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SET-BASED REQUIREMENTS, TECHNOLOGY, AND DESIGN DEVELOPMENT FOR SSNX

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SUMMARY

Maintaining affordable undersea capability will require modern design methodologies to minimize costly design changes while continuing to address evolving threats. An aggressive timeline and broad uncertainty around design requirements has led the U.S. Navy towards a set-based strategy for requirements, technology and design development for future submarines [1]. Set-based methods enable informed and defendable decisions by systematically understanding tradeoffs prior to commitment [2], and have successfully been implemented on several ship programs [3] [4] [5]. This paper will provide an introductory background on set-based methods including: definition and clarification of terminology, a history of application within the Naval Sea Systems Command, and a qualitative comparison to traditional point-based methods. Next, the paper will discuss the motivation for adopting set-based methods for SSNX. Finally, a detailed overview of a set-based strategy for future submarine requirements, technology, and design development will be presented.

NOMENCLATURE

DSE	Design Space Exploration
PMS 450	VIRGINIA Class Program Office
RSDE	Rapid Ship Design Environment
SBD	Set-Based Design
SSBN	Ship, Submersible, Ballistic, Nuclear
SSCTF	Small Surface Combatant Task Force
SSN	Ship, Submersible, Nuclear
SSNX	Future Nuclear Attack Submarine
VCS	VIRGINIA Class Submarine

1. INTRODUCTION

The United States Navy operates three classes of attack submarines: LOS ANGELES, SEAWOLF, and VIRGINIA. The early-stage design work for these classes began in 1963, 1978, and 1988 respectively. The long-range naval shipbuilding plan calls for the continued block procurement of the VIRGNIA Class, with a plan to support construction of a follow-on class in 2034 [6]. These timelines indicate that future VIRGINIA blocks will still be in service post 2070, 80 years after design began, and a follow-on SSN, SSNX, could be in service post 2090. The timelines also suggest that requirements, technology, and design development are already behind the curve for the next generation submarine, Figure 1.

Requirements, technology, and design development for submarines facing a 2070-2090 world is a major challenge, even greater than that for recent classes and blocks. The Block I VIRGINIA Class submarine (VCS) development effort benefitted from clear requirements, recent SEAWOLF Class technology research and development, and a very experienced workforce. Blocks II-IV have focused on evolutionary improvements and cost reduction. Block V adds a significant payload module amidships, but is technologically evolutionary. The COLUMBIA Class SSBN in development incorporates many new technologies, but is a single mission platform with a clear requirement. In contrast, the requirements future VIRGINIA blocks and SSNX will be expected to meet and the technologies to do so are yet to be defined, and could significantly change throughout their lifecycle. Uncertainty in requirements and rapidly advancing technology defines a high risk development environment, further compounded by a workforce reduced in size and experience through attrition.

To meet this challenge, a set-based strategy for submarine requirements, technology, and design development is being formulated. Traditionally the Navy has used iterative methods for submarine design. Though flexible and accurate, iterative methods require starting points, i.e. fixed requirements and technologies, and end with single design solutions. Iterative methods are far from ideal when the starting points are uncertain or likely to change. Set-based methods require starting sets, i.e. ranges of requirements and technologies, and end with a range of design solutions. The variability of requirements and technologies is captured from the outset. The objective is to enable timely and robust acquisition decisions by systematically understanding tradeoffs prior to commitment.

This paper provides an introductory background on set-based methods, a history of application within the Naval Sea Systems Command, and a qualitative comparison to traditional point-based methods. Next, the paper discusses the motivation for adopting set-based methods for future submarines. Finally, an overview of a set-based strategy for requirements, technology, and design development is presented, including an example specific to SSNX.

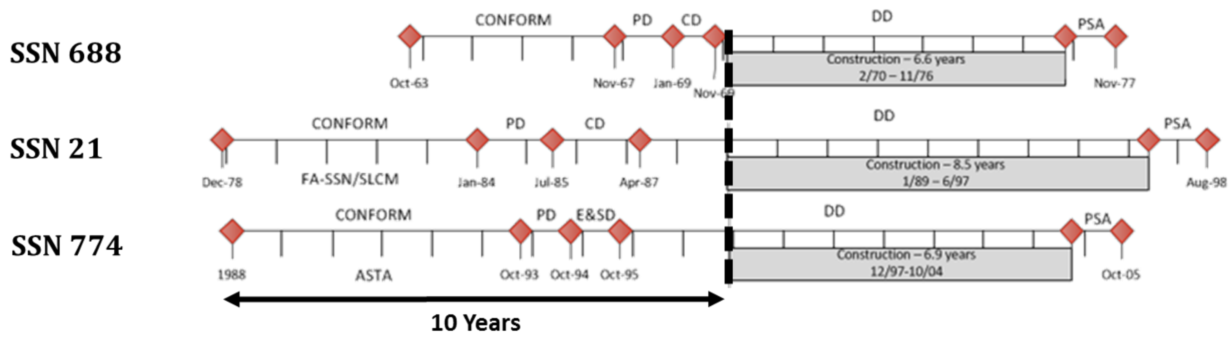

Figure 1: U.S. Navy SSN Design Development Timelines [1]

2. SET-BASED DESIGN

2.1 DEVELOPMENT OF SET-BASED DESIGN

In the late twentieth century Japanese manufacturing firms were extensively studied because of their higher efficiency and quality relative to firms in the United States. A special focus was placed on the Toyota Motor Company because it was also outperforming other Japanese automotive companies. By traditional measures Toyota’s production system seemed inefficient, yet put high quality automobiles on the market faster than the competition. This was termed the “First Toyota Paradox” [7]. Part of the paradox was identified as strong parallel rather than sequential links between traditionally separate disciplines, e.g. manufacturing and product development, consistent with a Concurrent Engineering approach. Recognizing and studying the importance of Toyota’s product development method to the company’s production success, Ward, Liker, Cristiano, and Sobek identified what they called the “Second Toyota Paradox”; the overall design phase was shorter and more efficient, yet purposefully withheld decisions, communicated ambiguous specifications, and produced excessive numbers of prototypes [7]. The term set-based design (SBD) was used to define this product development method, and quantitative research later verified that Toyota’s success was not in spite of the second paradox but in part because of it [8]. Research at the University of Michigan beginning in the late 1990’s explored naval design applications for the method, and introduced it to the U.S. Navy [9]. Since then, the Navy has applied versions of the method on several surface ship and vehicle programs [3] [4] [5] [10]. Set-based methods have also been applied commercially outside the automotive industry, notably in aerospace [11]. Within academia submarine set-based design has also been explored, but never applied [12].

2.2 TERMINOLOGY

The terminology used within design research often varies. The following definitions based on the work of McKenney are used for clarity [13]:

- Design Method: The way in which design alternatives are understood, analyzed, and selected
- Design Process: A series of structured steps to implement the design method
- Design tool: In support of design methods, tools are used to provide information that enables decision making as part of a design process.

SBD is a design method. It is implemented in the context of a design process that may or may not employ design tools. In applying SBD, as is true with most design methods, a customized design process is usually developed to implement the method.

2.3 A SET-BASED DESIGN PROCESS

SBD arrives at a design solution by a process of elimination rather than iterating around a small number of potential design solutions. A single solution is determined by sequentially excluding regions of the design space that are either infeasible or highly dominated. A feasible solution is one that meets known hard design constraints, such as neutral buoyancy, stability, and validated minimum performance requirements. It is important to exclude “desirements” from feasibility criteria to avoid over constraining the design space. A highly dominated solution is a feasible solution with properties (typically cost) that are greatly inferior to another feasible solution; and therefore, a highly dominated solution is not likely ever to be a preferred solution.

An SBD process enables groups of domain experts to evaluate the design space semi-autonomously. Each domain provides its evaluation of the design space in terms of feasibility, dominance, and preference. Typically, the feasibility evaluation is communicated as regions in the design space where the solutions are feasible, not feasible or uncertain with respect to the domain analysis. As each group completes its evaluation, the results are integrated with the results developed by the other groups. Once combined, if the uncertain region is still relatively large (and the uncertain region is not evaluated as infeasible by any domain), higher fidelity analysis is typically performed to reduce uncertainty and refine the borders of the feasible and infeasible regions. An SBD process has the following characteristics:

- Communicating broad sets of design values

- Developing sets of design solutions
- Evaluating sets of design solutions by multiple domains of expertise
- Delaying design decisions to eliminate regions of the design space until adequate information is known
- Documenting the rationale for eliminating a region of the design space

Figure 2 depicts an example with 3 domains. In this example, Domain 2 performs higher fidelity analysis to refine its uncertain region. Domain 3 takes advantage of the knowledge that certain regions of the design space have already been shown to be infeasible to limit the design space it explores. Once all the domains have completed their analysis, any solution in the remaining feasible region in the integrated design space is acceptable.

2.4 DESIGN SELECTION STRATEGIES

Selecting a single design solution from the feasible region can be done with a number of different strategies. It is uncommon for the ultimate decision authority to rest on those with technical authority, thus it is necessary to provide clear and defendable technical information to the stakeholders responsible for the decision. When many options are under consideration as is common with SBD, this quickly leads to the challenge of data visualization. Ultimately decision makers are looking for a cost vs. capability curve, but a single plot does not readily convey the tradeoffs in a multi-dimensional design space.

2.4 (a) Qualitative Stakeholder Decision Making

In the end, the ideal is to provide insight on the differentiating characteristics within the feasible design space to stakeholders; allow them to negotiate among

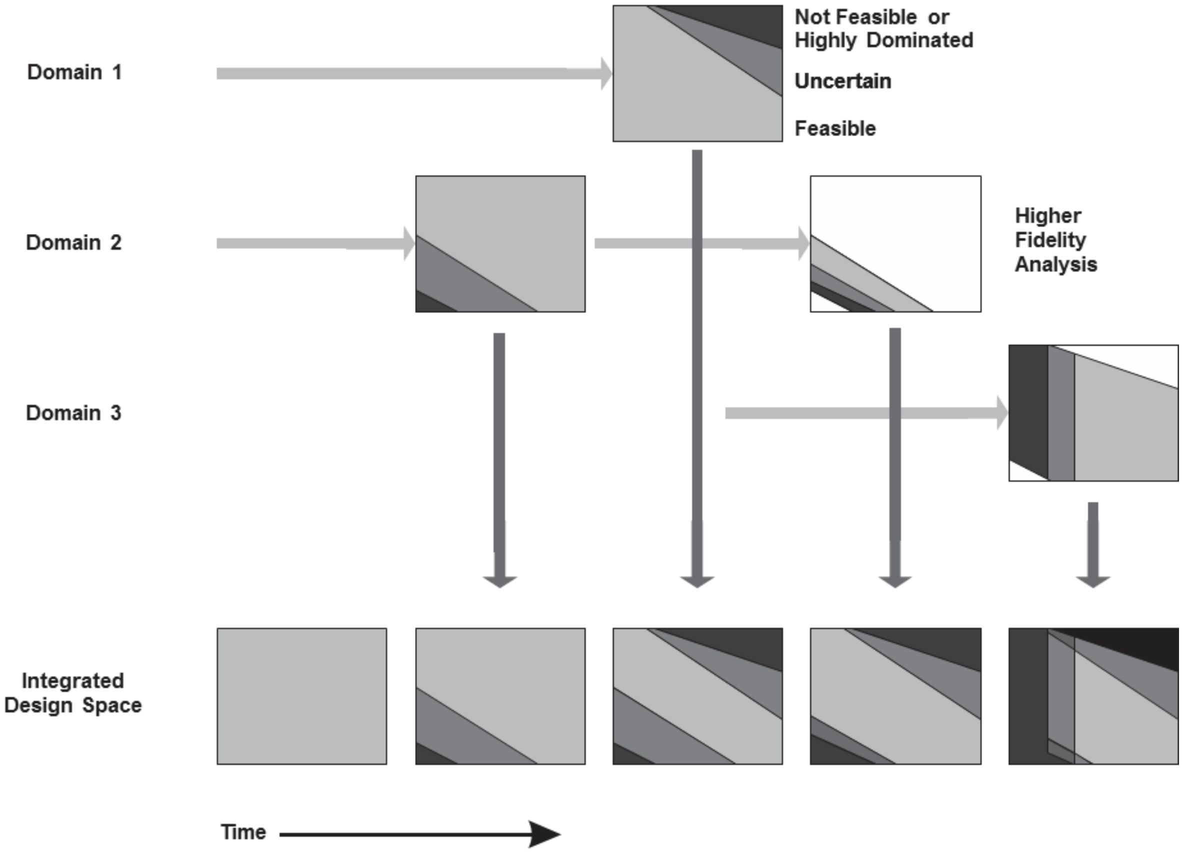

Figure 2: Set-Based Design Process Example

themselves to select a single design solution. When there are legal source selection procedures that must be followed the selection cannot be perceived as arbitrary. In this case the differentiating characteristics must be more formally documented, i.e. specifications, such that the decision is clearly defendable.

2.4 (b) Quantitative Stakeholder Decision Making

If decision makers are more interested in a quantitatively defendable single point solution, there are several familiar methods to narrow the feasible set.

Traditional optimization tools are one option, based on preferences or utility functions obtained from stakeholders. Caution is required to hold the use of optimization until selecting from an all feasible set, as optimizers seek a best solution as opposed to the SBD principle of selection by elimination.

Given the qualitative nature of preferences but a desire for quantitatively based decisions, fuzzy logic tools have been developed to aid set-based decision making [14]. Though fuzzy logic is not necessarily required, the general idea is for stakeholders to designate regions of the design space into one of three categories: highly preferred, preferred, or not preferred. Using techniques similar to those identified for Figure 2 in establishing feasibility of the integrated design space, an integrated design space depicting regions of preference is constructed. The design space is narrowed to the highly preferred region if it exists. If a combined highly preferred region does not exist, stakeholders may negotiate to select a solution.

Risk based methods can also be appropriate. The objective is to eliminate until a robust subset of the feasible design space is revealed. A robust subset is one that is impervious to remaining risk, but minimizes the cost of continuing multiple design alternatives.

Multiple designs from the subset are continued until remaining risks are resolved. A risk is resolved when it has been reduced to insignificance, no longer warranting tracking or mitigation, or realized. The robust subset contains solutions which are not impacted by the realized risks; these solutions can be continued and the design will progress in a risk-tolerant manner.

2.5 WHEN TO APPLY SET-BASED DESIGN

During the past decade, most Naval Sea Systems Command applications of SBD have focused on requirements development and early-stage design. This differs from later stages in that the main focus is on understanding requirements, the design problem, and potential solutions. This stage is analogous to “Requirements Elucidation” as defined by Andrews [15], and occurs prior to the creation of a formal acquisition program. The majority of a program’s life-cycle costs are locked in during this time; early decisions have a greater influence on outcomes than later decisions [2] [11]. As a result, the penalty for mistakes is greatest during requirements elucidation. Set-based design has the most benefit early on in the design process when critical design decisions must be made well.

Set-based design is not always the right method, but is a good candidate when there is large trade space that is not fully understood:

- A large number of design variables
- Tight coupling among design variables
- Conflicting requirements
- Uncertainty or flexibility in requirements
- Uncertainties in technologies
- Design problems that are not well understood
- Learning is required for a solution

U.S. Navy warship designers will attest that most recent early-stage design projects have all of these attributes.

The purpose of using set-based design is to make the right decisions the first time by methodically understanding tradeoffs prior to commitment. The benefit of good decisions during the early-stages is better designs, at lower costs, on shorter schedules.

2.6 COMPARISION TO POINT BASED DESIGN

The traditional design method is point based design. The method proceeds as follows: requirements are defined as specifically as possible, several concepts are generated, and there is some interpolation between concepts. A single concept (point design) is selected early to lock in major characteristics, and the concept is further developed until it can meet all requirements. If the concept fails to meet requirements or the requirements change, the process repeats. For naval architecture, the process to implement point-based design is commonly illustrated as a design spiral [16], often credited to Evans in 1959 [17].

The distinguishing feature of the design spiral is that each discipline (e.g. combat system, propulsion, arrangements, weight, displacement) is analysed for the concept in a sequence, handing results “over the wall” to the next discipline. The sequence is repeated (spiralling) to increase design fidelity or to adjust if the initial result is infeasible. The challenge that Evans was addressing in developing the design spiral was the high cost and limited bandwidth to produce and communicate design information. The “over the wall” approach minimizes the amount of communication required between disciplines, and spiralling on a single concept reduces the calculation required at any point in time. These were very important considerations in 1959 when design calculations were largely done by hand and information was communicated on paper.

The sequential nature of a manual point-based design process reduces the number of design points that can be evaluated, translating to a limited understanding of tradeoffs [1]. For design projects that do not have a large trade space, e.g. little requirements uncertainty and an experience base to select a good starting point, the design spiral remains very effective. It is in these cases where set-based design can be fairly criticized as slower, less efficient, and potentially unnecessary. However, even in these situations set-based design will still produce a "more defensible design with greater resilience to requirement changes [13]." If the requirements don't change set-based design may appear wasteful, but the data set can be maintained for potential future evolutions.

It should be noted that many other design approaches, methods, and processes have been developed for early-stage design, but they cannot all be described here. McKenney provides a more comprehensive overview of these methods and how they related to SBD in a chapter on early-stage design [13].

2.7 NAVY APPLICATIONS OF SET-BASED DESIGN

The Navy has applied various degrees of set-based methods to several programs including the: Ship to Shore Connector, Amphibious Assault Ship, Amphibious Combat Vehicle, and a Small Surface Combatant Task Force (SSCTF) [3] [18] [4] [5].

2.7 (a) The Small Surface Combatant Task Force

The SSCTF example is the most relevant to future SSNs because requirements, technologies, design, and acquisition were considered in a holistic manner. The following brief description is derived from Garner et al. [5].

The task force was created in 2014 in response to a Secretary of Defense directive to develop alternatives for a "capable and lethal small surface combatant generally consistent with the capabilities of a frigate." The SSCTF was tasked to establish a requirements trade space, requirements, evolutionary and clean sheet designs, and a cost and acquisition schedule for each design. The task force was focusing on potential changes to the Littoral Combat Ship program which had already delivered ships to the fleet, meaning the time horizon was present day. There was a very short schedule in order to produce results in time to inform the FY16 budgeting cycle. Set-based methods were adopted for requirements development and clean sheet design. Given the limitations of current design tools, set-based methods were not applied as broadly to evolutionary designs.

For requirements, the SSCTF defined four primary mission areas with varying levels of possible capability. A specific combination of mission areas and the associated concept of operation was defined as a Capability Concept. The initial set included 192 capability concepts, a full factorial expansion of four primary mission areas and between three and four capability levels for each. The initial set was reduced down to eight through several rounds of set reduction.

In parallel, separate teams were also working to define and reduce the trade space for combat systems and platforms (ships) to carry those systems. More than 2000 discrete possible combat system architectures were mapped to the 192 capability concepts. Space, weight, power, and cooling requirements to support each combat system were generated as part of this exercise.

Rather than sequencing the platform design after capability concepts and associated combat systems were generated, the platform team generated more than 15000 ship configurations in parallel. Parallel development required the naval architects to decompose potential combat systems into variables for space, weight, power, and cooling that spanned the range under consideration. Each ship and combat system configuration were assessed for cost.

Within the overall trade space of capability concepts, combat systems, and ship configurations, extensive use of regression was used to make estimates for in between designs, increasing the numbers further. After several rounds of set reduction a cost vs. capability trade space was produced, displayed as scatter plots. Ultimately this was simplified into a two dimensional cost vs. capability curve on which existing, modified, and clean sheet designs were placed. A single solution was selected from this curve by senior Navy leadership. The set-based approach provided the information necessary to make defendable acquisition decisions through a full exploration of the trade space in a short period of time. In the event that those decisions are revisited or warfighting requirements change, the full data set is maintained.

2.7 (b) Navy Design Tools

One of the many misconceptions about set-based design is that it is a tool, tool suite, framework, framework of tools, or that it requires one of the above. Set-based design is merely the specific method by which a trade space is analyzed, understood, and a single design selected. There is no explicit requirement for tools.

However, recent U.S. Navy implementations of set-based ship design have started by generating a broad trade space through design space exploration (DSE), including the SSCTF. DSE was conducted using the Navy developed Rapid Ship Design Environment (RSDE) software. The purpose of the software is not to automate a design method, but to populate a trade space of many ship designs and evaluate them for basic naval architecture feasibility criteria. In short, software served to broaden the trade space that could be explored.

There is no submarine capability within the Rapid Ship Design Environment. Recognizing the broad trade space that SSNX presents, a submarine design tool is the focus of ongoing development to enable set-based submarine design [19]. Submarine DSE presents unique challenges, namely that submarines are not surface ships and have very different fundamental equations. A small change in one area of a submarine design has farther reaching and greater impacts on other elements of the design. This stems from a near zero margin for error, mandated by physics and safety. The design fidelity required to account for those interactions is often higher.

3. FUTURE SUBMARINE DEVELOPMENT

3.1 MOTIVATION FOR A SET- BASED STRATEGY

Maintaining affordable undersea capability will require timely acquisition decisions that minimize costly design changes while continuing to address evolving threats. This is a high risk development environment, further compounded by a workforce reduced in size and experience through attrition.

Both academic research and practical experience with set-based design have demonstrated that methodically understanding tradeoffs prior to commitment leads to better, faster, and cheaper programs. Additionally, the structured communication, negotiation, and information transfer between domains is well suited for a smaller and less experienced workforce [2]. As a result, the U.S. Navy is working toward a set-based strategy for requirements, technology and design development for future VIRGINIA Blocks and SSNX. The ultimate objective is to enable informed and defendable decisions by clearly presenting tradeoff information between cost, schedule, and capability.

3.2 SET-BASED STRATEGY

The trade space for future submarines includes both Block development for the VCS and SSNX, spanning near, mid, and far term time horizons. This is a broader scope than previous Navy implementations of set-based design, a reflection of the broad early-stage decisions that must be supported. These decisions include:

- What capability gaps do future SSNs need to fill in the near, mid, and far term?
- Which technologies should be invested in to provide capability, and when does that investment need to occur?
- Which capability gaps can evolutions of the VIRGINIA Class fill?
- Which capability gaps require SSNX, and when does design development need to begin?
- What is the cost of technology and design development to provide required capabilities when needed?

Answering these questions requires that a broad decision space be produced of capability concepts, feasible enabling technologies, feasible submarine designs, and feasible acquisition plans. As a result, the four primary domains for a holistic future submarine set-based strategy are:

- Capability Concepts
- Technology Concepts
- SSN Concept Design
- Program Assessment

3.3 SET DEFINITION

3.3 (a) Capability Concepts Set Definition

The Capability Concepts Set Definition will define the range of warfighting capabilities future submarines could be required to have. The initial inputs to form this set will include: historical data, fleet engagement, and other subject matter expertise. To generate the trade space, those inputs will be used to conduct alternative futures studies, future threat assessments, mission engineering, and war gaming. The primary output of these activities will be a fully documented set of capability concepts. It is important to specify that capability concepts should be independent of specific technology or platform assumptions.

3.3 (b) Technology Concepts Set Definition

The Technology Concepts Set Definition will define the range of technologies future submarines could employ and the development timelines needed to mature them. Inputs to this set include known science and technology frontiers, research and development frontiers, and current technology. To generate the trade space, those inputs will be used to conduct technology assessments and generate representative architectures and design integration information, forming a future SSN technology database.

3.3 (c) SSN Concept Design Set Definition

The SSN Concept Design Set Definition will define the range of whole ship architectures possible for future submarines. Pre-studies will be conducted to define the naval architectural characteristics and boundaries for these architectures forming a future SSN hull, mechanical, and electrical database.

3.3 (d) Program Assessment Set Definition

The Program Assessment Set Definition will define the range of acquisition strategies, cost, industrial base limits, and design and build timelines applicable to future submarines.

3.4 SET REDUCTION & COMBINATION

The overall trade space for future SSNs is construction start date independent, but each time horizon will use unique set reductions. The design timelines shown in Figure 1 indicate that any near term fleet impacts can only be realized with a VIRGINIA Class evolution.

For purposes of example a VCS Block development will be considered, imposing a specific set of technology, platform, and programmatic constraints.

3.4 (a) First Set Reduction

The first round of set reduction can be conducted individually by each domain, eliminating infeasible options with documented and defensible analysis. Within the Capability Concepts set this would be alternatives that lose when war gamed for current or near term scenarios. The capability concepts set is almost time independent, as a Capability Concept that is infeasible today is highly unlikely to be feasible in the future.

For Technology Concepts, only currently available technologies, at a minimum ready for prototyping and at-sea testing, can be considered in the near term. Within the SSN Concept Design set, alternatives outside of VIRGINIA Block evolutions would be infeasible, in addition to any that violate the laws of physics. For the Program Assessment set, infeasible acquisition plans would include those outside the authority of the VIRGINIA Class program office (PMS 450), costs in excess of Congressional authorization, or design and build plans outside of the industrial base's capability. At this point there are four distinct sets with individually assessed infeasible options removed, as shown in Figure 3. The outer boxes represent the bounds of the trade space. The shaded ovals represent the potentially feasible concepts, per that domain, within the trade space. Concepts outside the oval but within the trade space are infeasible per that domain.

3.4 (b) Combining the Sets for Feasibility

After the first set reduction the individual sets can be combined, as shown in the upper left of Figure 4. It is at this point that communication and subsequent analysis between and within domains really begins. Information flows in all directions, but the first pass is likely to be sequential. First, the Capability Concepts set is mapped to the Technology Concepts set. For example, a particular anti-submarine warfare capability concept requires a shipboard sonar array of particular sensitivity. If array(s) exist within the Technology Concepts set that meet the requirement, these two sets overlap. Second, the technology concepts set is mapped to the SSN concept design set. The shipboard sonar array(s) have specific weight, displacement, location, power, and processing requirements. If there are feasible VCS platform designs within the SSN Concept Design set to handle any one of the possible arrays, the three sets overlap. Finally, the SSN Concept Design set is mapped to the Program Assessment set. If concept design(s) are assessed to fall within cost, schedule, and industrial base capacity for the VCS, the four sets overlap and a feasible region exists, as shown in the upper middle of Figure 4. In this fashion a capability concept is now linked to enabling technologies, platform designs and acquisition plans with an assessed cost. This region is carried forward and further refined from subsequent reductions as described in Section 2.3 based on additional design, analysis, or preference.

3.4 (c) Combining the Sets for Infeasibility

Almost as important as a feasible region, infeasibility is also identified and can be assessed. The capability impacts of technology gaps, platform gaps, or unaffordable solutions can be demonstrated. This is particularly relevant to a strategy with multiple time horizons. Each horizon imposes a specific set of feasibility constraints and uncertainty bounds. Near term feasibility is tightly constrained but uncertainty is low, whereas far term feasibility is less constrained but uncertainty is high. In other words, the feasible region is a function of time. A primary purpose of using set-based methods in this context is to methodically and continuously identify infeasible and uncertain areas and invest in them to push the boundaries where possible. In order to do this smartly, investments should relate back to desired capabilities.

The upper right of Figure 4 represents an infeasible region where block development technology investment is required, i.e. a technology pull signal. This will occur if sufficient capability cannot be provided with available technology, but the existing platform and programmatics are sufficient. The lower right of Figure 4 represents an infeasible region where technology is available that does not directly map to a capability concept, i.e. technology push. This is not altogether uncommon, and the capability concept set may expand if a warfighting advantage is found for the new technology.

In the VCS block development example, perhaps the most important result outside of the existence of a feasible region is the identification of the SSNX pull signal. This is shown in the lower right of Figure 4. A new class is required if sufficient capability cannot be provided within existing platform or programmatic constraints; technology investment needs will also be apparent.

3.5 DECISION INFORMATION

Repeating the set-reduction and combination process for the range of time horizons will produce information on technology and design development options, schedules, and costs, to achieve capabilities. This information will enable informed decisions for the Navy's schedule driven budget cycle. The analytical link between capability, technical solutions, schedule, and cost for a broad trade space makes decisions defendable at the highest level, which is a valuable attribute in a fiscally constrained environment.

4. CONCLUSION

An aggressive timeline and broad uncertainty around design requirements has led the U.S. Navy towards a set-based strategy for requirements, technology and design development for future submarines [1]. The purpose of using a set-based strategy is to make the right decisions the first time by methodically understanding tradeoffs prior to commitment. The benefit of good decisions during the early-stages is better designs at lower costs on shorter schedules.

To achieve this, a set-based strategy has been outlined that considers capabilities, technologies, SSN concept designs, and program assessments to produce defendable decision information in terms of cost, schedule, and capability. In the near term this strategy will inform acquisition decisions on VIRGINIA Class Block upgrade developments, and technology and design development for SSNX.

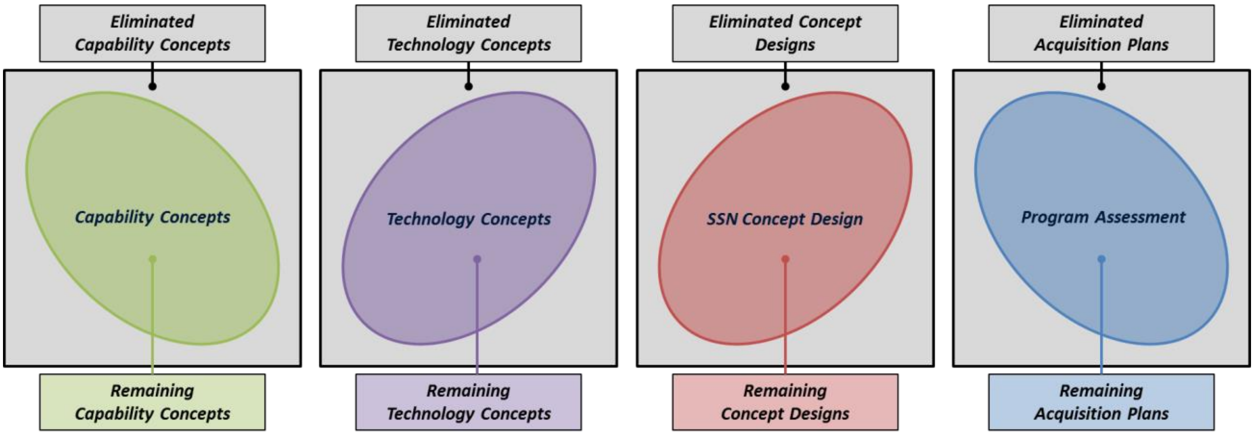

Figure 3: First Set Reduction

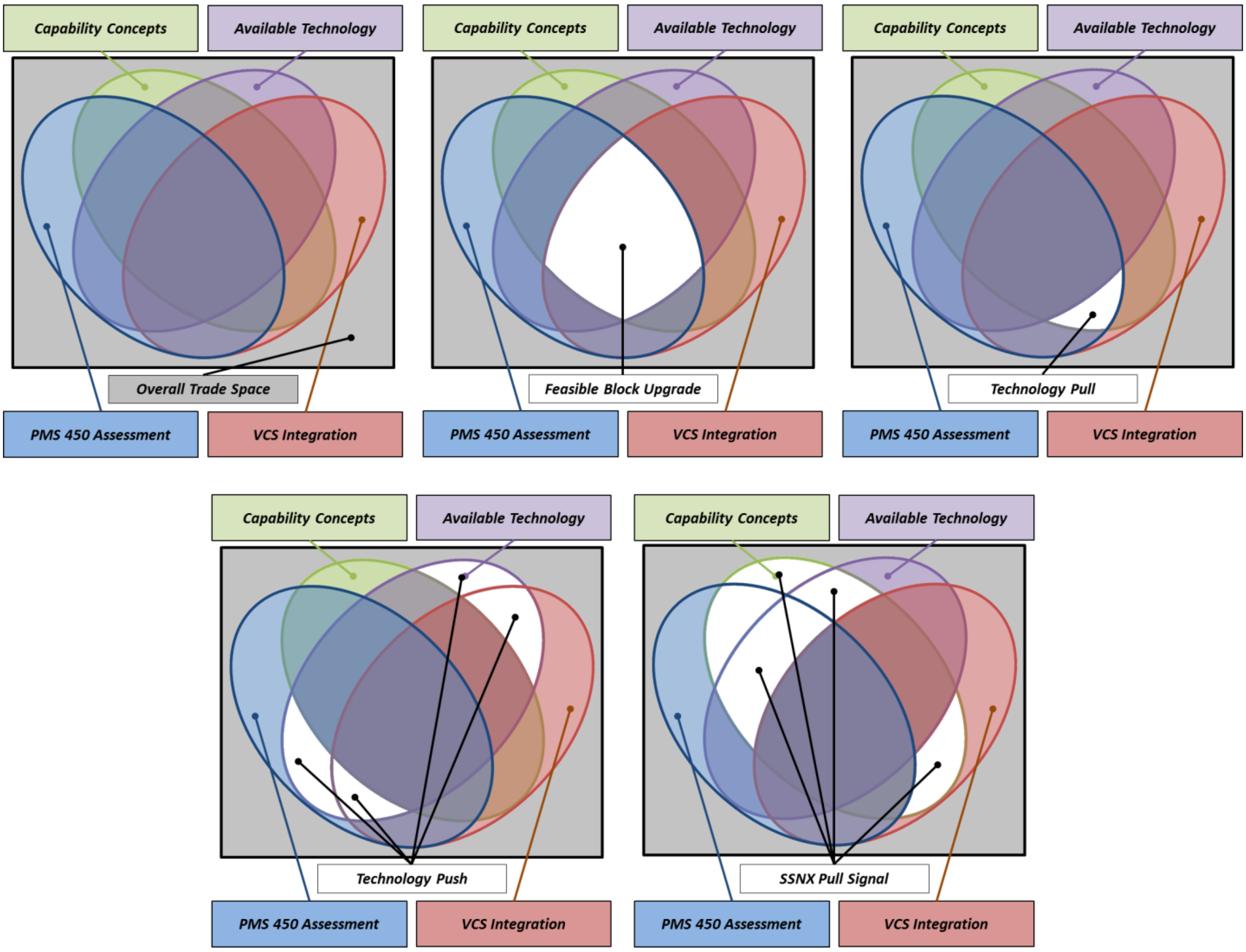

Figure 4: Set Combination “Kaleidoscope” for VCS Block Development

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