Concept Exploration Methods for the Small Surface Combatant

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In 2014, the Small Surface Combatant Task Force completed an innovative study on alternate proposals to procure a capable and lethal small surface combatant. Modified Littoral Combat Ship (LCS) concepts, new design concepts, and existing design concepts were examined. This paper describes the set-based design approach employed to conduct this study.

KEY WORDS

concept exploration; warship; set-based design

NOMENCLATURE

ASCM	Anti-ship Cruise Missile
ASSET	Advanced Surface Ship and Submarine Evaluation Tool
AW	Air Warfare
ASW	Anti-Submarine Warfare
CCA	Combat Systems Configuration Alternative
CONOPS	Concept of Operations
EC	Enabling Capability
ERS	Engineered Resilient Systems
FACT	Framework for Assessing Cost and Technology
HM&E	Hull, Mechanical, and Electrical
LCCE	Life Cycle Cost Estimate
LCS	Littoral Combat Ship
MA	Mission System Alternative
MCO	Major Combat Operations
MIW	Mine Warfare
O&S	Operating and Support
PMA	Primary Mission Area
R&D	Research and Development
RDT&E	Research, Development, Test and Evaluation
RSDE	Rapid Ship Design Environment
SBD	Set-Based Design
SLA	Service Life Allowance
SSC	Small Surface Combatant
SSCTF	Small Surface Combatant Task Force
SUW	Surface Warfare
SWAP-C	Space, Weight, Power and Cooling

INTRODUCTION

In February 2014, the Secretary of Defense directed the Department of the Navy to submit alternate proposals to procure a "capable and lethal small surface combatant generally consistent with the capabilities of a frigate" to assist with Presidential Budget 2016 deliberations. In response to this direction, the Navy (Stackley and Greenert 2014) established the Small Surface Combatant Task Force (SSCTF) and tasked it to accomplish the following:

a. Establish the requirements and requirements trade space of a small surface combatant.
b. Assess the impact of the requirements delta to LCS (both sea frames)
c. Translate the requirements delta into design concepts for a small surface combatant, considering the following alternatives:
   (1) Modified LCS design
   (2) Existing ship design
   (3) New Ship Design
d. Include with each design concept:
   (1) Top level requirements (including sensors, weapons, combat systems requirements)
   (2) Cost
   (3) Major Milestone Schedule
   (4) The lethality of the ship to air, surface, and undersea threats

This paper describes the methodology used by the SSCTF to answer these questions during the spring and summer of 2014.

CAPABILITY CONCEPTS AND CONFIGURATIONS

For this effort, the requirements trade space of a small surface combatant was represented by a set of Capability Concepts. A Capability Concept is a set of operational capability levels and an associated CONOPS for employing the capabilities. The operational capability levels are depicted in "bullseye" charts such as depicted in Figure 1. For each level in the bullseye chart, specific capability statements are defined. Levels are greater in capability and in some cases cumulative moving from the center of the chart to the outer edge. The Primary

Mission Areas (PMA) are defined as AW, ASW, MIW and SUW. The remaining elements of the capability concept are designated “Enabling Capabilities (EC).”

Figure 1: Capability Concept “Bullseye” chart

A configuration is a potential material solution for meeting the capabilities of a Capability Concept. In general, a Capability Concept can be fulfilled by either many (infinite) configurations, or by no configurations (infeasible). A feasible configuration refers to a configuration that has been evaluated to meet the Capability Concept based on the current fidelity of modeling and analysis. Viability refers to the evaluation that a configuration meets the Capability Concept based on future more detailed modeling, analysis and testing.

SET BASED DESIGN (SBD)

The SSCTF employed Set Based Design methods to develop Capability Concepts and New Design configurations. While tool limitations precluded a complete application of SBD to the LCS modifications, SBD principles were employed in developing the LCS modification concepts where possible.

In a traditional design process, a few “point designs” are created, iterated, and compared to develop a limited understanding of the trade space; solutions are chosen and modified until they “work.” This approach is heavily dependent on the experience of the designers, as well as a comprehensive understanding of the implications of new technologies or ship design configurations. In SBD, the design solution emerges from systematically eliminating sets of design configurations shown through analysis to NOT be a good solution. As rigorous analysis eliminates more and more of the solution space, feasible solutions become apparent. The first step in SBD is defining bounds for regions of the solution space. This can be either a bounding variable range, such as length or speed, or discrete states of design such as electric drive or a traditional reduction gear driven vehicle. Once the regions are established, different specialties explore tradeoffs by designing and evaluating multiple alternatives within their domain. As the specialists explore the design alternatives they communicate their analysis based preferences for different regions of the design space to the study integrators. The study integrators integrate the domain solutions produced and evaluated by specialists into total system solutions. Study integrators "integrate by intersection" by identifying intersections of the preferred variable ranges among the specialist groups. Those subsets of the variable ranges that do not fall within the intersections of preferred variable ranges are considered for "reduction" based on an assessment on the possibility that future analysis may prove solutions within the subset to be viable. (Singer et al. 2009) (McKenney and Singer 2014)

Three principle concepts for implementing SBD are (Bernstein 1998):

1. Consider a large number of potential solutions.

2. Have specialists evaluate sets of solutions from their own perspective.

3. Intersect the sets to optimize a global solution and establish feasibility before commitment.

SBD assumes that if a configuration is declared not feasible, then it will also likely not be viable. If a configuration is declared feasible, future analysis or testing may validate the configuration as viable, or may show the configuration not to be viable.

Early in the design process, SBD will not result in a specific design; rather the solution space will still be a set of feasible configurations. The set should be rich enough in diversity of configurations such that additional, more detailed analysis will validate that a subset of the feasible configurations still remain viable; the set of feasible configurations should not have a common mode of failure. (Doerry et al. 2014)

The set of feasible solutions should also include the potential outcomes of requirements decisions that have not yet been made. For example, if it is unknown whether a single propulsion shaft design will be acceptable, then the set of feasible configurations should contain both single propulsion shaft and twin propulsion shaft configurations.

A representative cost for a capability concept should be based on a diverse set of the feasible configurations. Since any one feasible configuration may not prove viable, basing the representative cost on a set of diverse configurations mitigates the risk that any one configuration will prove not viable.

In later stages of design where feasibility also implies viability, configurations may be eliminated based on Pareto Optimality; that is, if a configuration is inferior in every way to another configuration, even under uncertainty, then it may be eliminated.

PROCESS OVERVIEW

Figure 2 depicts a high level view of the SSCTF process. Using a common set of capability concepts enabled much of the work to occur in parallel before being fully integrated as part of the final report development.

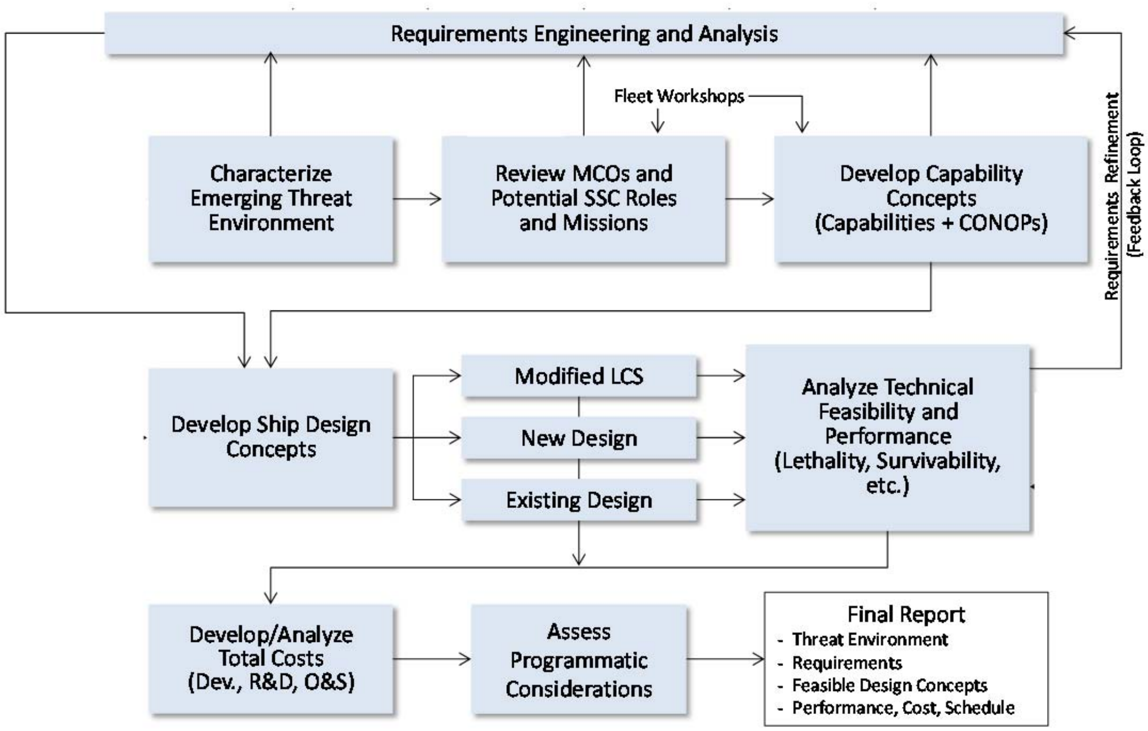

Figure 2: SSCTF Process

CAPABILITY CONCEPT DEVELOPMENT

Initially 192 capability concepts representing the permutations of the four primary mission areas were considered. A logical process was used to reduce this set of capability concepts down to 13 which were further analyzed. For each of the 13 remaining capability concepts, the other “spokes” of the bullseye chart (AKA enabling capabilities) were established based on the expected CONOPS associated with the capability concept. These enabling capabilities were also informed by feedback from the fleet engagement.

During the technical modeling of these 13 capability concepts, the physical systems used to implement local ASW and area ASW that were considered were found to differ insignificantly. Hence the local and area ASW capability concepts were combined, leaving only the eight shown in Table 1.

The logical process employed to reduce the 192 capability concepts to 8 is an example of Set-Based Design. One set of specialists performed the initial set reduction to 13 based on an analysis of the Navy’s force architecture and the capabilities suited for a small surface combatant that are not already being fulfilled by other warships within the fleet. The subsequent reduction to 8 was based on a different set of specialists: Combat Systems Engineers conducting the technical modeling. The study continued to provide additional insight to enable a further reduction and generate the final set of desired capabilities.

Table 1: Capability Concept Mission Area Capabilities

	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

COMBAT SYSTEMS MODELING

Combat system configurations alternatives were developed for each of the eight capability concepts. Candidate combat systems elements, such as sensors, command and control systems, and weapon/engagement sensors were compiled from recent combatant studies, existing US and foreign combat system designs, and responses to Requests for Information. These candidate elements were screened for programmatic feasibly, where only those expected to be available to support an FY 19 lead ship acquisition were retained.

Combat systems elements were assembled into mission system alternatives (MAs) designed to achieve a complete detect-to-engage capability for a mission area capability level (Figure 1). Multiple MAs were developed for each PMA capability level to provide a range of feasible options as part of the SBD process. The feasibility of an MA was established in part through mission thread analysis (Figure 3) to ensure a complete detect-control-engage kill chain.

A complete combat system configuration alternative (CCA) consisted of a mission system alternative for each of the primary mission areas. Creating valid combinations of mission systems alternatives resulted in over 2000 discrete CCAs, yielding a rich combat systems trade space. For each CCA, Space, Weight, Power, and Cooling (SWAP-C) estimates were developed in addition to cost and manpower inputs.

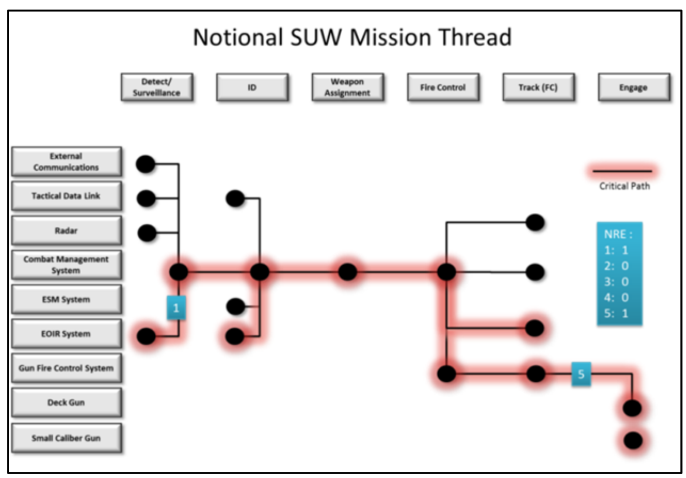

Figure 3: Mission Thread Analysis Example

LCS MODIFICATION MODELING

Spreadsheet models were employed to determine the feasibility, impact, and cost of modifying the LCS to achieve capability concepts. For the LCS modifications, the PMA and EC performance requirements were not considered absolute; requirements tradeoffs were expected to achieve feasibility. Excursions were explored which: (1) traded ECs to preserve PMA capabilities; (2) traded PMA performance to levels that would still provide operational utility; and (3) implemented engineering tradeoffs among design features to address space, weight, power, cooling, and center of gravity concerns. This excursion analysis was an important element in helping to fully explore the design trade space; (4) explored means to increase space, weight, power, or cooling, or lower center of gravity to provide additional trade space for capability concept exploration.

Figure 4 depicts the process for developing LCS modification configurations. Individual removals and additions were identified to meet the capability concepts. Each addition or removal was characterized by size, weight, vertical center of gravity, electrical power needs, cooling water needs, and manpower impacts. At a total ship level, impacts to speed, endurance range, and endurance days were evaluated. Additionally, changes were characterized to enable effective cost estimation.

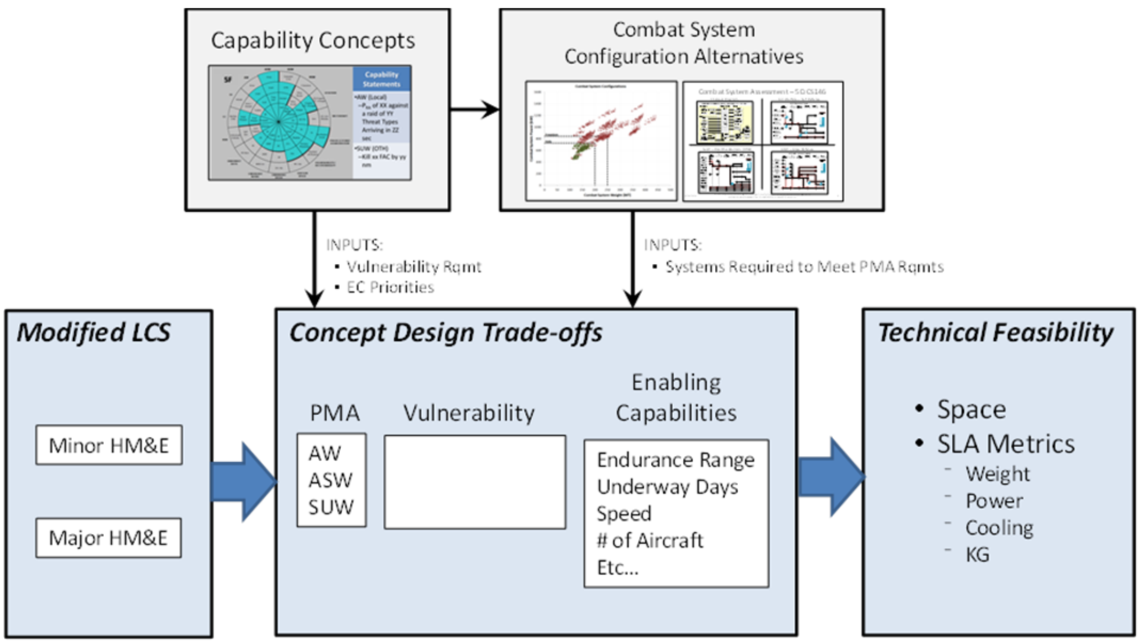

Figure 4: LCS Modification Analysis Process

NEW DESIGN MODELING

Figure 5 depicts the overall process for modeling new designs. The Advanced Surface Ship and Submarine Evaluation Tool (ASSET) and Rapid Ship Design Environment (RSDE) were used to create a Table of "RSDE Configurations" that represent a data space of small surface combatants with the capability of carrying varying combat suites. Five different Hull, Mechanical, and Electrical (HM&E) baseline seed configurations served as a basis for creating about 15,000 different RSDE configurations:

- Mechanical Drive twin shaft
- Mechanical Drive single shaft
- Integrated Power System twin shaft
- Integrated Power System single shaft
- Integrated Power System twin shaft, adjacent motors

The baseline seed configurations represent different propulsion options that cannot be treated as a simple variable within RSDE. The ~15,000 RSDE configurations are not tied to capability concepts. These configurations were analyzed to produce cost estimates (minus combat system costs), and annual fuel consumption. The results of the analyses were appended to the table of "RSDE Configurations" for further analysis.

The "RSDE Configurations" did not directly model the combat system. The combat system was represented by a SWaP-Box that decomposed the primary naval architecture design details of the combat system into a common set of variables. These SWaP-Box variables were varied over the expected range of the properties for all the CCAs as part of the generation process for the "RSDE Configurations." See

McCauley et al (2015) for more details on the use of a SWaP-Box.

Separately, a smaller sample of configurations was generated using RSDE and then analyzed for seakeeping and stability performance.

The statistical analysis program JMP was used to convert the "RSDE Configurations" into five sets of regression equations (one set per baseline seed). These equations enable approximations of configuration properties between the specific configurations comprising the table of "RSDE Configurations." For example, the SWaP box parameters used to create the RSDE Configurations spanned, but did not match the specific values from the CCAs. Because the CCAs were being developed at the same time as the RSDE Configurations, it was not possible to specify CCA values for the RSDE Configurations. JMP was also used to develop regression equations to predict seakeeping and stability performance. The regression equations also enabled much faster computation of configurations; many more configurations could be developed.

The combat system modeling described above occurred in parallel with the process to create the regression equations. The CCAs created by the combat system modeling were analyzed to develop the SWaP-Box variable values, combat system manning requirements, mission area feasibility evaluation, vulnerability assessments, and combat systems cost elements.

A manning analysis was conducted to develop an algorithm for predicting the required crew size (minus the crew required to support the combat system).

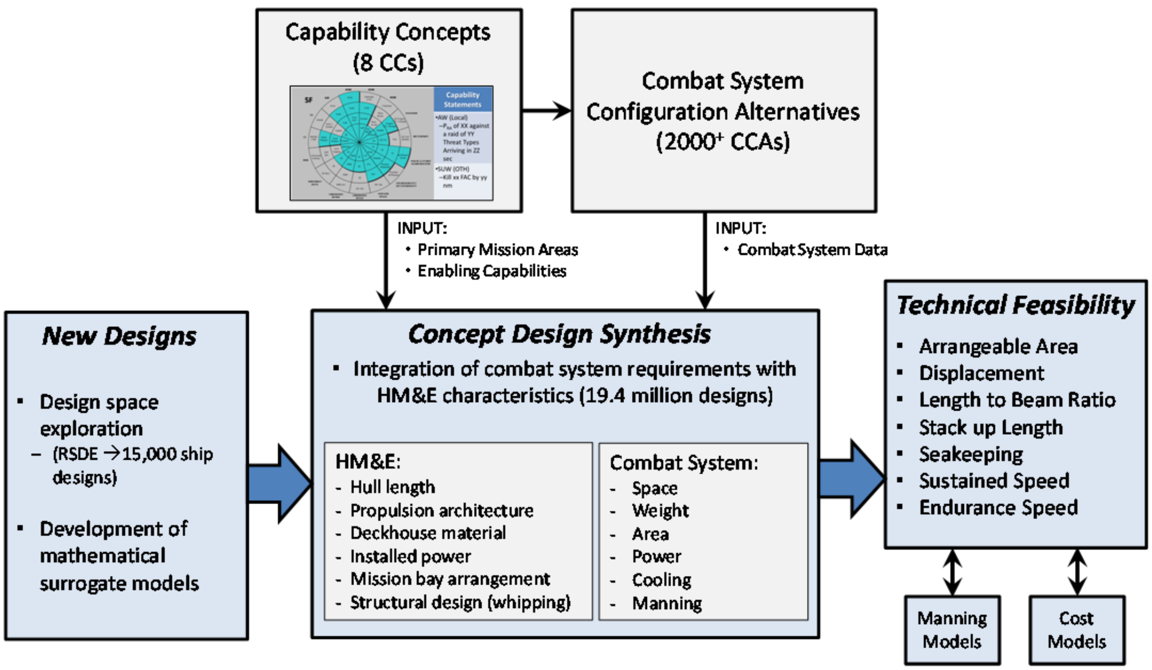

Figure 5: New Design Overall Process

The regression equations, the cost algorithms, HM&E crew size algorithms, combat system crew size algorithms, other algorithms and the data associated with the CCAs were imported into the Engineered Resilient Systems (ERS) Tradespace Toolkit. The ERS Tradespace Toolkit implemented five models as shown in Figure 6: Combat Systems Calculator, Regression Model, Cost Model, Feasibility Element Calculator, and Configuration Feasibility Calculator. The Combat Systems Calculator integrates the CCA data including, Combat system manning, SWaP-Box variable values, combat system feasibility assessments, vulnerability calculation, enabling capabilities, and combat system cost. The Regression Model implements the mathematical surrogate models developed in JMP. The Cost Model combines the costs produced from the Regression Model with the Combat Systems Cost to produce the configuration cost estimates. The Cost Model also calculates Operating and Support Cost estimates.

The Feasibility Element Calculator produces feasibility assessments (Feasible Excessive, Feasible, High Risk for Feasibility, or Not Feasible) for the following feasibility elements:

- SUW Performance
- ASW Performance
- AW Performance
- Sustained Speed
- Endurance Speed
- Arrangeable Area
- Displacement
- Length to Beam Ratio
- Stack up Length
- Seakeeping

"Feasible Excessive" implies that the configuration greatly exceeded the required performance. "Feasible" implies confidence that the required performance will be met, but not met excessively. "High Risk for Feasibility" implies low confidence that the required performance will be met. "Not Feasible" implies confidence that the performance will not be met. Criteria were developed based on a comparison of the required value to the calculated value for each feasibility element.

For example, stack up length is the minimum length of a ship necessary for a feasible arrangement. In this study, the required stack up length was determined by the topside arrangement based on the size of helicopter deck and hanger and the selection of weapon systems. The degree to which the ship's length exceeded the stack-up length determined whether this feasibility element was evaluated as feasible, high risk for feasibility, or not feasible. The feasible excessive category was not used for this feasibility element.

These feasibility elements combined in the Configuration Feasibility Calculator to produce an overall assessment of configuration feasibility based on the following criteria:

Feasible: All Feasibility Elements "Feasible"

Not Feasible: Any Feasibility Element "Not Feasible" or if greater than five Feasibility Elements are "High Risk for Feasibility"

High Risk for Feasibility: If one to five Feasibility Elements are "High Risk for Feasibility" and the remaining Feasibility Elements are "Feasible" or "Feasible Excessive"

Feasible Excessive: At least one Feasibility Element is "Feasible Excessive" and the remaining Feasibility Elements are "Feasible"

Compound integration risk is incorporated into the overall assessment by stating that if greater than five Feasibility Elements are "High Risk for Feasibility," then the configuration is "Not Feasible." With greater than five "High Risk for Feasibility" elements, the chance is very high that one of the risks will be realized.

The ERS Tradespace Toolkit, implementing Monte Carlo simulation, assigned a subset of the regression equation input variables to parameter values specified by the Capability Concept, and randomly choose the values for the remaining input variables. About 10,000 feasible configurations were generated for each capability concept. Each configuration has a cost estimate, a feasibility assessment, and mission performance metric. The many configurations for a given capability concept were visualized on scatter plots as depicted in Figure 7. Feasible configurations are green, high risk for feasibility configurations are yellow, and not feasible configurations are red.

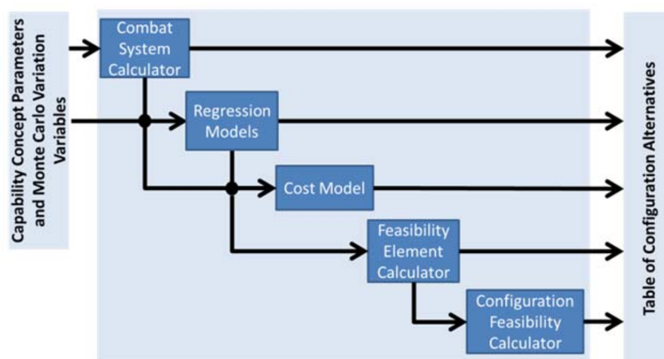

Figure 6: ERS Tradespace Toolkit model structure

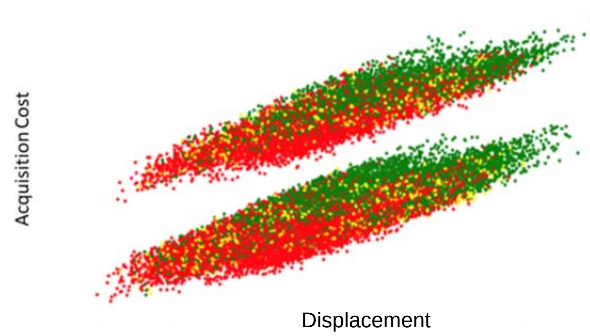

Figure 7: Scatter Plot Visualization

EXISTING DESIGN ANALYSIS

The existing design analysis fundamentally differed from the LCS modifications and new design concepts in that the process started with existing small surface combatant designs provided by industry or identified by the SSCTF instead of starting with a capability concept. As depicted in Figure 8, existing designs were characterized and mapped as closely as possible to a capability concept. Since by definition, existing designs were developed without thought to capability concepts, none of the existing designs mapped directly to a capability concept. These designs were also evaluated with respect to operational risk. While cost data, if available, was captured, the cost data was not analyzed in detail or modified to enable a direct comparison with the LCS modifications and/or new designs.

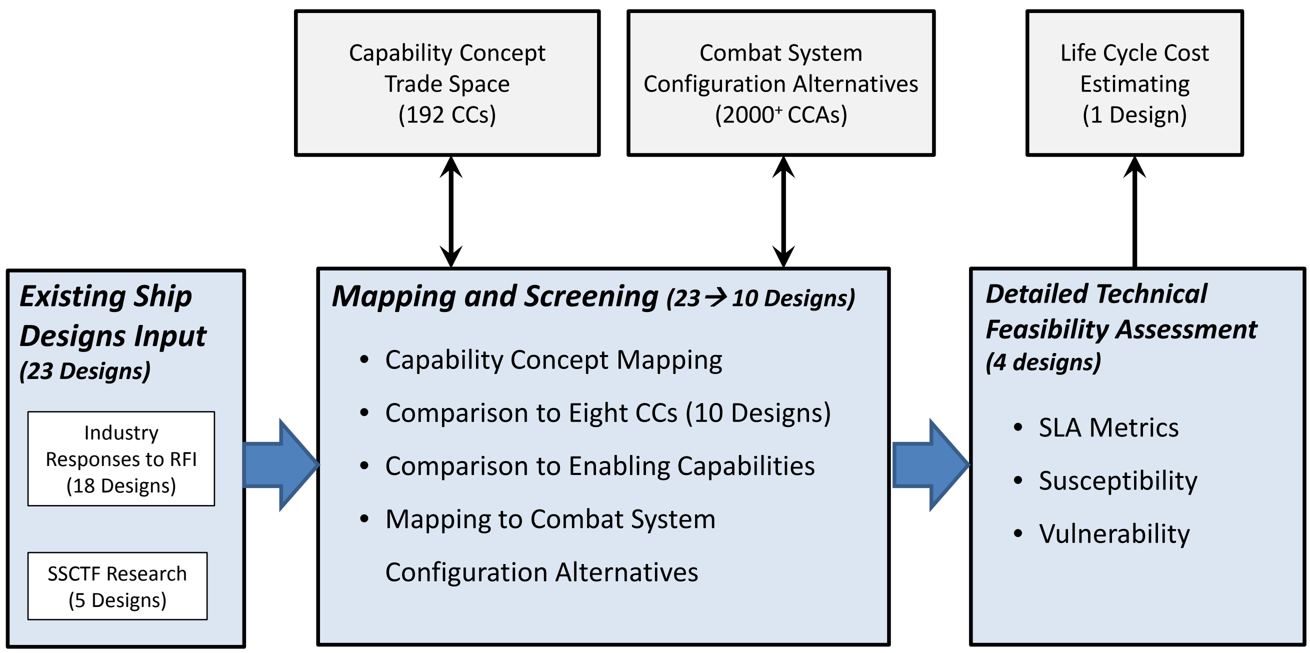

Figure 8: Existing Design Analysis Process

COST ANALYSIS

Life cycle cost estimates (LCCE) were developed for each capability concept design alternative (modified LCS, new design, and existing design). LCCEs included the following:

- Research, Development, Test and Evaluation (RDT&E)
- Procurement
- Operating and Support
- Disposal

The overall process for developing cost estimates is depicted in Figure 9.

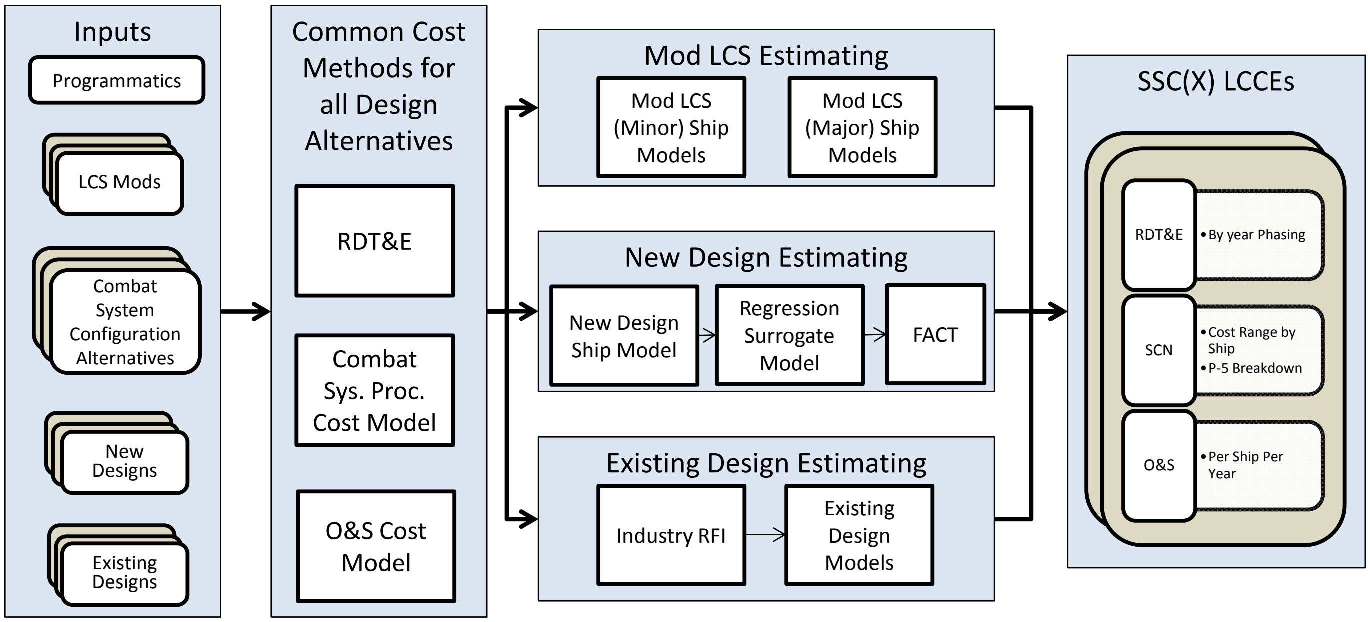

Figure 9: Cost Analysis Process

SET-BASED DESIGN

The methods employed by the SSCTF adhered to the principles of Set-Based Design:

1. **Consider a large number of potential solutions**: Not only were modified LCS designs, new designs and existing designs considered for each capability concept, multiple configurations reflecting multiple CCAs were developed for each capability concept. Over 10,000 feasible new design configurations were developed for each capability concept.

2. **Have specialists evaluate sets of solutions from their own perspective**: The CCAs were developed and evaluated by the Combat Systems Modeling Team independent of the HM&E Modeling. The new design regression models were developed independent of specific CCAs (and Capability Concepts), but covered the range of applicable CCAs. The new design Feasibility Element algorithms were developed based on the results of analysis conducted by subject matter experts. For the LCS modifications, where possible, multiple configurations were development for each capability concept. Costs were assigned at the LCS-mod, new design, and existing design level based on the set of feasible solutions for a specific capability concept.

3. **Intersect the sets to optimize a global solution and establish feasibility before commitment**: For the new designs, the Configuration Feasibility Calculator intersected the feasible solutions as evaluated by the Feasibility Element algorithms. Incorporating compound integration risk was one technique used to establish configuration level feasibility. The representative costs for each capability concept were based on multiple configurations to reflect the global solution rather than specific point designs.

CONCLUSION

The SBD approach used to fully explore the trade space for the small surface combatant was very successful in providing senior Navy and DOD leadership the insight needed to make critical acquisition decisions for the small surface combatant. In particular, the scatter plots enabled a good visualization of the range of solutions possible for a given Capability Concept. By allowing meaningful work to be conducted in parallel, SBD enabled an unprecedented amount of analysis to be conducted in a study lasting less than six months; in time to impact the FY16 budget process.

Desired improvements for the future include developing more automated methods and tools for conducting modified designs, incorporating more feasibility elements in new designs to reduce the probability that a feasible configuration will prove not to be viable in future stages of design, developing meaningful metrics on sets of configurations beyond average and limiting values, employing fuzzy logic or other methods in evaluating feasibility elements, and improving the manner in which a base ship architecture is scaled for specific configurations.

In summary, the SSCTF fully explored the potential solution space for a small surface combatant using innovative methods. Modifications to the LCS, new ship designs, and existing ship designs were all fully considered.

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