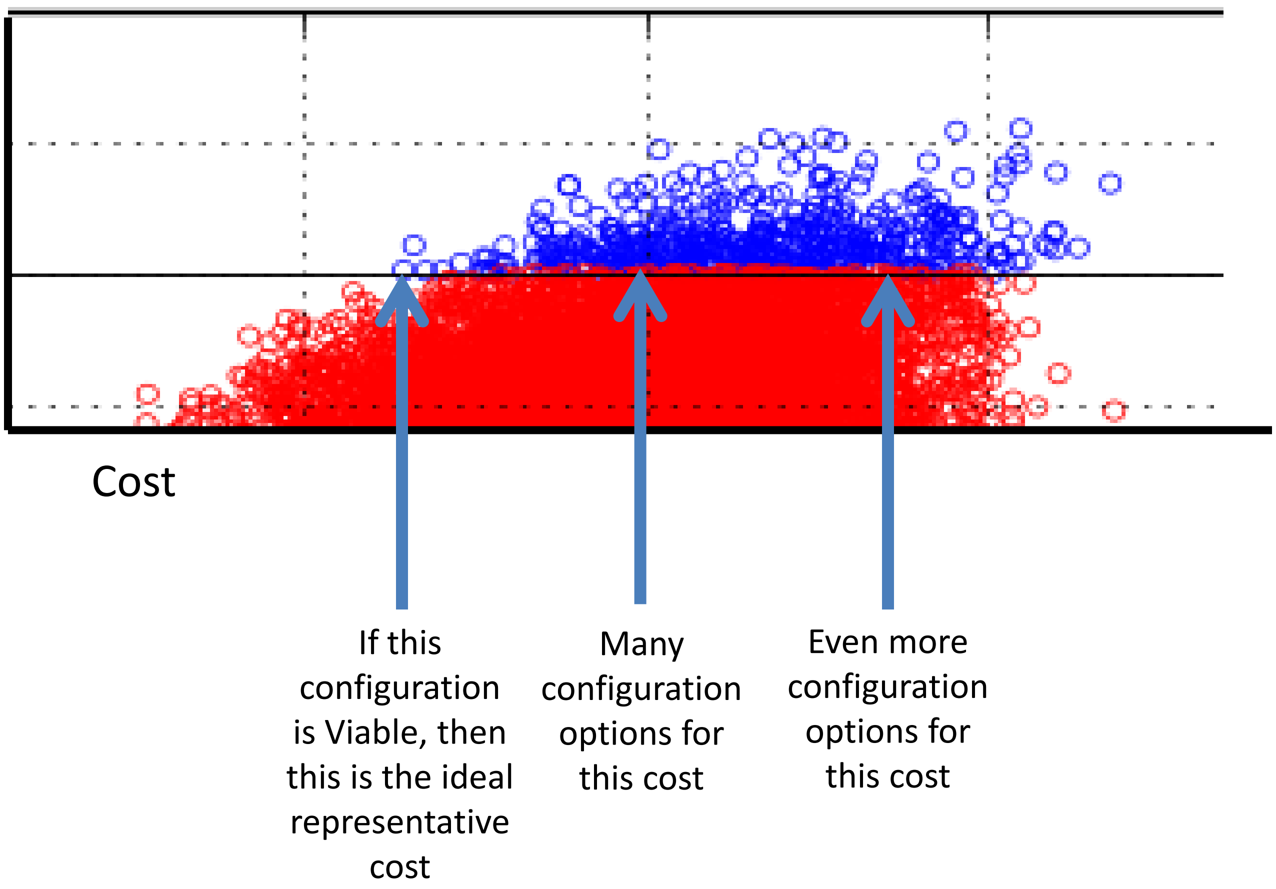
Scatter Plot



All the Blue Points are feasible configurations for a single capability concept

What is a good representative cost?

Answer: The lowest cost for which the risk that all feasible configurations with a lower or equal cost are not viable is low. The risk is evaluated via a Diversity Metric

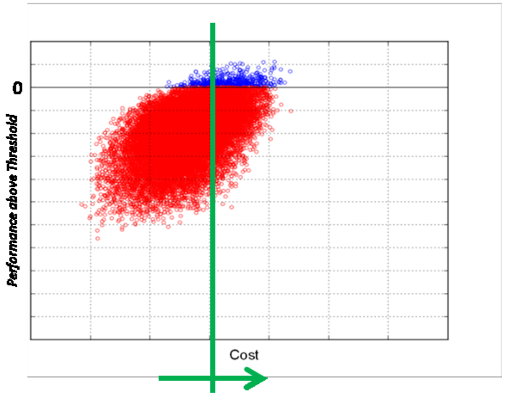


Diversity Metric

- Measures how different the feasible configurations within a set of configurations are from each other
  - Order the feasible configurations by cost, then measure the diversity for all configurations less than a given cost.
- Higher diversity implies that the chance that all feasible configurations with the set are not viable is lower

Using a Diversity Metric to identify Ship Design Technology Risks and Opportunities

Diversity Variable	Number of Configurations to meet Diversity criteria
AAW suite	40
SUW suite	43
ASW suite	51
Weight Equation	54
Deckhouse Material	57
Propulsion Architecture	119
Main Engine Power	153
Hogging Constant	164



Risks and Opportunities: Concentrate near term design activity on understanding these options

Comparing Capability Concepts Technical Risk

Capabilities	14 Troops; "A" Direct Fire Protection	14 Troops; "B" Direct Fire Protection	17 Troops; "A" Direct Fire Protection	17 Troops; "B" Direct Fire Protection
"C" Under-Blast Protection; Weapon "X"	**Feasible**	**Feasible**	**Feasible**	**High Risk Feasibility**
"C" Under-Blast Protection; Weapon "Y"	**Feasible**	**Feasible**	**Feasible**	**High Risk Feasibility**
"C" Under-Blast Protection; Weapon "Z"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "X"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "Y"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "Z"	**Not Feasible**	**Not Feasible**	**Not Feasible**	**Not Feasible**

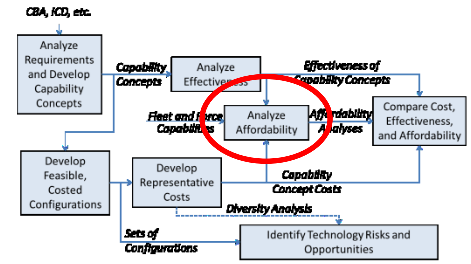
Comparing Capability Concepts Effectiveness

Capability Concepts

	Mission A	Mission B	Mission C
AAA	7	0	7
AAB	10	0	3
ABA	5	4	8
ABB	8	6	4
BAA	6	0	8
BAB	9	0	4
BBA	4	5	9
BBB	7	7	5

Performance / Effectiveness Metrics

Assess Affordability



- Establishing value of capability with respect to cost
- Part of Portfolio Analysis
  - Navy-wide considerations
- May include user feedback to prioritize capabilities
  - Resource constrained war games

ACV Workshop conducted at Ellis Hall on 9-11 July 2013

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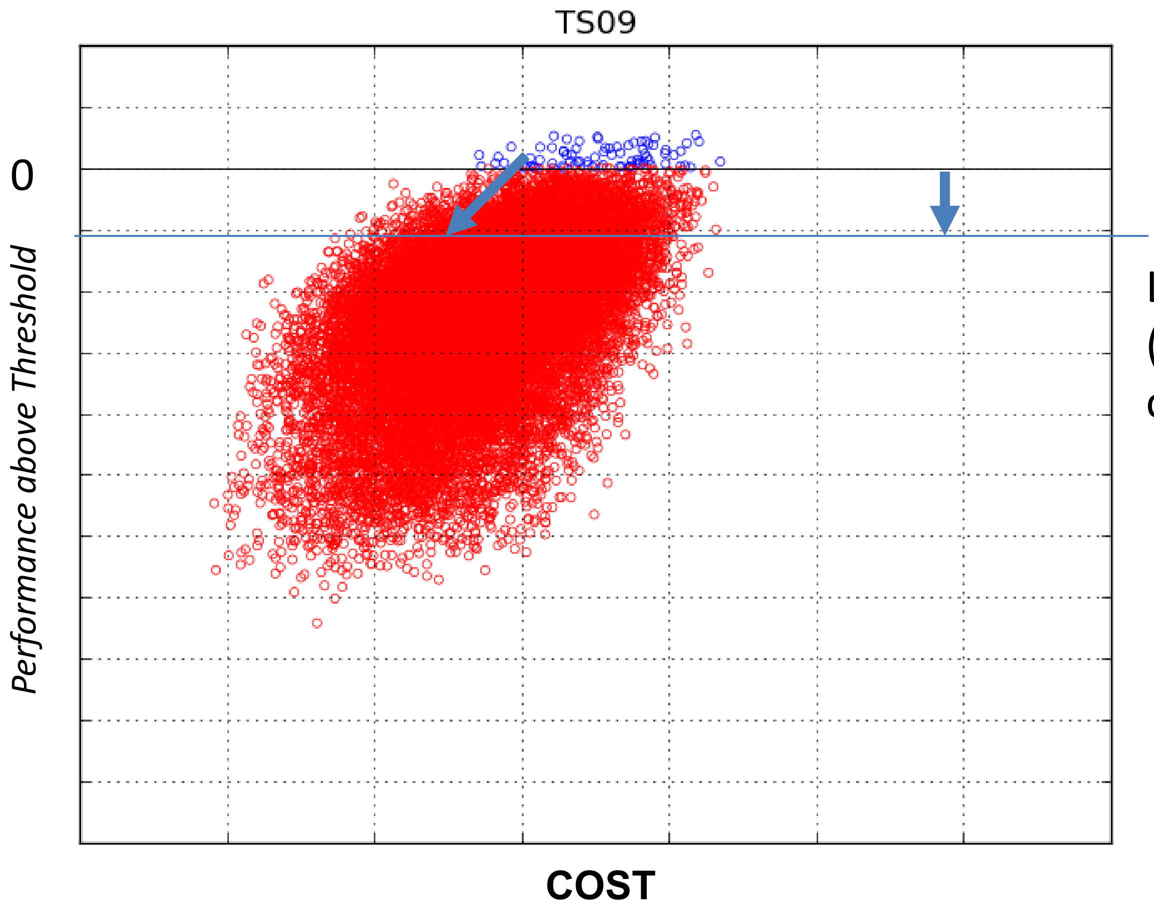
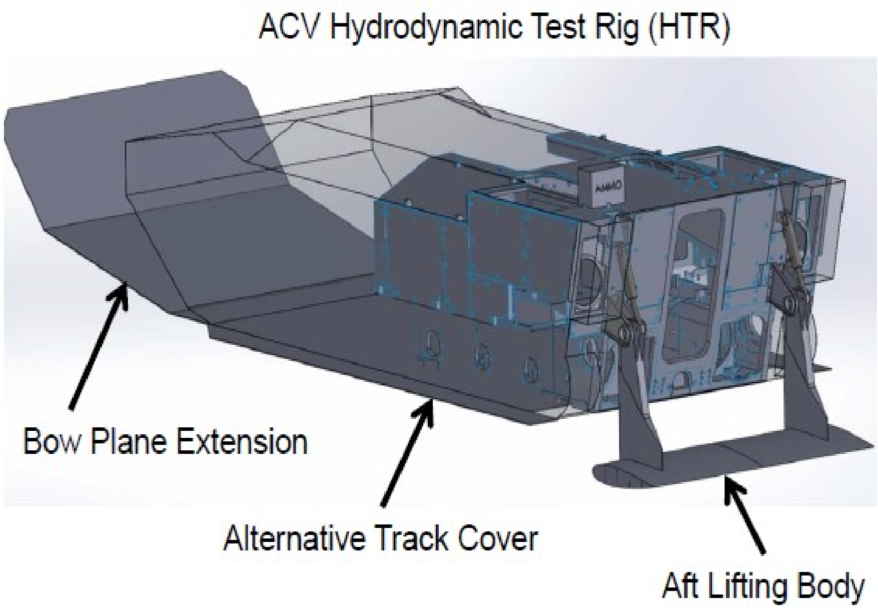
Insight

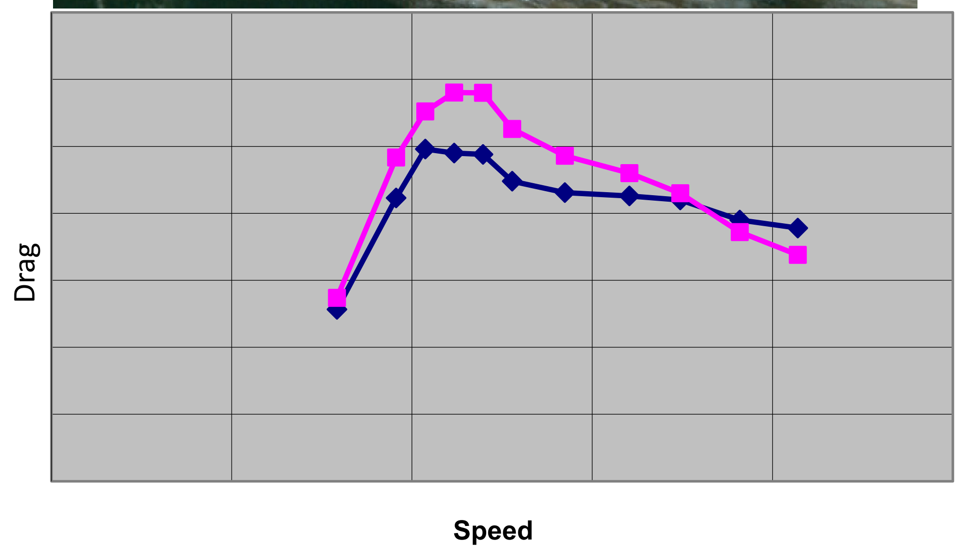


Lowering Threshold (constraint) enables cost reduction

Innovation Team: Aft Lifting body



Need to test at full-scale to confirm



Model Testing: Aft Lifting Body Reduced Drag

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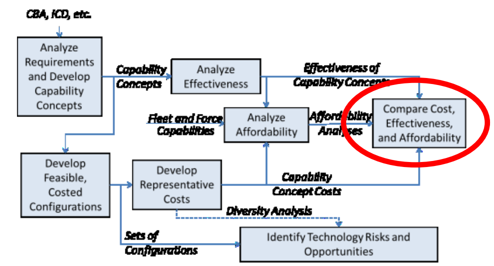
Compare Cost, Effectiveness and Affordability



- Intersect the findings of
  - Effectiveness Analysis
  - Affordability Analysis
  - Cost and Feasibility Analysis
- Highlight Technology and Risk Opportunities

Capabilities	14 Troops; "A" Direct Fire Protection	14 Troops; "B" Direct Fire Protection	17 Troops; "A" Direct Fire Protection	17 Troops; "B" Direct Fire Protection
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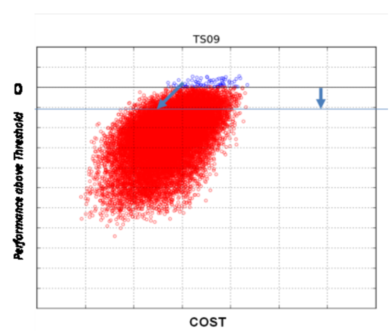

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Flexibility and Modularity

Flexibility

- Exact value of a requirement not yet determined
  - A range for the value is established.
- Time when requirement will be determined specified
  - Short Term: Before MS A
  - Mid Term: Within 1 year after MS A
  - Far Term: Before MS B
- Design must affordably accommodate range of requirement until the value is established.
- Enables deferring decision until more is known about the impact of the requirement on cost and value.

Modularity

- Ability to inherently meet the current threshold and accept the modularity impacts in order to grow to the final desired capability
- Categories:
  - Field: modules selected and changed out in the field
  - Depot: modules changed out in a depot environment
  - Variant: design modularity; variant with high commonality ordered for production, but not designed to be modified later.
- Modularity requirements documented in pairs:
  - Threshold requirement at Initial Operational Capability (IOC)
  - Modularity features for future upgrades

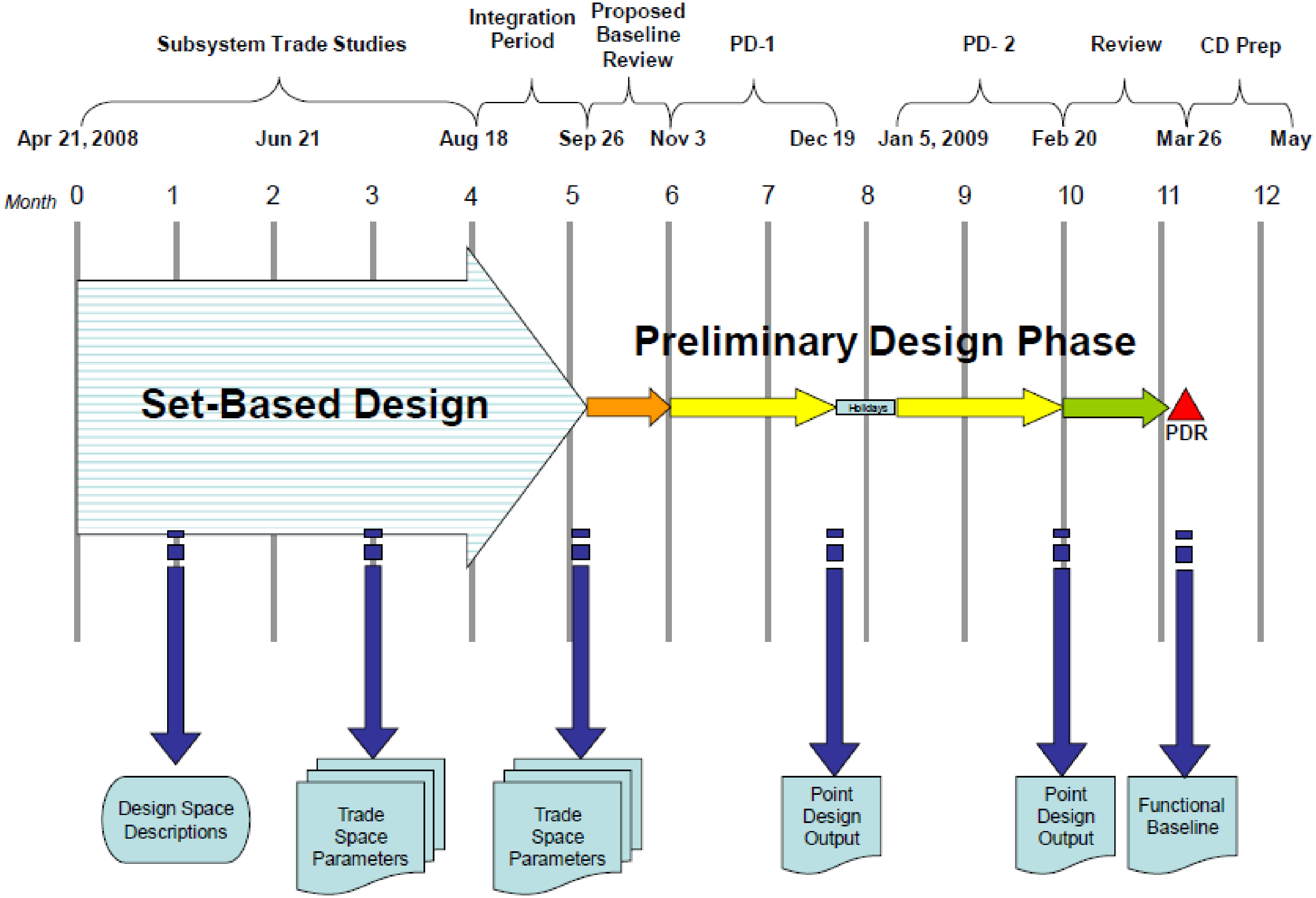
Key Take Aways

- Set Based Design (SBD) is a methodology: The way design alternatives are understood, analyzed and selected.
  - Implemented through Design Processes
  - Enabled by Design Tools (typically within a Model Based Systems Engineering Environment)
- **The key idea is that decisions are systematically made (and documented) to eliminate regions of the design space.**
  - Easier to show something is not the answer than prove something is best
  - The final answer is chosen from the design space remaining after all the potential solutions that aren't the answer are eliminated.
- SBD methodology can apply to Capability/Requirements Development and Design Development
- SBD demonstrated its power to inform senior Flag/General Officer decisions regarding capability concept alternatives, design alternatives (per capability concept), and technical and programmatic risks.
- SBD does not make decisions, it informs decisions … most importantly, it preserves decision space for leadership until the time is right
  - Make decisions when knowledge is sufficient.
  - Avoid "re-making" decisions or back-tracking.

SBD and Preliminary Design: Ship to Shore Connector

- Replacement for the LCAC
- Deploys in LPD, LSD, LHD Amphibious Well Deck Ships
- Transports weapon systems, equipment, cargo and personnel
  - High speed (over 35 knots)
  - High payload (74 Short Tons)
  - Over the Horizon (25nm or greater)
  - Over-the-beach operations
  - Through NATO Sea State 3 (significant wave height of 4.1 ft)
- Operate independent of tides, water depth, underwater obstacles, ice, mud, or beach gradient

SSC Design Schedule



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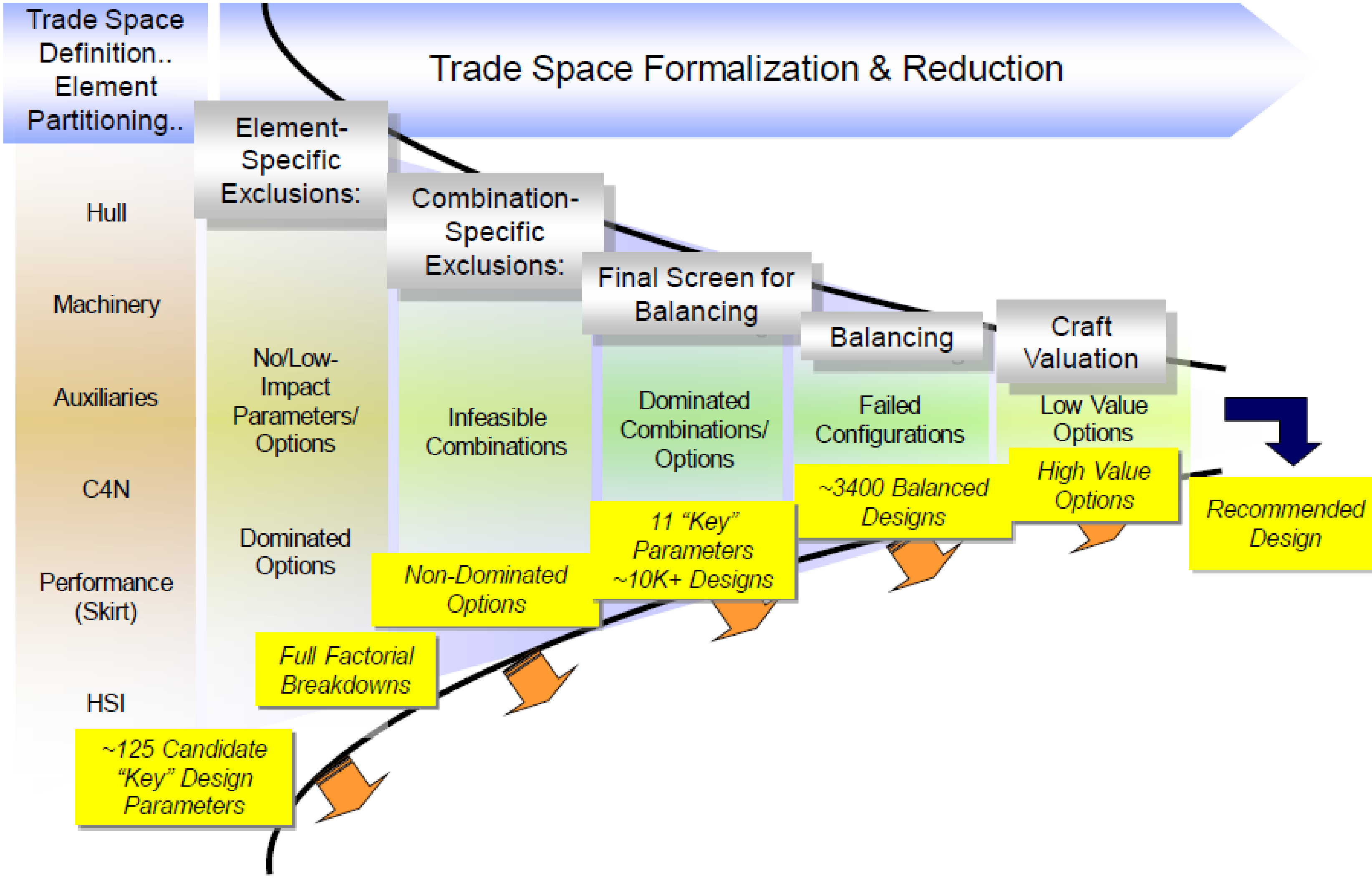
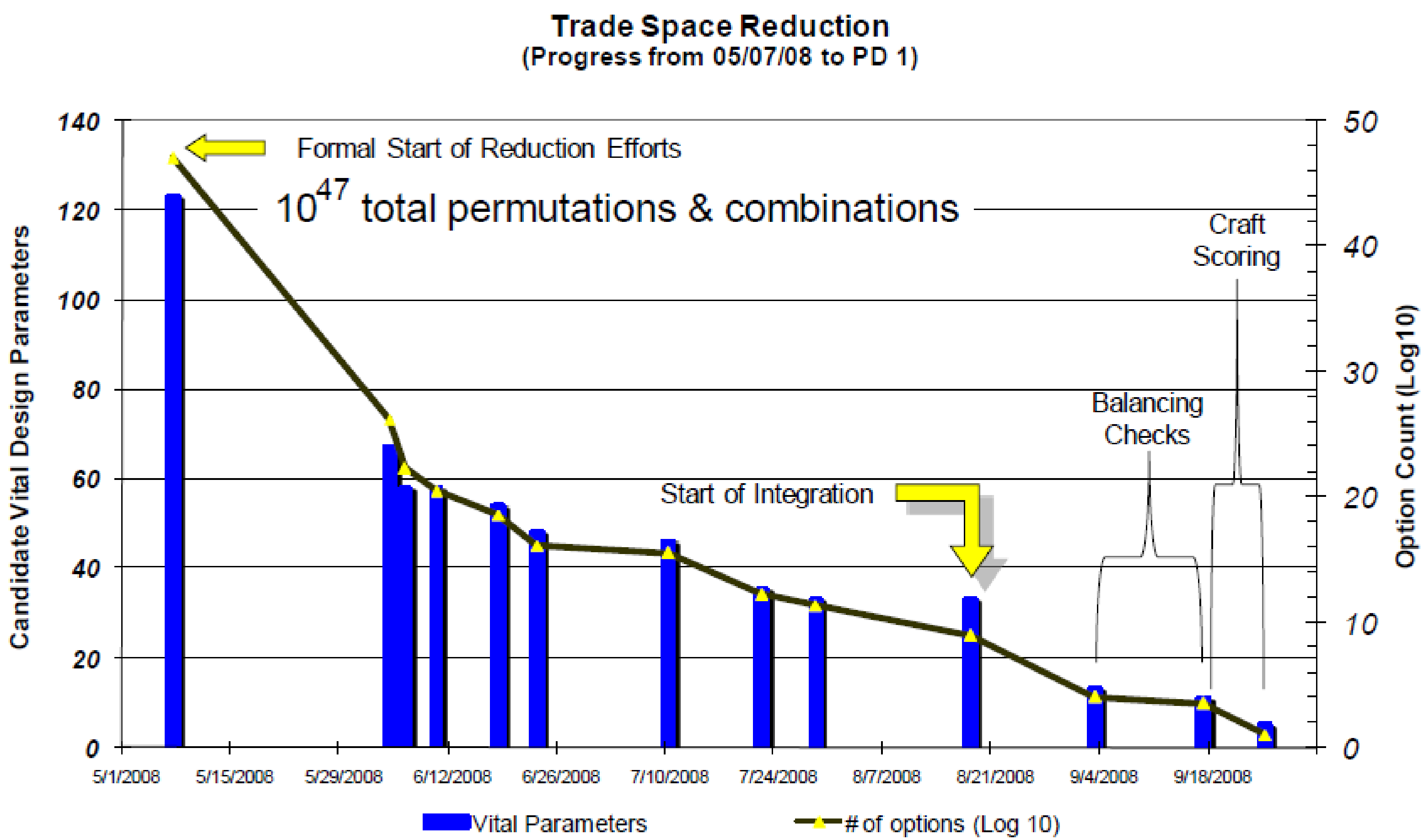
SSC SBD Implementation



SSC SBD Trade Space reduction



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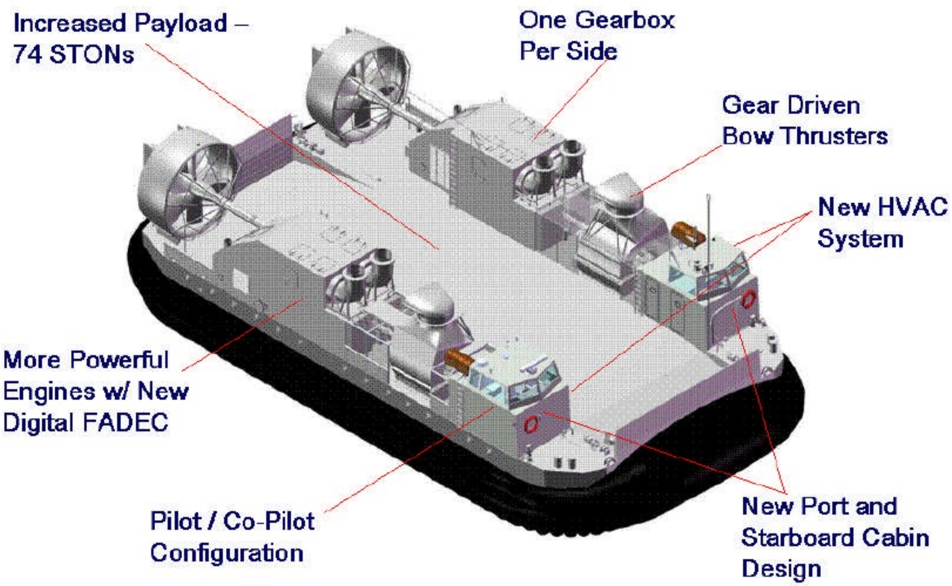
Key Findings with SBD on SSC

- Allowed evaluating a large range of options
- Optimum solution determined through traceable process
- System engineers were familiar with many of the key tools:
  - Design of Experiments
  - Regression Techniques
  - Factor Screening
- Meaningful Measures of Effectiveness are difficult to evaluate
- Overcoming point-based design practices was challenging

SSC Outcome

- SSC Preliminary design completed on schedule
- SSC Preliminary design was less than 10% over the original budget
- No design margin was consumed
- Lead unit (test and training craft) fabrication began in November 2014
- Delivery planned in 2017



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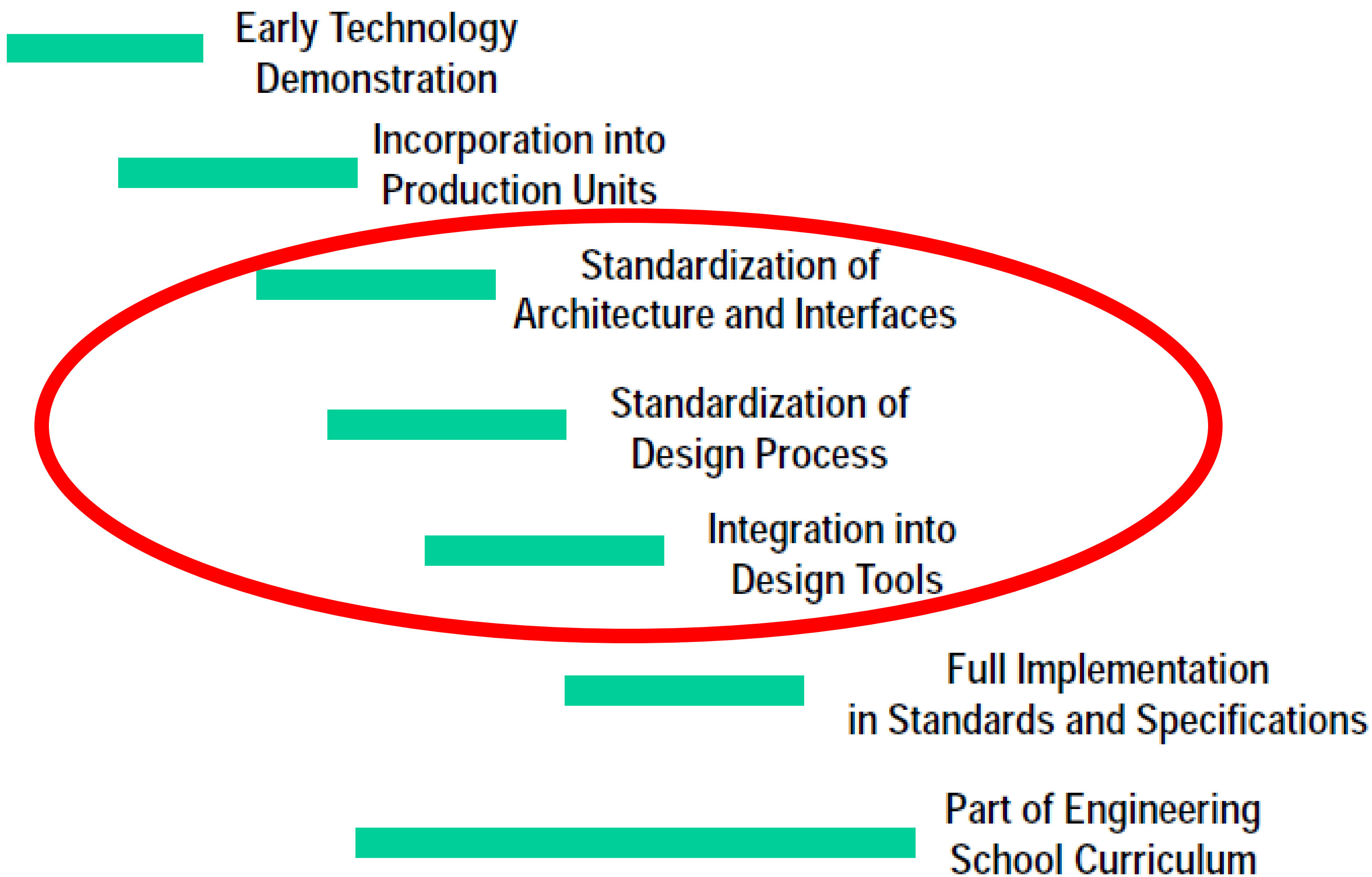
Institutionalizing SBD



Definitions

Capability Concept

- Requirements set + Concept of Operations (CONOPS) / Employment + Acquisition / Support Strategy

Configuration

- A specific set of components comprising a complete system
- Many configurations (or no configurations) can be developed for a given capability concept

Feasible Configuration

- A configuration that our current analysis shows will work and meet the requirements of the associated capability concept

Viable Configuration

- A configuration that actually works when produced and meets the requirements of the associated capability concept
- Configurations currently deemed Feasible may prove not to be Viable due to future analysis or testing

Feasible Concept

- A Capability Concept with sufficient feasible configurations of sufficient diversity such that the risk that none of the feasible configurations are viable is low

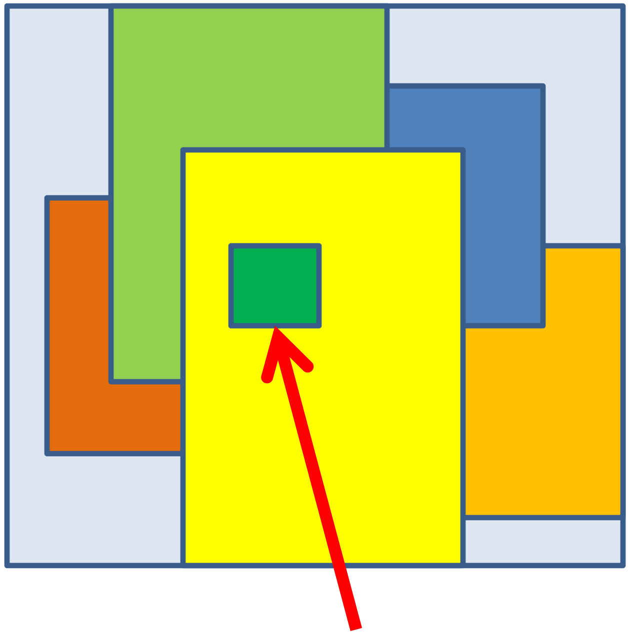
Diversity

- A metric of the degree to which the feasible configurations within a design region are different from each other
- High diversity implies lower risk

Preparing for concept exploration:

Design the Design Process

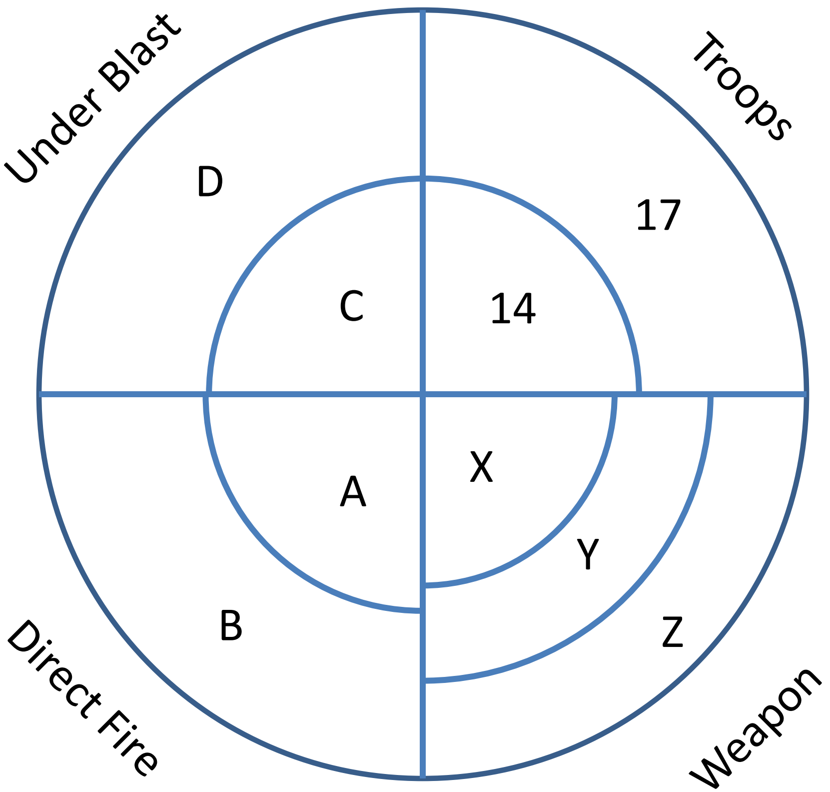
- Understand the requirements trade space:
  - Fact of Life: just do it (ship must float)
  - Low Impact: assume value and address later
  - Medium Impact: assume baseline and treat as an incremental change
  - High Impact: explore the design space
- Understand the types of analysis domains needed:
  - Technical Feasibility and cost
  - Acquisition Feasibility
  - Military Effectiveness
  - Affordability
- Develop methods to intersect the results of the analyses from the different domains
  - If a configuration is infeasible in one domain, it is infeasible
  - Can strategically order analyses to reduce design space early
- Develop methods to compare attributes of the sets of feasible configurations for each capability concept across all the capability concepts
  - Representative cost based on diversity



Intersect Analyses results to define Feasible Design Space for a capability concept

ACV Capability Concept

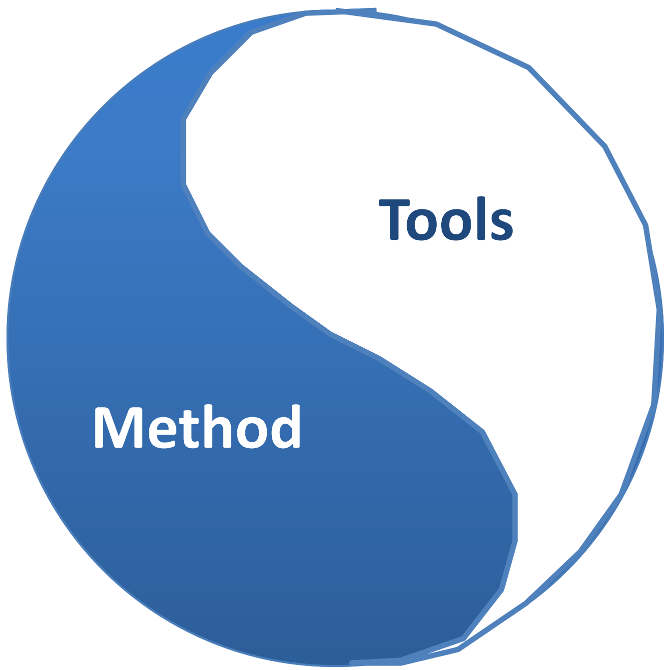
- Capability Concept
  - Number of Troops
  - Weapon
  - Under Blast Protection
  - Direct Fire Protection
- Domains
  - Technical Feasibility and Cost
  - Military Effectiveness
  - Affordability



24 Different Capability Concepts

Synergy Between Tools & Method

- Tools without a Design Method are of little value.
- A Design Method without the necessary tools cannot be executed.
- Requires a pragmatic combination of innovative methods and capable tools.



We do not have a sustainable approach for developing and maintaining Design Tools & Associated Data