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6. AUTHOR(S)
NSAM
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NSAM 315 Sigma Drive, Summerville, SC 29486
MIT 77 Massachusetts Ave., Room E17-355, Cambridge, MA, 02139

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14. ABSTRACT
MIT conducted a major study on U.S. manufacturing with emphasis on better harvesting of upstream innovations into downstream manufacturing and services. This study - known as Production in the Innovation Economy (PIE) [http://web.mit.edu/pie] - gathered data about the strengths and weaknesses and prospects for U.S. manufacturing and its relationship to innovation. It released a major report in 2013. MIT proposed to add a standalone module to the study that addressed specifically the issues of U.S. shipbuilding and defense manufacturing, assessing several key 'legacy' processes and activities for opportunities to optimize production.

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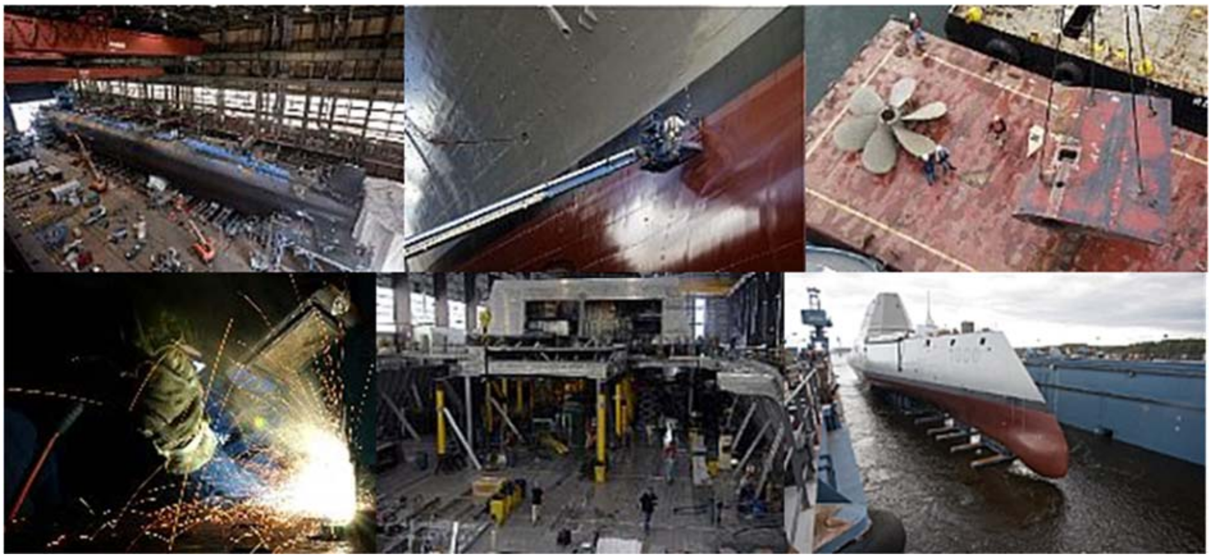

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MIT Contact:

Dr. Eric Rebentisch—Principal investigator (erebenti@mit.edu) 617-258-7773
77 Massachusetts Ave., Room E17-355, Cambridge, MA, 02139

Massachusetts Institute of Technology

Production in the INNOVATION ECONOMY

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Any errors or omissions are solely the responsibility of the authors and not that of the US Navy, ATI, or those who provided financial or research support for this study.

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1.0 Overview

This report summarizes work completed for the MIT *Production in the Innovation Economy: How to Create Excellence Through Competition and Benchmarking in the U.S. Shipbuilding and Defense Industry* study during the period of performance from 1 May 2015 to 31 August 2017. The period of performance comprised Phase I (the first year of the study) and Phase II (remainder of the period). A list of the MIT participants in the project during this period is provided in Appendix A of this report.

1.1 Background

MIT conducted a major study on U.S. manufacturing with emphasis on better harvesting of upstream innovations into downstream manufacturing and services. This study - known as Production in the Innovation Economy (PIE) [http://web.mit.edu/pie] - gathered data about the strengths and weaknesses and prospects for U.S. manufacturing and its relationship to innovation. It released a major report in 2013. MIT proposed to add a standalone module to the study that addressed specifically the issues of U.S. shipbuilding and defense manufacturing, assessing several key 'legacy' processes and activities for opportunities to optimize production.

The first PIE study on shipbuilding was conducted from 19 November 2012 to 31 August 2013. At the conclusion of that study period, a follow-on study was conceived, leading to the work reported here.

1.2 Study Tasks

Four primary tasks were defined for the study in the baseline plan. A fifth task was added in September 2016 to fill a gap in the initial study objectives as requested by the sponsor during a project review. The complete list of study tasks are:

1. Complexity assessment for acquisition decisions
2. Technical and organizational strategies for commonality
3. Set-based design strategies for naval shipbuilding
4. Tradeoffs between ship survivability and cost
5. Framework to integrate the PIE shipbuilding study research findings

1.3 Study Deliverables

Deliverables during the period of performance include:

- Quarterly Progress reports (4 May 2015, 3 August 2015, and 2 November 2015, 2 May 2016, 1 August 2016, and 4 November 2016)
- Annual report first year (1 February 2016)
- Final report Phase II (31 August 2017)

The Quarterly Reviews/Progress reports were provided on/around the dates of those respective reports.

In addition to the formally-defined deliverables, seven student theses and related overview presentations were generated. The reports of these individual projects is summarized in the section of this report entitled “Completed Research Project Descriptions”.

A project status briefing was provided to the project sponsor (ASN(RDA) Hon. Sean J. Stackley) on June 6, 2016. An additional project briefing was provided to Ms. Allison Stiller (Principal Civilian Deputy, ASN RDA) on August 12, 2015. Because of the change in administration and Sec. Stackley’s new responsibilities, a final project presentation was provided to Ms. Gloria Valdez (DASN SHIPs) on 26 July 2017. This presentation is captured in Appendix B of this report.

1.4 Overview of this report

The findings from work on each task have been reported in previous quarterly reports or in the annual report. The detailed findings reported in previous reports will serve as the primary reference for the content and findings produced by the study. Relevant details from each task will be summarized in the following sections along with references to the prior reports.

Completed Research Project Descriptions

2.0 Task 1: Complexity Assessment for Acquisition Decisions

Over the past three decades, the cost of U.S. Naval Shipbuilding has grown around 10% per year, far outpacing inflationary effects during the same timeframe. The reports on cost growth in U.S. Navy shipbuilding repeatedly return to the theme of the ever-increasing complexity in modern naval vessels as a substantial contributor to cost growth. Understanding the cost-complexity interaction could potentially help drive down cost uncertainty for U.S. Navy policymakers and help refine predictive cost-estimation tools currently in use by the Navy’s cost estimation groups, particularly in the early stages of a program where there is considerable uncertainty.

2.1 Overview of the task

This task builds upon research findings from the previous phase of the PIE study. It examined the relationship between complexity and cost to define an approach to enable complexity-based architecture tradeoff decisions for improved cost estimates and program planning during the early stages of a ship program. This research extends those findings in both scope (at the ship level, rather than subsystems within a ship) and area (exploring the measurement of organizational complexity and its potential relationship with cost).

The sub-tasks in this research task include:

a) Develop and validate complexity-based assessment tools at the level of a complete system (e.g., ship).
b) Identify cost-estimating relationships based on the characteristic complexity of the complete system.
c) Develop measures of organizational complexity.

d) Explore the implications of complexity-based metrics to acquisition program management.

2.2 Summary of the findings

2.2.1 Product structural complexity analysis

2.2.1.1 Background and elements of complexity

The complexity of today's highly engineered products is rooted in the interwoven architecture defined by their components and their interactions. System architectures can be represented by graphs and an associated adjacency matrix. Representing system architectures in this way is an important step because to evaluate a complex system and to compare it to other systems, numerical assessment of its structural complexity is essential.

There are three components that constitute system structural complexity. The first represents the sum of complexities of individual components alone (the local effect) and does not involve architectural or relationships information. The second component represents the complexity of each pair-wise interaction, and the third component manifests the impact of the arrangements of the interfaces or the overall system architecture. The effect of system architecture represents a global, system level effect that is not visible at the local level (i.e., component engineering or pair-wise interface management) and cannot be obtained from 'local' information alone. This quantity is not amenable to simple addition with its impact realized during system integration. Also, it is likely to have profound impact on various aspects of performance and other life-cycle properties. This approach was adapted in the previous study with naval vessel sub-systems by Dobson.

Structural Complexity and Modularity measure two different structural aspects of the overall system architecture. Modularity can be seen as a system decomposition method that alters the distribution of complexity over parts (i.e., modules or subsystems) of the system. The actual underlying complexity remains invariant if the system is only reorganized (without changing the connectivity details or component details). Consistent with system decomposition strategies, complexity may be encapsulated into modules but that does not necessarily imply reduced overall complexity. Such a decomposition is used to enable effective design abstractions for system design. Therefore, a highly modular architecture with very complex modules can result in a complex architecture, but may still be desirable from system decomposability viewpoint.

The work on this task was done primarily by MIT researcher Kaushik Sinha, based on previous development of the complexity analysis framework for other research projects at MIT.

2.2.1.2 Methods

Extension of the complexity analysis framework to the naval system-of-systems context requires contextual adaptation of the methodology with respect to specific component complexity influencing factors, modeling of interfaces and construction of system dependency matrix (represented as a Design Structure Matrix or DSM). This methodology is calibrated/validated on a range of ships with diverse mission profiles, starting with a US Coast Guard example.

The complexity analysis framework was adapted to naval application by applying it to the USCG Fast Response Cutter (FRC) case study. The entire ship was represented using a DSM that captures the interfaces between different elements of the system. The level of decomposition used is level 3 (L3) of the system architecture, resulting in number of system elements on the order of 130 elements. Choice of L3 level system decomposition is based on prior experience with engineering systems and was found to keep the size of the DSM reasonable while gleaning the primary insights about system architecture.

The data source for the DSM was system schematic drawings of the FRC provided by the US shipbuilder. These schematics provided useful information for components and dependencies within individual systems, but often failed to identify connections between the various systems on the ship. To overcome this, function and discipline boundaries as defined in the ESWBS codes as detailed in NAVSEA system partition manual were used to define interdependencies between the major systems on the FRC. This resulting system representation DSM had 9 modules. This FRC DSM served as the developmental testbed for adapting the complexity analysis framework to naval ships and the development of a toolset for architecture analysis. The details of this development effort were reported in the MIT PIE Shipbuilding Study First Annual Report dated 1 February, 2016.

2.2.1.3 System Architecture Generation Toolkit (AGT) and System Architecture Analysis Toolkit (SAAT)

The complexity evaluation framework has been adapted to large naval systems that are composed of various heterogeneous sub-systems, or more appropriately at the level of System-of-Systems. The structure of the System Architecture Generation Toolkit (AGT) for making these assessments is shown in Figure 1.

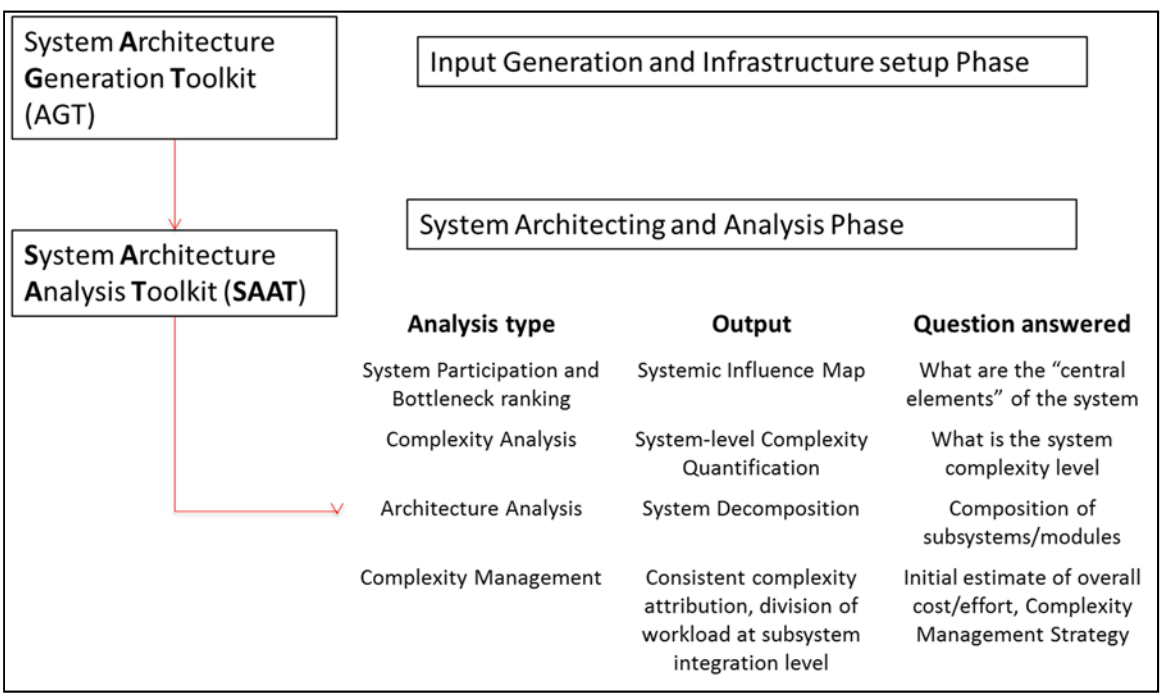

Figure 1. The System Architecture Generation Toolkit (AGT) and System Architecture Analysis Toolkit (SAAT) structure and process flow.

The System Architecture Generation Toolkit (AGT) is the basic approach to defining and representing the system (in this case ships) in a format that lends itself to further analysis and was first described in the MIT PIE Shipbuilding Study Quarterly Report dated 9 April, 2016.

The System Architecture Analysis Toolkit (SAAT) uses the information from the AGT (typically in the form of a DSM representation of a ship) to perform various analyses to assist the naval architect in optimizing the architecture configuration. These include system partitioning analysis to identify central elements in the system, complexity analysis to assess the overall system complexity, and architecture analysis to define modules within the architecture that optimize along desired attributes (e.g., minimize interface complexity).

The core capabilities of the SAAT framework have been implemented with enhancements to enable constrained system decomposition in final stages of development. An algorithm for constrained system decomposition is capable of incorporating engineering and packaging constraints using a soft penalty function approach. Such constraints would include those related to (a) packaging/spatial constraints; (b) thermal constraints (i.e., two components can't be part in close proximity); (c) module dissociation constraints, etc.

2.2.1.4 Example application of SAAT: TWR

The tools in the SAAT can be employed to vary the level of realized modularity while keeping the system complexity constant. To continue development of the SAAT, another shop DSM was created and used in the analysis. A DSM was created of the US Navy Torpedo Weapons Retriever (TWR). The TWR DSM was used to demonstrate various elements of the SAAT analysis. For instance, the integrative complexity (e.g., the part of overall system complexity that is due to the integration of the modules) reduces almost by a factor of 3 by creating a system decomposition that maximizes the realized modularity of the system. The decomposition strategy implied by maximum modularity criteria leads to a smaller number of modules with a high degree of modularity.

Using this strategy, most of the system complexity is concentrated within modules, with the two largest modules having much higher complexity than the rest. This concentrates complexity inside certain modules and not in others. This aspect of non-uniform distribution of module complexity has important implications for the system development process. For example, the most complex module would get relatively disproportionate attention during the development process since the within-module development work in these complex modules is likely to be a bottleneck if not managed properly.

The TWR architecture is fundamentally more distributed than the FRC architecture, leading to higher integrative complexity (i.e., lower degree of modularity). This is manifested in higher topological complexity and a higher fraction integrative complexity. The degree of modularity is consequently smaller as compared with the FRC architecture. The comparison of these two ship examples shows how variations in architecture approaches can vary in ships.

To explore the trade-space between the spread in module complexity and the associated modularity index (Q), we performed multi-objective optimization using Simulated Annealing as described in our previous report. The resulting Pareto frontier (i.e., optimal tradeoffs) solutions show that modularity maximization leads to increasing Spread (C). This leads to undesirable asymmetric module complexity distribution. From a development process management perspective, this could have an undesirable impact on system modularity (there is no free lunch). These observations are completely in accordance with the nature of results found during the FRC case study.

These examples illustrate the potential architecture analysis opportunities presented by the SAAT, and how the insights gained from the analysis might be used to define the architecture differently to manage complexity, or to focus management of the development effort differently to focus attention on particularly complex areas in the architecture. A more detailed discussion of this analysis is reported in the MIT PIE Shipbuilding Study Quarterly Report dated 4 November, 2016.

2.2.1.5 Extending SAAT usefulness by automatically generating ship DSMs

The primary input to the SAAT is the DSM representation of the system. The system architecture generation/representation stage currently requires manual generation of DSMs using disparate sources of information. This is a time-intensive activity and may act as a barrier to widespread use of the SAAT with the system development process chain. It seems that the data required for automatic generation of DSM are largely present within the CAD (Computer Aided Design) and PLM (Product Lifecycle Management) software suites that have become standard tools in digital system development workflow for engineered systems.

In the case of naval vessels, LEAPS (Leading Edge Architecture for Prototyping Systems) is the primary CAD/PLM system. Work began with the MIT Sea Grant and the Naval Surface Warfare Center Carderock Division to explore automatic generation of system-level DSMs from the LEAPS database using the Application Programming Interface (API) of LEAPS Editor. This is imperative for building a suitable historical database of about 15 to 20 existing ship architectures over time with their design effort or cost information embedded to enable calibration of the complexity-cost CER. The opportunity presented by automatically generating DSMs from design data in CAD/PLM systems led to the definition of Task 5 of this study. The specifics of that effort are discussed later in this report in the section that addresses Task 5.

Complexity management and budgeting requires integration of system architecting and system performance evaluation capabilities. For system level performance evaluation during the early-phase of the system architecting process, a mid-fidelity simulation tool is needed that can abstract out ship performance behaviors from detailed analysis such as generated by ASSET and execute at a fraction of computational cost. Such a method has been developed for aircraft engines and this capability can also be built at the level of a complete ship. This could then be integrated with the SAAT framework in a modular fashion to enable system value driven active complexity management.

2.2.2 Organizational complexity analysis

An associated problem from an organization design viewpoint is the organizational impact of such a new ship development/acquisition paradigm that incorporates such active complexity management. This might imply possibly some re-structuring in design and project organizational structure. Research relating to this topic is summarized in section 2.1.5.

2.2.2.1 Pott research findings

Alex Pott, a visiting graduate student from the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University (Germany) developed an approach for assessing the impact of changes in technical systems based on their structural complexity. His study helped to demonstrate how understanding the relative complexity of different options can highlight options that reduce cost and schedule in technology development efforts. As a part of his study, he created a ship-level DSM of the US Coast Guard Fast Response Cutter (FRC). He completed his studies at MIT and returned to Germany in December 2015. His research findings were summarized in detail in the summarized in MIT PIE Shipbuilding Study First Annual Report dated 1 February, 2016 and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only the outcomes of his study will be presented here.

The basic motivation for his research was to try to estimate the savings that might result from redesign efforts that take into account the structural complexity associated with alternative design solutions. This was done by developing a method to enable designers to make product change decisions with an understanding of the costs, durations and performance impacts based on an assessment of the resulting structural complexity of the competing approaches.

Initially, the intent was to use a system representation from the USCG FRC in this research. However, that presented a challenge because of the incomplete data available from that ship. In fact, no pre-existing DSMs for naval ships were available to use. The development of the FRC DSM resulted from system schematics and the use of ESWBS-code based components. This represents a unique approach and contribution to DSM datasets, and enables follow-on research based on a consistent ship design nomenclature.

In the absence of a ship-based dataset, a simplified design choice based on an actual product was developed. Two design change options with significant differences in scope were used to execute the process and produce outcomes. In the analysis, the less-complex option was clearly preferred based on differences in cost, duration, and performance.

As a demonstration of the concept, this study showed how decision guidance based on structural complexity analysis using basic design knowledge can potentially improve product development performance. To extend this into practice, the development of software tools that can generate these DSMs automatically from CAD models, for example, would be particularly useful. This was much of the underlying data generation needed for this approach would be automated.

2.2.2.2 Stracke research findings

Felix Stracke, a visiting graduate student from the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University (Germany) developed an assessment of organizational complexity that defined interdependencies and relationships within organizations, building on previous related research. The research borrowed some of the structure and processes used to model product system complexity. He completed his studies at MIT and returned to Germany in October 2015. His research findings were summarized in detail in the summarized in MIT PIE Shipbuilding Study First Annual Report dated 1 February, 2016 and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only the outcomes of his study will be presented here.

Organizational Complexity is the complexity associated with the human behavior aspect of the system realization process. Organization theory suggests that as the underlying product system complexity increases, so does the organizational complexity of system development organization. It is presumed that as organizational complexity increases, the costs associates with maintaining the organization and its capabilities also increases, while the predictability of outcomes decreases.

For this research, an organizational network representation (similar to a DSM) is defined using system architecture dependencies with responsibilities (i.e., component ownership information) from the Project Development Plan. Human and organizational interfaces are also modeled, drawing on research findings from domains including technology management, human psychology and organizational behavior.

The overall organizational complexity framework comprises four primary dimensions and forms the basis for a measurement framework. The four dimensions of the framework are diversity, interdependence, ambiguity, and flux. The resulting measurement framework was exercised using a product development process with 3 consistent, hypothetical scenarios with a base scenario A that performs all tasks internally, a scenario B that outsources to an external contractor with whom the organization has worked in the past in the same geographic region, and a scenario C where the company anticipates the highest cost savings by outsourcing to a supplier located in a different continent and with no prior working relationship. The base scenario A has an organizational complexity of about 50, due to an aligned development procedure and an experienced collaboration. Scenario B has a significantly higher complexity, due to spatially divided work, not fully aligned processes, systems and incentives. Scenario C has an even higher complexity due to inexperienced collaboration, cultural differences and mostly unaligned systems and processes. The impact of outsourcing is significant due to the high interdependence of the chosen tasks. Outsourcing around 20% of the product development tasks causes a complexity increase of around 40% to 75%, depending on the scenario.

This complexity measurement and analysis approach allows a focus on specific interdependencies, identifying “complexity hotspots” when displayed in a matrix format. The differences in complexity arise from a combination of different levels of interdependencies, varying locations and personality scores. Outsourcing and emerging complexity are not a bad thing by definition as they may bring commensurate benefits along with the additional complexity. This approach allows one to be aware of the possible issues to be able to handle and manage them. Visualization of project alternatives showing the complexity of each alternative may enable selection of the project configuration with the lowest complexity or best complexity-benefit ratio. This formal approach may be useful to enhance project managers’ awareness of complexity inside a project organization and thereby empower them to avoid overly complex, unmanageable structures.

2.2.2.3 Fey research findings

Phillip Fey, a visiting graduate student from the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University (Germany) built upon the work of Stracke (2016) to identify a way to match the demands placed on an organization due to product complexity with the resources the organization has available to meet those needs. The goal of Fey's study was to develop a method to evaluate the complexity of an intended new product development project during its early stages, as well as to provide insights into how to adapt it to ensure a fit with the organization's capacities and thus achieve a better project performance. He completed his studies at MIT and returned to Germany in September 2015. His research findings were summarized in detail in the summarized in the MIT PIE Shipbuilding Study Quarterly Report dated 3 February, 2017and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only the outcomes of his study will be presented here.

The primary research question during the development of the method was: "How can one evaluate and adapt the complexity of new product development projects to ensure a fit with the organization's capacities?" In the formulation of this method it is assumed that a reference product development project exists and resource estimations for individual product development activities are known. The method attempts to explain the resource demand caused by additional complexity, which impacts an alternative project in comparison to the reference project. The starting point is the project plan with its activities based on the reference project. For each activity, complexity impacts of the alternative project on the estimated resource demand is evaluated and then aggregated over all activities and compared with the existing capacities of the organization. A Resource Breakdown Structure (RBS), provides the required input data to evaluate the activities regarding the complexity impact. The RBS lists in a structured and hierarchic manner the resources that are needed to successfully execute a project.

Simulations evaluate the impact of complexity at the level of activity, department, and all teams and all activities using Monte Carlo simulations, to explore every resource that is relevant for the activity. Histograms depict the possible resource demand scenarios caused by all complexity drivers affecting the resource, where exceeding existing capacities may become likely, and which complexity drivers affect which resources of the project and by what estimated magnitude and probability. Thus, the most critical drivers of project complexity can be derived and ranked by their impact.

The method was applied with empirical data from a medium sized company in the mechanical engineering sector. Through structured interviews with the departments a reference development project was established, consisting of the activities and their resource demand for all units. 15 complexity drivers were identified after the aggregation. By exploring the resource demand for one of the departments with 40.000 Monte Carlo simulations, the additional resource demand due to the complexity drivers ranged from 105 hours to 530 hours, where the baseline resource demand for the reference processes was 604 hours. This means that in the worst case scenario, excess resource demand caused by additional complexity is equivalent to 51% of the baseline resource demand. In the most likely case, excess resource demand caused by additional complexity is equivalent to around 25% of the base line resource consumption.

The test case verified that the method can feasibly be used to estimate the impact of complexity and identify the most critical complexity drivers of the project.

2.2.3 Summary

An existing complexity analysis method was adapted through this study to apply at the level of an entire ship. The resulting System Architecture Generation Toolkit (AGT) and System Architecture Analysis Toolkit (SAAT) provide a number of ways to analyze and optimize ship system architectures. The application of these tools was demonstrated on two ship examples, the FRC and the TWR.

Previous work identified a cost relationship between structural complexity and cost at the ship subsystem level. One goal of this task was to extend those findings to the level of a complete ship. The FRC analysis provided one data point at the ship level. Generally speaking, far more data points (i.e., ship-level DSMs) would be required to develop formal cost-estimating relationships. The availability of ship-level DSMs therefore become a critical bottleneck in the development of complexity-based cost estimating relationships.

Typically, at least 15 to 20 data points would be needed to generate a statistically robust complexity-development effort relationship that can be used as a cost-estimating relationship (CER) for future ship development and acquisition programs (typically, the sample size needed would be much larger, but in this case the sample is limited by the relatively small population size of naval ships). The major barrier to creating this database of DSMs is that this step is currently performed manual and usually takes months to build one to completion. In order to streamline the process and also ensure perfect compatibility with the existing design data, an automatic (or semi-automatic) way to construct these DSMs is needed. This need precipitated the definition of Task 5 to identify methods to use existing digital models of U.S. Navy combatants and other classes to automatically generate DSMs. Paired with publicly available ship cost data, this should allow the development of any cost estimating relationships that may exist between structural complexity and ship cost. This effort and its outcomes are discussed in detail in the section describing Task 5. Unfortunately, since task 5 reached completion at the end of the study period, the development of additional DSMs and CERs were not possible in the time available.

2.3 External reports of findings

Several presentations and publications resulted from this task effort.

2.3.1 Presentations of findings

The findings from these studies in this task area were presented to the study sponsor and at conferences. The specific presentations included:

- The findings from the study in this task area were presented to the ASN(RDA) during a project update meeting on 6 June 2016. The presentation slides were captured in MIT PIE Shipbuilding Study Quarterly Report dated 1 August 2016.
- Rebentisch, E., Schuh, G., Sinha, K., Rudolf, S., Rudolf, S., Riesener, Mattern, K., Stracke, F., “Measurement of Organizational Complexity in Product Development Projects”, PICMET '16 Conference, 4-8 September 2016, Honolulu, Hawaii.

- Schuh, G., Rebentisch, E., Riesener, M, Mattern, C., Fey, P., “Method for the Evaluation and Adaptation of New Product Development Project Complexity”, 27th CIRP Design Conference 2017, 10-12 May 2017, Cranfield, UK.

2.3.2 Publications of findings

The findings from these studies in this task area were documented in these theses and conference papers:

- Pott, Christian, “Method for the Assessment of Changes in Technical Systems and their Effect on Structural Complexity”, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen Master’s thesis, February, 2016.
- Stracke, Felix, “Measurement of Organizational Complexity in Product Development Projects”, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen Master’s thesis, January, 2016.
- Fey, Philipp, “Method for the Evaluation and Adaptation of New Product Development Project Complexity”, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen Master’s thesis, January, 2017.
- CIRPe (Pott) - Assessment of Changes in Technical Systems and their Effects on Cost and Duration based on Structural Complexity, Procedia CIRP, Volume 55, 2016, Pages 35-40, Eric Rebentisch, Günther Schuh, Michael Riesener, Stefan Breunig, Alexander Pott, Kaushik Sinha.
- Rebentisch, E., Schuh, G., Sinha, K., Rudolf, S., Rudolf, S., Riesener, Mattern, K., Stracke, F., “Measurement of Organizational Complexity in Product Development Projects”, PICMET '16 Conference, 4-8 September 2016, Honolulu, Hawaii.
- Schuh, G., Rebentisch, E., Riesener, M, Mattern, C., Fey, P., “Method for the Evaluation and Adaptation of New Product Development Project Complexity”, 27th CIRP Design Conference 2017, 10-12 May 2017, Cranfield, UK.

2.4 Other deliverables

Work in this task area evolved over time and resulted in the creation of a new task area (see task 5, section 2.5 of this report), and support for significant US Navy maintenance efforts subsequent to the period of performance of this contract.

- The AGT and SAAT application code is provided as-is for use in system architecting and for further development.
- Task 5 creation and evolution resulted in the development of demonstration software to aid in the automatic generation of ship DSMs from LEAPS data models (see the section in this report describing Task 5 for more details).
- The SAAT analysis was used in support of the CVN73 Refuel and Complex Overhaul (RCOH) to help define a better partition of the combat system architecture. This activity began shortly after the end of the contract period and is on-going as of this writing. The outcome is a new combat system architecture partition into 5 primary modules. These modules could potentially be used to define teams to coordinate and integrate work across the many systems within those modules, as well as streamline planning for verification and validation work to come near the conclusion of the RCOH.

3.0 Task 2: Technical and Organizational Strategies for Commonality

Naval vessels have operational lifecycles measured in decades, and even longer when the requirements, design, and construction phases of the lifecycle are considered. During this time, threats, missions, priorities, and available resources may change significantly. In some historic examples, ship classes have been retired ahead of schedule because the cost of adapting them to a new operational reality was impractical.

One approach to more easily and cost-effectively adapting navy ships to new missions is by giving them modular architectures with use of common elements and interfaces between components. One movement underway that embraces these principles is the so-called "flexible warship initiative" in the US Navy. The principles of flexibility in naval vessels have been demonstrated in various ship classes internationally, and the principles of modular design are reasonably well understood, but the US Navy has struggled through the years to fully embrace modular product architectures in its surface combatants.

The objective of this task is to define technical and organizational strategies and approaches to help accelerate the implementation and realization of the full potential benefits of commonality, modularity, and flexibility for naval ship platforms.

The sub-tasks in this research task include:

a) Develop a framework for managing modularity and commonality in ships to improve their overall system lifecycle performance.
b) Identify specific elements in a ship with associated modularity and/or commonality management strategies and resulting potential for savings.
c) Identify organizational boundaries/relationships that need to be actively managed for greater benefits from commonality/modularity.

3.1 Overview of the task

The benefits of flexible ships to the U.S. navy has been studied since the 1970s, with the benefits recognized and articulated. U.S. navy studies of modular and flexible ship concepts through the years include:

- 1975 : SEAMOD , Sea systems Modification and Modernization by Modularity
- 1980 : SSES, Ship Systems Engineering Standards
- 1992: ATC : Affordability through commonality
- Ships: LCS, VCS (common modules)
- 2014: NAVSEA 06 - Acquisition and Commonality
  - e.g., Virtual Shelf, Specification Changes, Contract Language

Flexibility encompasses different concepts such as modularity, commonality, open standards, etc. The U.S Navy is deploying some of these concepts with a new class of ship called the Littoral Combat Ship

(LCS). These are modular ships which have their mission payloads decoupled from their platform, allowing mission flexibility and easing modernization or repairs.

The benefits of flexible ships have been realized in ships produced by other countries and in some foreign navies such as the Royal Danish Navy in Denmark. In some cases these foreign ship designs directly borrowed the lessons captured in the reports created by the U.S. Navy (e.g., common interface standards) and put them into practice, while ships produced for the U.S. Navy that were contemporary did not employ those practices to the same extent.

The objective of this work is to characterize the lifecycle benefits and costs of designing flexibility into U.S. Navy ships. We use the definition of flexibility outlined by the Global Shipbuilding Executive Summit (GSES) VI as a starting point. According to GSES VI, flexibility aims to achieve “affordable relevance” throughout a ship’s lifecycle by reducing maintenance and modernization time and cost. In this sense, flexibility allows ships to be constructed, reconfigured and maintained cheaply, enabling navies to better meet evolving requirements. GSES VI outlined 5 tenets of flexibility: (1) de-coupled payloads (capabilities) from platforms (ships); (2) standard platform-to-payload interfaces; (3) rapid re-configuration; (4) pre-planned access routes; and (5) sufficient growth margins for distributed systems.

There were two tasks in this study to explore the application of commonality and flexibility strategies to ships. The first study was conducted by Pablo Klemm and explored the value of flexibility in ship operations. The second study was conducted by Narek Shougarian and explored the value of flexibility over the ship’s lifecycle. Both studies contributed to an understanding of whether there is a viable economic and operational case for the flexible ships approach. The summary findings from both studies are presented here. Both studies were described in detail in previous reports, which are referenced.

3.2 Summary of the findings

3.2.1 Klemm study findings

Pablo Klemm, a student visiting MIT from the Ecole Polytechnique Fédérale de Lausanne (EPFL), developed a simulation model to characterize the role that commonality and modularity can play in aligning the capabilities of Navy ships and the shipbuilding industry with the evolving technology and threat environment. He completed his studies at MIT and returned to Switzerland in December 2015. His research findings were summarized in detail in the MIT PIE Shipbuilding Study Quarterly Report dated 2 November 2015 and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only the outcomes of his study will be presented here.

To better understand the fit and potential benefits of flexibility in the context of the U.S. navy mission set, a model to simulate a fleet of ships was developed to model the dynamics of a fleet of representative ships. Mission length and occurrence profiles are chosen by the user for each model run. The model then steps through combinations of missions with different fleet flexibility strategies. The model explored the value of a fleet of flexible ships with modular payloads which can be swapped depending on the mission, compared with other flexibility strategies. The flexible ships are compared to a fleet of "classic" ships, either single-purpose ships or relatively more expensive multi-mission ships.

The model revealed that given the current cost structure of the LCS, the LCS flexibility strategy (i.e., swappable payloads) yielded a high cost relative to its utility value. In no comparison cases between flexible ships and single-purpose ships or multi-mission ships are the flexible ships seen to be providing more utility (value) than the other ships. Regardless of the mission profile and weights or relative importance given to the number of missions accomplished or the time it took to execute the missions, the flexible ships never presented the highest value. This is due to the high acquisition and O&S costs of the flexible ships with the swappable payloads strategy.

However, the model showed that if it were possible to produce flexible ships within the same order of cost to acquire and operate as the ones utilized by the Danish Navy, a flexible ship strategy would start to be attractive from a cost/value perspective. In most of the cases under this lower cost structure, regardless of the importance given to the number of missions accomplished or the time it took to execute the missions, flexible ships presented the highest value.

These findings suggest that the acquisition strategy, ship system architecture, and cost structure of a specific ship makes an important difference in whether flexible ships achieve their potential benefits in terms of utility for a given cost of the ship's operating lifecycle.

3.2.2 Shougarian study findings

Narek Shougarian, a graduate student at MIT, developed a simulation model to characterize the benefits of architectural flexibility in Navy ships over the operating lifecycle of the ship, taking into consideration uncertainty and changes in technology and the threat environment. He completed his dissertation at MIT in February 2017 and graduated. His research findings were summarized in detail in the MIT PIE Shipbuilding Study Quarterly Reports dated 4 November 2016 and 3 February 2017 and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only the outcomes of his study will be presented here.

As part of this study, interviews were conducted at ThyssenKrupp Marine Systems (TKMS) in Hamburg, Germany from the producer of the MEKO (*Mehrzweck-Kombination*) family of modular/flexible warships. The data from these interviews were used to define model parameters and to ground the simulation model with real ship data. They also showed the difference in cost structure, comparing factors such as installation cost, maintenance cost or non-recurring engineering cost between modular/flexible and inflexible ships at both the ship and the module levels.

To examine the value of flexibility in the context of warships, two different analyses were carried out using data on different ship configurations in a frigate class. The first examines the set of different configurations that a ship can evolve through that maximize the overall ship utility over its lifecycle given a known fixed mission and different budget constraints. In scenarios where the initial acquisition budget is low, the optimal path consists of many reconfigurations with flexibility designed into the ship platform to reduce the cost of these reconfigurations.

The initial utility of flexible ships is higher than for inflexible ships in each time step and overall. Greater flexibility designed in the platform enables many more changes because the cost associated with each incremental change from one configuration to the next is lower. That does not mean that the relative improvement in capability is low, however, since the changes occur primarily in a favorable region of the tradespace where relatively small increases in cost produces relatively large increases in utility. How much each reconfiguration costs depends on the individual subsystems that are made flexible as well as the cost of designing flexibility into the platform. In a scenario with a higher initial budget, fewer reconfigurations occur and the first configuration is initially highly capable.

Given tight budget constraints, building flexibility into the ship allows less capable ships that are cheaper to be purchased initially, which are then upgraded in capabilities over time. The reality of strategy was confirmed in interviews about the German MEKO class of modular warships, where it was stated that some smaller navies that operate the ships exploit the flexibility built into the ships in this way.

In the second analysis expected lifecycle survivability was maximized subject to mission uncertainty and budget constraints. It assumed that the operating environment (in this case, littoral and blue water environments, respectively) can change at discrete points in time, producing a complex and branching set of potential mission scenarios that the ship must address. The model stepped through 64 different possible mission combinations over the lifecycles of flexible and traditional ships. The normalized difference in expected survivability over the mission lifecycle was 0.684 for inflexible ship and 0.925 for the flexible ship. The evolutionary dynamic (especially in budget-constrained scenarios) is that initial ship configurations with fewer subsystems are more diverse and tailored to specific missions, but evolve and eventually converge toward multi-mission capable designs that are more fully-populated with offensive and defensive subsystems and are more expensive. By the end of the 6 upgrade periods, flexible ships have achieved greater overall survivability than inflexible ships, including:

- Roughly 2% increased overall survivability for littoral-only missions (the most challenging mission mix in the model)
- Roughly 10% increased overall survivability for blue water-only missions
- Roughly 7% increased overall survivability when mission scenarios randomly move between littoral and blue water mission emphasis

A variant of the second analysis was to assume that an optimal upgrade path could be determined at the outset of the ship lifecycle, with changes made in systems that maximize the utility. The criteria to allow these upgrades to take place were that they maximized expected survivability over the life cycle of the ship, subject to budget constraints, and any change in the ship would have to increase its design utility. In this scenario the inflexible ship configuration was static for 10 time periods since the configuration changes exceeded the available budget. On the other hand, the flexible ship was upgraded in every period because the cost of incremental upgrades did not exceed the annual budget allowance. In both cases the flexible and inflexible ships both had the same overall budget. The significant configuration changes made to the inflexible ship toward the end of the period examined almost attain the overall level of capability of the flexible ship, but the cumulative capability deficit (the area under the curve of utility over time) is substantial since the flexible ship is upgraded almost continuously while the inflexible ship configuration does not change for much of the period examined. In average and maximum utility and expected average survivability, the flexible ship was significantly better-performing than the inflexible ship.

3.2.3 Summary

These simulation analyses found that flexible ships enjoyed higher utility (mission fulfillment) and survivability over the lifecycle, greater improvement in mission capability (i.e., upgrades with greater benefits earlier in the ship lifecycle), and better performance and ability to respond to unpredicted changes in mission.

Both models showed that a primary driver in the cost-effectiveness of flexible ships is the reduction in the cost of changes enabled by a flexible architecture. If flexibility is designed into the ship, the cost of upgrading the capabilities is lower and capabilities can be upgraded more frequently to better adapt to changing threats. As the cost to make changes to the ships capabilities increases, upgrades occur less frequently and tend to occur in major batch upgrades that are more costly. Both of these flexible and inflexible ship upgrade dynamics are observed in operations in different navies that have adopted the different strategies, respectively.

3.3 Presentations of findings

The findings from these studies in this task area were presented to the study sponsor and at a conference. The specific presentations included:

- The findings from task 2 were presented at the American Society of Naval Engineers (ASNE) Technology Systems & Ships (TSS) 2017 conference (formerly ASNE Day) in Crystal City, VA on February 15th, 2017. The session was entitled "Flexible Ships: Enabling Efficient and Effective Capability Upgrades". The presentation slides were captured in the MIT PIE Shipbuilding Study Quarterly Report dated 5 April 2017).
- Overview presentation to the DASN SHIPs on 26 July 2017 (see Appendix B of this report).

3.4 Publications of findings

Findings from this study were documented in Pablo Klemm's thesis:

- Klemm, Pablo, "Valuing Flexibility in Naval Ships to Improve their Overall System Life Cycle Performance", Master's Thesis, Ecole Polytechnique Fédérale de Lausanne (EPFL), October 5, 2015.

In addition, a summary of the ASNE TSS panel presentation and discussion during the session was reported in the Defense Daily ("Building 'Flexible' Ships With Open Architectures Delivers Vessels Superior 'In All Cases'", By Dan Parsons, *Defense Daily*, 15 Feb 2017). This write-up prompted an inquiry from the office of the CNO two days later, requesting more information about the task 2 study findings that were reported at the session. A modified version of the ANSE TSS presentation (adapted to focus on the key findings and to make it better as a stand-alone briefing) was sent to the CNO's office in response to the inquiry and were captured in the MIT PIE Shipbuilding Study Quarterly Report dated 5 April 2017.

4.0 Task 3: Set-based Design Strategies for Naval Shipbuilding and Acquisition

Set-based design (SBD) is an approach to product development that proponents claim dramatically reduces product development cycle time, improve quality, and reduce overall costs. It has been successfully demonstrated in product development operations in a few instances, primarily in high-volume product industries, but is only in the early stages of application in the shipbuilding sector in the US. Set-based design has been used in a small number of cases by the US Navy to explore and optimize new ship concepts. The objective of this study task was to develop a framework to understand the benefits, enabling conditions, and specific approaches for using set-based design (SBD) methods in shipbuilding.

The sub-tasks in this research task included:

a) Explore the applicability and potential benefits of set-based design tools and concepts to naval shipbuilding and acquisition.
b) Define the necessary tools, structures, and organizational relationships that would be needed to enable the use of a set-based design approach.
c) Develop strategies for implementing the appropriate elements of set-based design methods in naval shipbuilding and acquisition.

4.1 Overview of the task

Figure 2 compares SBD with a traditional design approach, sometimes referred to as point-based design (PBD). The PBD approach is relatively linear with a focus on refining and validating a single design through successive iterations. Alternately, SBD identifies sets of options and strives to converge on an optimal design as late in the process as possible so as to thoroughly explore the option space and make decisions based on the best available evidence.

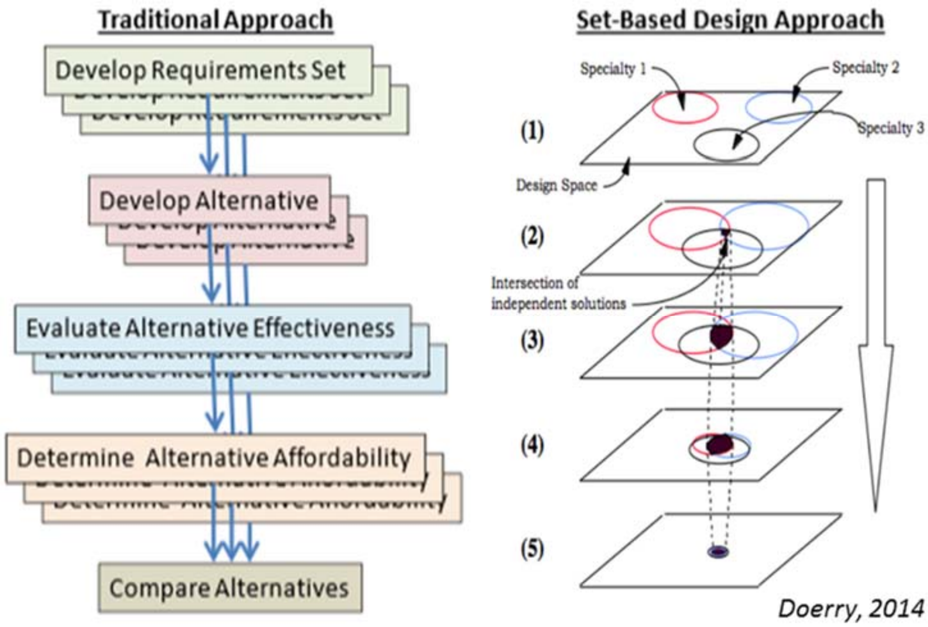

Figure 2.Comparison of set-based design with a traditional design approach.

The set-based design approach operates in accordance with two key principles:

1. Establish the design space and sub-divide along areas of expertise: concurrent subsystem evaluation
2. Gradually and deliberately reduce the design space by integrating preferred sub-spaces: discovery by elimination

SBD forces teams of designers to communicate in an effective and efficient manner along the lines of product architecture and interfaces – performing design using Principles 1 and 2. SBD-driven communication enacts a decision making process that enables effective and logical decisions to be made with confidence. Fundamentally, SBD is a design method that discovers the optimal solution by a gradual elimination of infeasible or inadequate designs within the design trade space. The claimed benefits of SBD are:

- Reduction of later stage rework when the cost of change is more expensive; therefore, lowering cost to design, build, and maintain the product
- Reduction of design cycle time; therefore, lower cost to design the product and greater market share gained from entering an opportunity market sooner
- Better design knowledge capture; therefore, less costly to incorporate customer changes during design or to perform future similar product designs
- A better solution is found because of the methodic reduction of the design trade space; therefore, higher customer satisfaction

There were two tasks in this study to explore the application of SBD to ships. The primary study was conducted by John Genta. A related and complimentary study was conducted by Roland Schmid. The summary findings from both are presented here. Both studies were described in detail in previous reports, which are referenced.

4.2 Summary of the findings

4.2.1 Genta Study Findings

LCDR John Genta, a U.S. Navy officer and a graduate student in the Naval Architecture (2N) program while at MIT, focused his thesis research on the use of set-based design in U.S. Navy ship design and acquisition. He completed his thesis research and graduated in June 2016. His research findings were summarized in detail in the MIT PIE Shipbuilding Study Quarterly Report dated 9 April2016 and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only a summary of his work and the outcomes will be presented here.

Recent USN design efforts using SBD were examined in this study using both literature and interviews. They included pre-product development activities on the Ship to Shore Connector (SCC), pre-AoA design activities for the Amphibious Combat Vehicle (ACV), and pre-AoA design activities by the Small Surface Combatant Task Force (SSCTF). In each case, some of the principles of SBD were observed and some of the proposed benefits of SBD were achieved. None of the cases presented an example of the textbook application of SBD, but nevertheless they provided useful insights into the application of the concept to real-world design challenges in complex naval systems.

The US Navy design cases demonstrated these benefits using SBD (using the claimed benefits of SBD as a template):

- *Reduction of later stage rework when the cost of change is more expensive; therefore, less cost to design, build, and maintain the product.*
    - Each of the US Navy SBD cases occurred early during the ship product development life-cycle so assessing the impact on overall acquisition cost performance of these programs is challenging. The SSC acquisition cost performance was superior to a number of recent ship programs, which while not conclusive, is encouraging of the benefits of SBD.
- *Reduction of design cycle time, meaning less cost to design the product and more market share gained from entering an opportunity market sooner.*
    - All three design teams reported producing results within a time-span previously not achievable in equivalent programs. US Navy leadership confirmed the claim of results not previously achievable for each of the cases.
- *Better design knowledge capture; implying less costly-to-incorporate customer changes during design or to perform future similar product designs.*
    - The SSC design team stated that future modernization or recapitalization efforts for the SSC would go smoother with the information gathered during the SSC design. The benefits to the ACV and SSCTF programs remain to be seen given their early stages in the design lifecycle. A Naval Surface Warfare Center (NSWC) Carderock Division study demonstrated this benefit in a structured ship design exercise comparing SBD with PBD approaches to the design of a naval combatant.

- *A better solution is found because of the methodic reduction of the design trade space; therefore, higher customer satisfaction.*
    - Navy leadership was satisfied with the results of each design, specifically in being able to better understand the information presented during design update or final briefs and understanding which potential solutions were infeasible and therefore out of consideration.

Overall, the set-based design process was seen to mitigate ship design cost and schedule risk. The ability of SBD to force communication about interfacial variables between different groups of experts leads to elimination of infeasible and dominated solutions through a gradual narrowing of the possible ship design trade space. This forced communication process greatly reduces the opportunity for later stage re-work, thereby reducing cost and schedule risk. Additionally, SBD reduces risk in future ship design. The structured SBD decision-making process captures critical design knowledge across inter-design negotiating relationships. It is those relationships that often take time to be re-discovered during modernization or recapitalization efforts in future ship design.

The research findings suggest that SBD can best contribute to the existing US Navy 2 Pass, 6 Gate (2P/6G) acquisition process specifically around the activities associated with and leading up to the Gate 2 and 3 decisions, respectively. Activities leading up to the Gate 2 decision are meant to explore the potential solution space and result in the creation of a formal Analysis of Alternatives (AoA) document. Activities leading up to the Gate 3 decision are meant to explore the feasibility of and relative attractiveness of the proposed solutions and result in the creation of a formal Capability Development Document (CDD).

SBD is well-suited to exploring a large tradespace, so it would add considerably to the existing AoA exercises by enabling a greater number of alternatives to be explored quickly. One specific approach, enabled by SBD, would be to separate the exploration of the combat system (e.g., mission payload) and ship hull, mechanical, and electrical system areas into parallel tradeoff analyses. Teams working in the separated areas would communicate across the interfaces between their respective areas via basic ship design parameters such as space, weight, power, and cooling (SWAP-C) and longitudinal and vertical center of gravity. A number of feasible alternatives (and importantly, a clearly-defined list of infeasible alternatives or attributes) could be generated quickly to support the development of the AoA and the Gate 2 decision.

After the Gate 2 decision, the SBD analysis could continue employing the same teams, but with an emphasis on exploring the feasibility of and refining the specific design parameters associated with the preferred alternatives. Experts in specific subsystems would be integrated into the teams as the SBD analysis reduced the design space to a few specific feasible designs. As more detailed information is generated from the analysis, less-attractive designs would be eliminated. The analysis would continue in this fashion until all areas of analysis have the necessary rigor to create a CDD and support the Gate 3 decision. The result would be a preferred system concept with a clear pedigree of decisions about why it is the preferred alternative and how its attributes outperform those of other alternatives.

Following from the research findings, the following recommendations for changes in the way the USN structures its ship design process were developed:

- *Re-designate the Analysis of Alternatives as the Analysis of Feasibility.* Although this change is only administrative in nature, it fits with the general process of trying to change the culture of an organization. During interviews with the USN ship design community, it became apparent that an Analysis of Alternatives suggested that the results should lead to a conclusion in which one single ship design configuration should be selected. Although recent efforts by the USN and CAPE have attempted to broaden and counter-act this point-based design mindset, changing the designation of the process to the Analysis of Feasibility should further support the cultural shift in ship design behavior towards a more set-based philosophy.
- *Direct NAVSEA 05D to create a temporary technical warrant holder (TWH) position for design process to champion SBD until all SDMs/SIMs have gained familiarity with the process.* In each of the cases of SBD use in the USN, there were paid design consultants to shepherd the SBD process. To transition away from continuing to pay for this service, the USN ship design community should capitalize on the in-house SBD process knowledge created from the SSC, ACV, and SSCTF events and create a temporary design process TWH group. This would be similar to temporary design tool TWH position creation in 2009 (McKenney, Buckley, & Singer, 2012) (Doerry N. , 2010b). The Design Process TWH would advise the SDM during Gate 1 – 4 design activities and replace the previously contracted design process experts. The temporary TWH position would only be created until all SDMs/SIMs in NAVSEA 05D/L/H/U/V obtain a to-be-determined level of satisfactory performance with SBD.
- *Direct AoA study plan to consider SBD as the overall design approach.* If the results of Exploratory and Pre-AoA design point towards a material solution, CAPE produces AoA Study Guidance during the end of Gate 1 activities. A USN ship program office creates an AoA Study Plan in response to the AoA Study Guidance. This Study Plan is concurred upon by USN stakeholders at the Gate 1 review board. In order to force the Analysis of Feasibility, or a more set-based, early ship design process, N8 can direct ship program offices to consider SBD during the staffing/review period of the AoA Study Plan.

4.2.2 Schmid Study Findings

Roland Schmid, a student visiting MIT from the Technical University in Munich, worked to develop a simulation model of a product development system to assess the differences between set-based and point-based design (PBD). He completed his thesis research and graduated in May 2015. His research findings were summarized in detail in the MIT PIE Shipbuilding Study Quarterly Report dated 1 February 2016 and in other documents referenced at the end of this section. Because the detailed observations and results have already been reported previously, only the outcomes will be presented here.

The objective of the study was to test the basic premises of SBD and better understand the working mechanisms and how they interrelated. He worked with Endris Kerga, a postdoctoral associate in the Consortium for Engineering Program Excellence (CEPE) at MIT to develop the model and derive publications from the effort. The modeling effort leveraged doctoral and postdoctoral research from

Endris Kerga on SBD in commercial settings. The study used a system dynamics (SD) modeling approach to simulate set-based design and compare it with the traditional product development approach using point-based design.

The primary insights of the modeling exercise helped to confirm the circumstances under which using a SBD approach would provide the most benefit. In general, a set-based design approach offers advantages over point based design if:

- Design loop-backs ("do over") are more costly the further downstream problems are found
- Feedback from testing back to design (validation) is slow
- Projects have high levels of innovation requiring new knowledge
- The rate at which design knowledge becomes obsolete (e.g., changing technology, dynamic environment) is high
    - SBD has an edge over PBD primarily through the use of formal knowledge capture and reuse mechanisms

4.3 Presentations of findings

The findings from these studies in this task area were presented to the study sponsor and at conferences. The specific presentations included:

- Presentation to the Principal Civilian Deputy, ASN(RDA) by LCDR Genta during a project update meeting on 2 May 2016. The presentation slides were captured in MIT PIE Shipbuilding Study Quarterly Report dated 1 August 2016.
- Presentation of the findings at the Portland International Conference on Management of Engineering and Technology (PICMET) 2016 Conference, 4-8 September 2016.
- Presentation of the findings at the 14th Annual Acquisition Research Symposium, April 26-27, 2017. The presentation slides were captured in MIT PIE Shipbuilding Study Quarterly Report dated 5 April 2017.

4.4 Publications of findings

The findings from these studies in this task area were documented in these theses and conference papers:

- Genta, John, "Using the Principles of Set-Based Design to Realize Ship Design Process Improvement", MIT SM Thesis, June 2016.
- Schmid, Roland, "Performance Measuring of Set-Based Concurrent Engineering in Comparison to Point-Based Concurrent Engineering Using System Dynamics", Technische Universität München Master's thesis, May, 2015.
- Rebentisch, E., Genta, J., "Applying Principles of Set-Based Design to Improve Ship Acquisition", 14th Annual Acquisition Research Symposium, April 26-27, 2017, Monterey, California.
- Kerga, E., Schmid, R., Rebentisch, E., Terzi, S., "Modeling the Benefits of Frontloading and Knowledge Reuse in Lean Product Development", PICMET '16 Conference, 4-8 September 2016, Honolulu, Hawaii.

5.0 Task 4: Tradeoffs Between Ship Survivability Attributes and Cost

Survivability in an inherent function of a warship that has little equivalent in commercial ships. Considerable additional cost in naval ships compared with commercial ships can be attributed directly to enhancing their survivability, to the point of driving naval ship construction and associated shipyards to be unique from and more costly than best commercial facilities. This is a major driver of the cost of naval vessels compared with commercial ships. In this context, there are no documented formal methods to make tradeoffs between ship survivability and affordability.

The objective of this task is to develop a generalized model of ship attributes associated with survivability and use that model to explore the tradeoffs between ship survivability and acquisition cost using multi-dimensional and multi-objective optimization/Pareto frontiers methods. Ship attributes associated with survivability could include e.g., detectability, speed, offensive and defensive capabilities, and damage resilience.

The sub-tasks in this research task include:

a) Identify and define ship attributes based on architecture and design choices (e.g., detectability, speed, offensive and defensive capabilities, damage resilience) that are linked to ship survivability.
b) Identify the relationships between cost and the ship survivability attributes to enable the creation of cost tradeoff functions.
c) Explore the tradeoffs between ship survivability and cost using multi-dimensional and multi-objective optimization/Pareto frontiers methods.

5.1 Overview of the task

A ship is a system of systems that must perform certain warfare mission functions and protect its crew after a combat or non-combat related disturbance. In the most recent version of OPNAVINST 9070.1, the U.S. Navy appears to be moving away from rigid survivability measures and towards survivability standards that are tailored to the specific ship and based on its required capabilities and concept of operations.

In addition to being survivable, a warship must be capable of performing its mission, and it must be cost-effective. Consequently, a means of exploring the survivability tradespace can be of great value, particularly prior to the detailed design phase where most of the current survivability analysis is conducted. The tradeoff between survivability, mission effectiveness, and cost-effectiveness is at the center of this study.

5.2 Summary of the findings

LCDR Johnathan Walker, a U.S. Navy officer and a graduate student in the Naval Architecture (2N) program while at MIT, focused his thesis research on analysis of surface ship survivability in the early stages of U.S. Navy ship design and acquisition. He completed his thesis research and graduated in June 2016. His research findings were summarized in detail in the MIT PIE Shipbuilding Study Quarterly Report dated 9 April2016 and in his thesis referenced at the end of this section. Because the detailed observations and results have already been reported previously, only a summary of his work and the outcomes will be presented here.

To conduct the study a literature review was performed, which included navy mission areas, threats and threat environments, navy survivability policies, damage mechanisms of naval vessels, survivability assessment methods, naval cost engineering, and tradespace exploration. From this diverse set of literature a framework and process for assessing ship survivability was developed (see Figure 3).

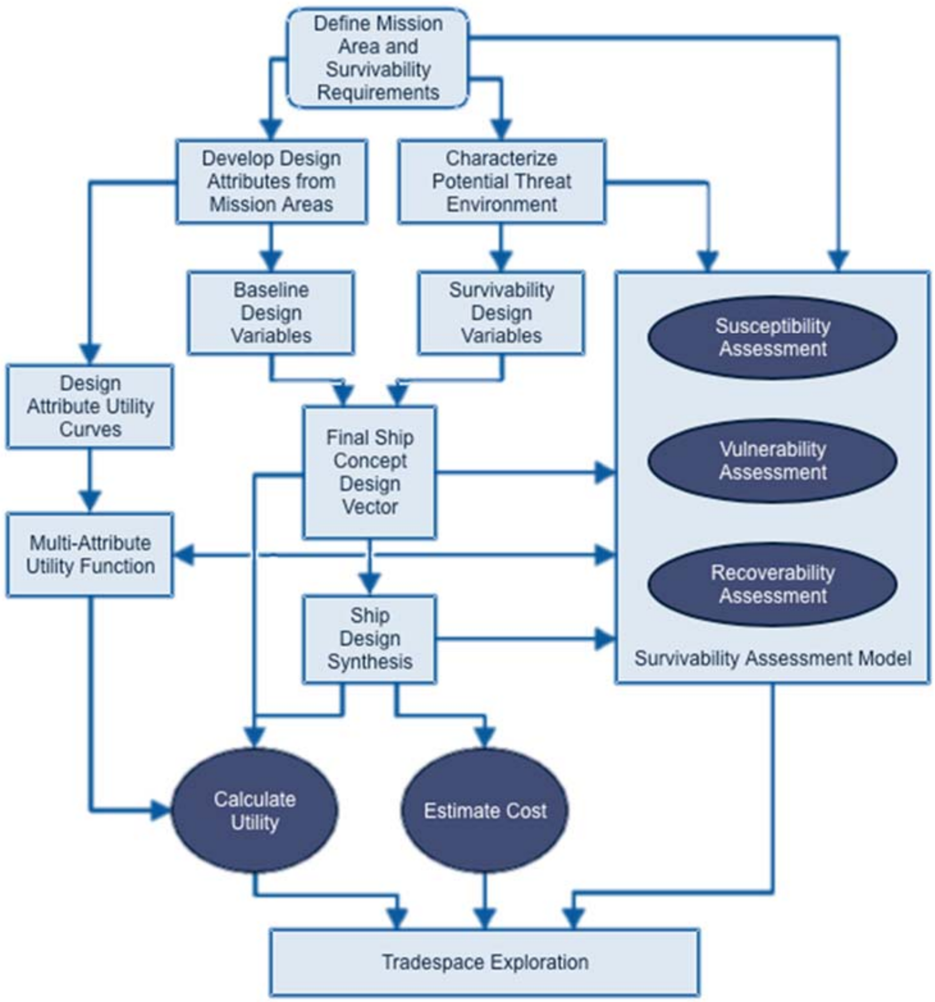

Figure 3. Ship survivability analysis process overview.

To develop the framework and process and to demonstrate it on a specific design challenge, the small surface combatant class was selected for the focus of this study. To address the wide range of possible architecture and design features, four design standards were defined, ranging from commercial class standards to highest navy combatant standards. Data to populate the model were obtained from a variety of sources, including NAVSEA 05C, NSWCCD, and industry. Data were collected by single-digit SWBS groups across several platforms that represent different survivability categories. Cost modeling was developed in accordance with the NAVSEA Cost Estimating Handbook, and used NSRP research on the cost premium associated with survivability to adapt single digit SWBS weight-based cost relationships to reflect the cost multipliers associated with different survivability levels.

The analysis using the resulting model found that the design standard has a large impact on the survivability and cost behavior. In Figure 4, the optimal ship designs from the thousands evaluated are projected onto the survivability-cost plane. The polygons with different shades correspond with the different design standards in the model. The Pareto surface designs (optimal ship designs) border design standard regions. Figure 4 shows that the survivability increase in Pareto surface designs is characterized by a steep rise in survivability with low-cost susceptibility reduction followed by diminishing returns with higher-cost vulnerability reduction and recoverability enhancement.

This effect is highlighted in Figure 5, where two dominant classes of ships are noted. The low-cost, commercial standard ships benefit from inexpensive susceptibility enhancements. The most survivable designs are high-cost designs based on combatant standards. The low-cost designs have impressive survivability scores, but that is due almost entirely to high susceptibility ratings. If they were to be hit, their vulnerability to damage is high and their likelihood of recovery would be low.

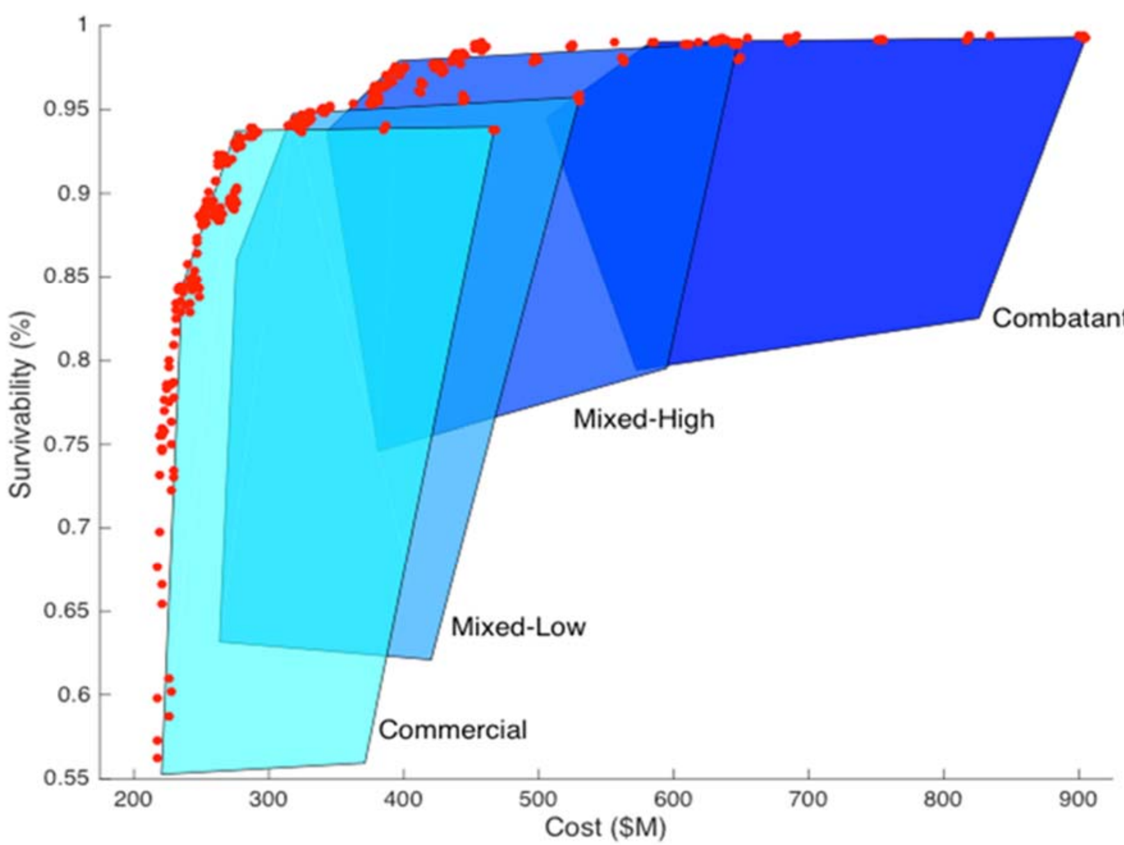

Figure 4. Breakout of design standards shows distinct survivability-cost trends.

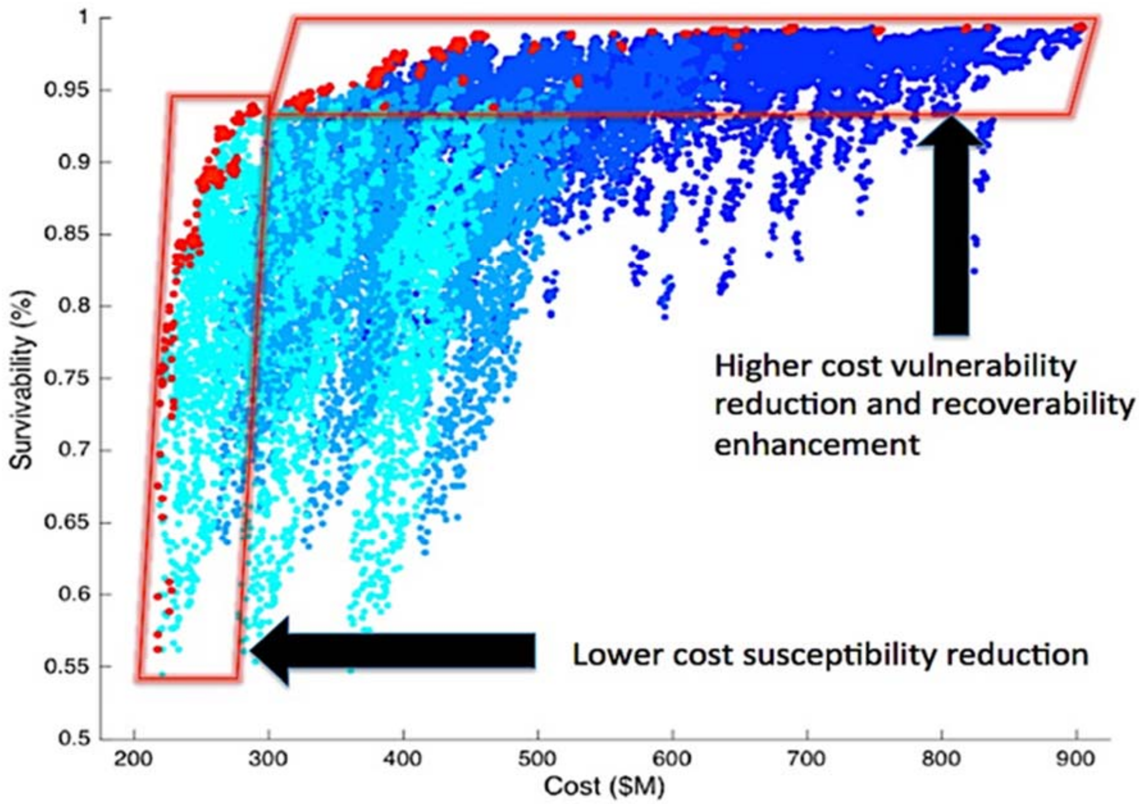

Figure 5. Two primary classes of survivable ships emerge with different architectures.

A number of insights were gained from this initial exploration of ship survivability tradepace exploration. The first is that this type of analysis appears to be unique for the U.S. Navy. The U.S. Navy currently lacks a concept design survivability assessment tool. Many of the survivability specialists in various branches of the navy were consulted as part of this study. The insights gained from those discussions are that much of the analysis focusing on survivability takes place once a relatively detailed ship design has been created.

Survivability analyses appear to be performed by a few specialized domain experts. This means that different analyses are performed by different entities, each with its own unique skillset. It also means that there is likely not one single integrated perspective on survivability, but rather many fragmented perspectives, until late in the design of a ship. By that point in the process, tradeoffs between cost, capability, and survivability will be difficult because design standards and mission equipment will already have been selected. Warships are uniquely different from other vessels, and one of the characteristics that distinguishes them is survivability. It stands to reason that a navy should have in-house the end-to-end capability to assess and manage survivability. Perhaps one solution would be to integrate this type of concept analysis into the Advanced Survivability Assessment Program (ASAP) that is currently used by the navy.

Three-dimensional (or possibly multi-dimensional) tradespace analysis is required to enable survivability tradeoffs. Interpreting multi-dimensional tradespaces is inherently challenging and difficult for people. It is not appropriate to aggregate capability and survivability into an overall value metric since important information could be lost in the process. Traditional capability-cost optimal designs ignore survivability, and survivability-cost optimal designs ignore desired capability. All perspectives are needed to make informed decisions that lead to the greatest overall value to the user.

5.3 Presentations of findings

The findings from the study in this task area were presented to the ASN(RDA) by LCDR Walker during a project update meeting on 6 June 2016. The presentation slides were captured in MIT PIE Shipbuilding Study Quarterly Report dated 1 August 2016.

Additionally, the model developed by Walker formed the basis for the additional analysis that was done in task area 2 of this study, the findings from which were presented at the ASNE Technology, Systems and Ships (TSS 2017) conference in February, 2017.

5.4 Publications of findings

The findings from this study were documented in LCDR Walker's thesis:

- Walker, Johnathan, "Multi-Attribute Tradespace Exploration for US Navy Surface Ship Survivability: A Framework for Balancing Capability, Survivability, and Affordability", MIT SM Thesis, June 2016.

6.0 Task 5: Framework to integrate the PIE shipbuilding study research findings

The advanced analysis tools developed in this study, including the complexity and architecture analysis tools developed in task, frequently depend on having a functional system representation as a point of departure in the analysis. Often, the system representation is in the form of design structure matrices (DSMs). Unfortunately, constructing DSMs manually can be a labor-intensive process spanning weeks or months. Despite many modern design processes being computer-based and built upon an extensive and detailed layer of product design information, the capability to extract DSMs in real time from these sophisticated design tools does not currently exist. This significantly reduces the likelihood that these tools will be used during the design process.

This task developed software and associated methods to interface with the NAVSEA LEAPS ship design database and ship models to extract DSMs and to enable new analyses to take place during ship design.

The proposed updates to the sub-tasks in this research task are:

a) Develop design structure matrix (DSM) extractor software that interfaces with existing NAVSEA ship design tools.
b) Integrate DSM extractor software and ship analysis tools developed in the PIE study with existing NAVSEA ship design approaches.
c) Link new analysis capabilities with other DSM-related analyses.
d) Promulgate the findings of Phase II of the PIE study to key DON stakeholders.

6.1 Overview of the task

DSMs are not a new concept. They have been known and used in academic studies for many years. However, those studies have generally relied on researchers to construct the DSM representations from completed system development efforts. The manual DSM creation process can take weeks to months to complete for complex systems. While a number of DSM-based system analysis tools have been developed over the years, the challenge and time to create the DSM itself has served as a significant barrier to DSM-based analysis being used in active product development projects.

Our assessment of engineering or product management tools in common use found no existing capabilities to automatically generate DSMs from product data within those tools. This applies not only to general engineering development applications, but also to ship design tools. Creating a tool that extracts system architecture information from a design database and exports it to the DSM format in real time would be a significant enabler to advanced system architecture analysis and design being used in product development efforts. This applies equally to tools used by the navy for ship design.

The investigation identified the Leading Edge Architecture for Prototyping Systems (LEAPS) tool and database used by the US navy as the target application for extracting information to generate DSMs in real time for ships. The LEAPS Editor is a cross-platform application that provides interactive visualization, construction and manipulation of a LEAPS database through a graphical user interface (GUI). The LEAPS product meta-model (PMM) for surface vessels is called FOCUS; this PMM is the defined format and relational structure for storage of ship data that enables a software tool to find needed data and to store data in a location that all other software tools operating with LEAPS can find as well. Data that meet the requirements of the FOCUS model are termed “FOCUS-compliant.”

While the LEAPS Editor has many capabilities and features similar to traditional CAD software, its primary strength lies in the realization of a three-dimensional digital model of a product into a logically organized database adhering to the formalized data model schema for a naval surface combatant (FOCUS) via a robust geometric representation of its structure, connectivity and associations. It is these system representations and underlying data that provide the data needed to construct and DSM of the ship.

A detailed summary of the LEAPS MetaModel structure and the approach to extracting the data in the MetaModel were documented in the 3 Feb 2017 quarterly report (appendix B).

6.2 Summary of the findings

The underlying data about the system, including elements, connections, and system aggregation tags, need to be accessed from the LEAPS data structure in order to be exported to a DSM builder program. The process for extracting system design elements from the LEAPS database and using them to build a DSM is shown in Figure 6.

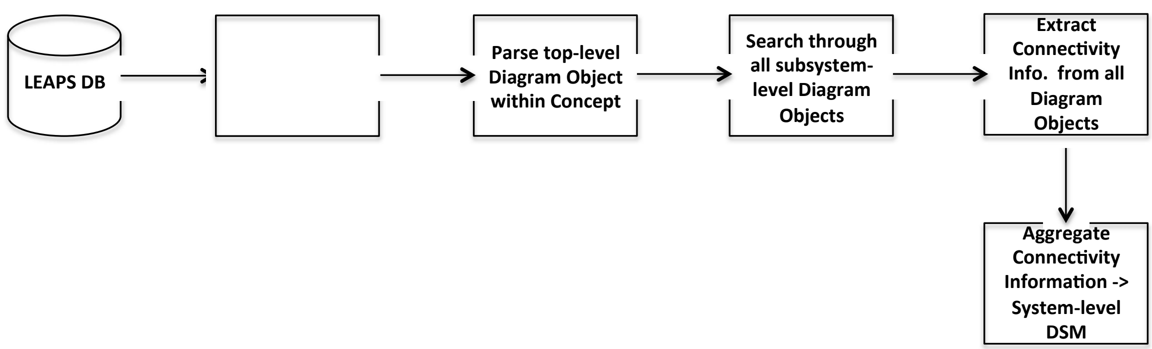

Figure 6. Proposed Flow Chart for the automatic DSM Constructor Tool.

The LEAPS data structure and model are implemented in the C++ programming language. It is through the LEAPS application programming interface (API) that information about system elements may be extracted. The LEAPS Meta Model is documented and can be accessed using C++ programs only. Unfortunately, C++ is not a current generation programming language, and programmers with the necessary skillset are somewhat specialized. MIT students don’t typically have that expertise, so help with the programming tasks was sought from outside vendors.

Some time was spent defining the requirements and searching for contractors who might be able to develop the C++ code to interface with the LEAPS data structure. Kors Analytics is computer programming services company that was engaged to provide the programming support. Additional sharing of data, code, and interactions with them were required to get to the point of developing the DSM extractor tool.

What was initially desired was a DSM extractor tool that could access any LEAPS database model, and possibly an Advanced Surface Ship and Submarine Evaluation Tool (ASSET) model, and produce a corresponding DSM. However, a significant challenge is that most LEAPS and ASSET models are not fully-defined (e.g., the LEAPS models are not FOCUS-compliant because they lack full definition or the elements, structures, or relationships). This means that in order to work around fundamental limitations or ambiguously-defined data in the models, the extractor software would have to have fairly sophisticated logic routines.

This fairly complex program was infeasible because of time and resource limitations in this project. Consequently, a proof-of-concept model was developed that only works with FOCUS-compliant models because they are more predictable in their data, structures, and relationships. The resulting software demonstrates the ability to extract design information from the LEAPS database, but only for FOCUS-compliant models. The software was developed with Linux and Windows versions, and included documentation in the form of README files. The quality of the output from the software strongly depends on the completeness of the LEAPS model from which it is extracting the design information.

To illustrate the power of this early software tool, it is helpful to benchmark DSM building efforts. The first ship-level DSM built for task 1 in this study was of the US Coast Guard Fast Response Cutter (FRC). That DSM was constructed using blueprints and schematic diagrams provided by the shipyard. However, because the documentation was incomplete and the connections between various elements at the ship system level were not fully defined, the Expanded Ship Work Breakdown Structure (ESWBS) was used to “connect” subsystems where interfaces were not explicitly defined. The resulting DSM contained 126 elements in 8 primary subsystems. The total effort took about 4 months, and the duration was ultimately limited by the tenure of the student researcher performing the DSM construction.

The next effort to reduce the time to create a DSM involved the use of a LEAPS model of a US Navy Torpedo Weapons Retriever (TWR). The model was recommended by US Navy ship design experts as being one of the most complete and refined LEAPS models available. Extracting the design information from the LEAPS model of the TWR manually resulted in the creation of a 152-element DSM. The total time to construct the DSM in this fashion was 2 months. This LEAPS model and DSM served as the source material and reference for the DSM extractor software.

The DSM extractor software enabled semi-automated creation of a DSM of the TWR (some of the DSM construction still had to be done by hand due to limitations in the LEAPS model). The same 152-element DSM was created, but the total time to complete the DSM was reduced to a few days. It is anticipated that these DSM creation cycle times could be reduced even further as the DSM extractor software becomes more refined and more attention is placed on producing higher-quality design models. The objective would be to have a tool that can produce a DSM and associated analysis within the timeframe of typical ship design iterations. This would allow the architecture analysis tools to contribute to the ship design process in real time. Based on the experience with the proof-of-concept software, this seems feasible.

The recommended next steps in the development of this DSM extractor software capability include:

- Enhanced ability to work with partially FOCUS-compliant legacy LEAPS models (by incorporating more sophisticated logic into the extractor software)
- Providing the user with the ability to customize the levels of aggregation in the generated DSMs (i.e., to be able to collapse or expand layers in the architecture hierarchy as dictated by the analysis needs)
- The ability to work with ASSET models in order to push the architecture analysis capabilities enabled by DSMs further forward in the ship design lifecycle.

Some additional developments of the software that would be nice to have include:

- The ability to draw on multiple model versions of the same ship in order to build an aggregate ship DSM
- Create Python bindings to access the LEAPS database in order to enable easier integration with the SAAT or other analysis tools
- Build a cross-platform graphical user interface (GUI) for the DSM extractor to enable its use by a wider array of potential users.

6.3 Presentations of findings

The progress on this task was presented to the DASN SHIPs at project update on 26 July 2017 (see Appendix B of this report).

6.4 Other deliverables

The DSM extractor software that resulted from this effort (as-is) has been provided to the project sponsor for unlimited use and modification.

7.0 Summary

Periodic interactions with the project sponsor were used to shape the direction of the study and provide status updates during the period of performance to ensure that the primary goals were being addressed. The project activities (e.g., reports, theses, presentations, meetings) have been documented and are available upon request. Many of the outputs of the tasks were converted into publications and/or presentations to create more widespread and enduring understanding of the knowledge that has been created through the study efforts. Additionally, analysis tools were created and are being distributed along with this report.

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Appendix A: MIT PIE Shipbuilding Study Project Staffing (Cumulative)

The project staffing at MIT during this period included:

Dr. Eric Rebentisch— Principal investigator, Researcher, MIT Sociotechnical Systems Research Center.

CAPT Joe Harbour USN—Advisor, Professor of the Practice and USN CAPT, MIT 2N program.

Prof. Olivier (Oli) de Weck—(On leave from MIT as of January 1, 2017) Professor of Aeronautics and Astronautics and Engineering Systems.

Task 1: Complexity Assessment for Acquisition Decisions: **Dr. Kaushik Sinha**, MIT postdoctoral associate in engineering systems; **Mr. Alex Pott**, graduate student in engineering at the RWTH Aachen University (Germany) **Graduated**; **Mr. Felix Stracke**, graduate student in engineering at the RWTH Aachen University (Germany) **Graduated**; **Mr. Philipp Fey**, graduate student in engineering at the RWTH Aachen University (Germany) **Graduated**; **Mr. Ferdinand Hoensbroech**, graduate student in engineering at the RWTH Aachen University (Germany) **Graduated**.

Task 2: Technical and Organizational Strategies for Commonality: **Mr. Pablo Klemm,** a graduate student in engineering at the École Polytechnique Fédérale de Lausanne (Switzerland) **Graduated**; **Mr. Narek Shougarian**, graduate student, MIT department of aeronautics and astronautics, **Graduated**.

Task 3: Set-based Design Strategies for Naval Shipbuilding and Acquisition: **LCDR John Genta (USN),** graduate Student, MIT 2N Program. **Graduated**

Task 4: Tradeoffs Between Ship Survivability Attributes and Cost: **LCDR Johnathan Walker (USN)** graduate Student, MIT 2N Program. **Graduated**

Task 5: **Dr. Kaushik Sinha**, MIT research scientist and independent consultant.

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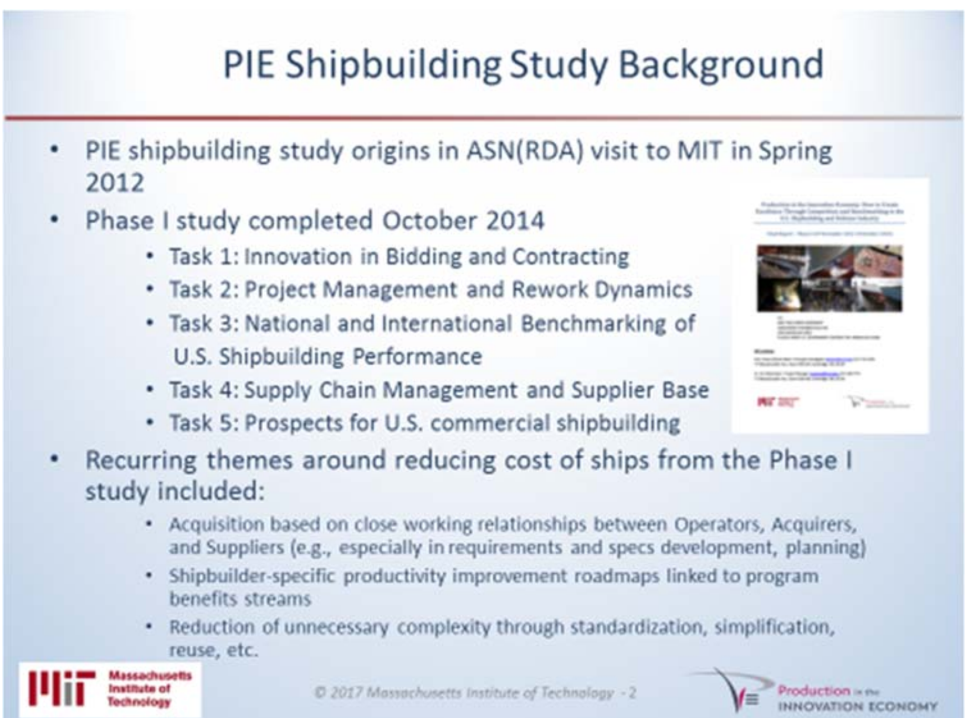
Appendix B: MIT PIE Shipbuilding Study Final Presentation to Ms. Gloria Valdez (DASN SHIPs), 26 July 2017.




Second Phase Emphasizes Design Aspects of Cost Reduction
• Phase II study began on 2 March, 2015
• Phase II Study Tasks:
1. Complexity assessment for acquisition decisions
2. Technical and organizational strategies for commonality
3. Set-based design strategies for naval shipbuilding
4. Tradeoffs between ship survivability and cost
• Heading update from 6 June, 2016 ASN RDA meeting :
• Bring the findings from the research to the USN ship acquisition workforce
• No-cost extension to August 2017 to complete task 5:
5. Help introduce PIE shipbuilding study research findings into practice in the Navy
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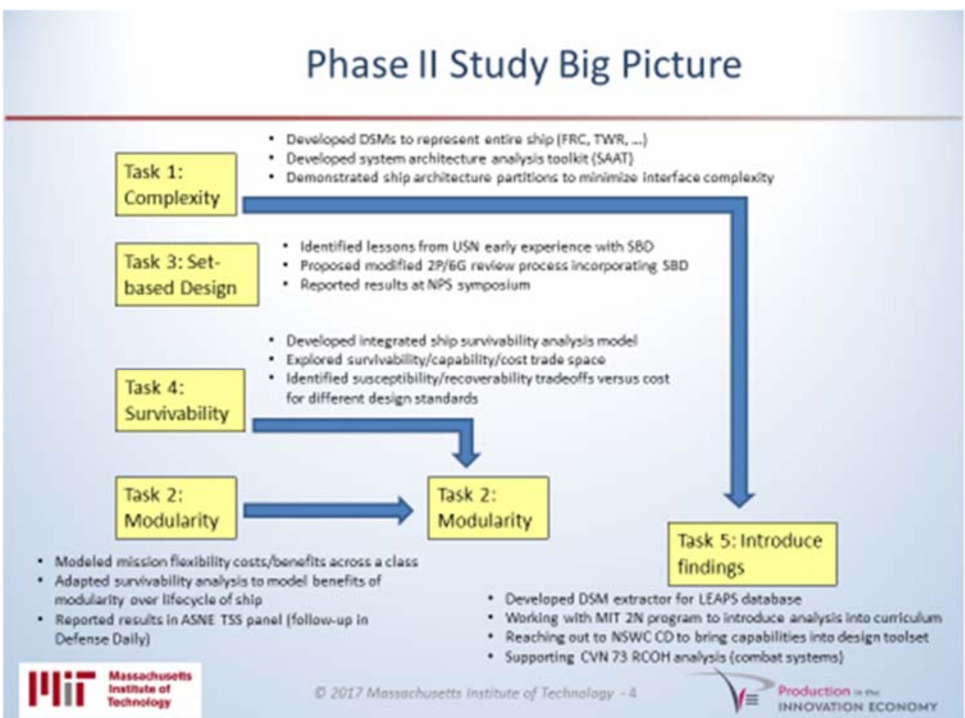
Phase II Study Big Picture
Task 1: Complexity
• Developed DSMs to represent entire ship (FRC, TWR, ...)
• Developed system architecture analysis toolkit (SAAT)
• Demonstrated ship architecture partitions to minimize interface complexity
Task 3: Set-based Design
• Identified lessons from USN early experience with SBD
• Proposed modified 2P/6G review process incorporating SBD
• Reported results at NPS symposium
Task 4: Survivability
• Developed integrated ship survivability analysis model
• Explored survivability/capability/cost trade space
• Identified susceptibility/recoverability tradeoffs versus cost for different design standards
Task 2: Modularity
Task 2: Modularity
• Modeled mission flexibility costs/benefits across a class
• Adapted survivability analysis to model benefits of modularity over lifecycle of ship
• Reported results in ASNE TSS panel (follow-up in Defense Daily)
Task 5: Introduce findings
• Developed DSM extractor for LEAPS database
• Working with MIT 2N program to introduce analysis into curriculum
• Reaching out to NSWC CD to bring capabilities into design toolset
• Supporting CVN 73 RCOH analysis (combat systems)
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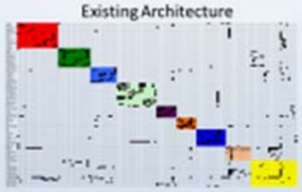
TASK 1: COMPLEXITY ASSESSMENT FOR ACQUISITION DECISIONS

Define an approach to enable complexity-based architecture tradeoff decisions for improved cost estimates and program planning at the ship level during the early stages of a ship program.

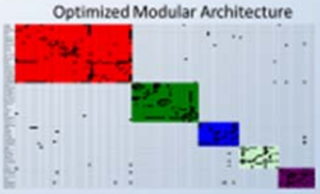
Using Complexity Analysis to Define More Effective Ship Architectures

- Created model of USCG Fast Response Cutter (FRC) architecture and adapted model of the Torpedo Weapons Retriever (TWR) at the ship level
  - Working on Arctic Frigate (MIT 2N project model) as additional test case
- System Architecture Analysis Toolkit (SAAT)
  - Identifies central elements of the system (ship), level of complexity, and optimal decomposition into modules
  - Overall ship complexity characterization with *hot spots* defined
  - Optimal definition of system modules with their impact on overall ship and module complexity, workload allocation and interface management, etc.
    - e.g., reduce integration complexity by 76% using same equipment but redefining interfaces

Existing Architecture



Optimized Modular Architecture



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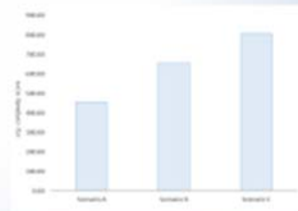
On-going—Characterizing the Impact of Organizational Complexity

- Developing methods to systematically measure organizational dimensions of complexity
  - Differentiate between impact of different approaches to structuring programs
  - Characterize the relative cost of managing more complex organizational approaches
  - Subject of on-going research
- Understanding the complexity-related impacts of engineering changes on cost/schedule
  - How to choose the best alternative among possible options to fullfill requirements?
- Developing agent-based models of projects to understand the benefits/limits of organizational complexity



TASK 3: SET-BASED DESIGN STRATEGIES FOR NAVAL SHIPBUILDING

Develop a framework to understand the benefits, enabling conditions, and specific approaches, in order to support implementation of the appropriate elements of set-based design methods in shipbuilding so as to improve ship acquisition program outcomes.

Set-based design (SBD)

- Identified with Toyota's product development process—thought of by many as "Lean product development"
- SBD considers a wider range of alternative sets in a design space in parallel—an optimal design is developed by rapidly converging on a preferred solution
- Relatively higher resource allocation at the front-end of projects for analyzing, prototyping, and testing multiple solutions to gather knowledge and reduce uncertainties, with the promise that the overall process will be more resource-efficient
- The knowledge obtained in the process is captured for future reuse
- In studies, the benefits of SBD are:
  1. Up to 75% reduction in project cost, 50% reduction in lead time, 50-75% improvement in product technical performance (innovation), and 50-100 % reduction in warranty cost and number of engineering changes
  2. 30% material and manufacturing cost reductions

USN experiments with SBD in recent years have been promising and its application is expanding

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Findings: When Set-based Design Has the Greatest Benefits

Prioritize set-based design (SBD) over point based design (PBD) if:

- Design loop-backs ("do over") are more costly the further downstream problems are found
- Feedback from testing back to design (validation) is slow
- Projects have high levels of innovation requiring new knowledge
- The rate at which design knowledge becomes obsolete (e.g., changing technology, dynamic environment) is high
  - SBD has an edge over PBD through the use of formal knowledge capture and reuse mechanisms

Focusing on the role of knowledge in product development particularly highlights the primary differences and benefits between SBD and PBD

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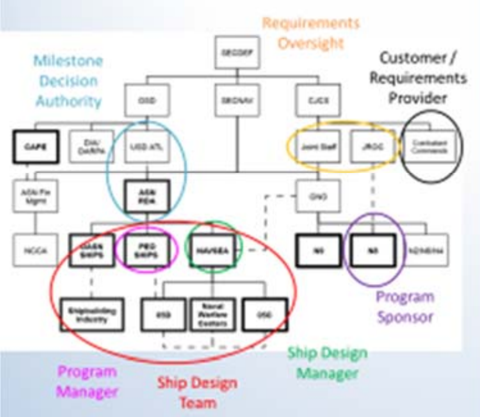
SBD and the Navy 2 Pass/6 Gate Acquisition Process

Ship Design Organizations



Gate	What	Type	Who	Priorities from Interviews
1	CBA & ICD	Exploratory & Pre-AoA	N8	Understand intelligence and technology risk Don't jump to conclusions
2	AoA	AoA	CNO	Large span of AoA variants Cost vs. capability trade-off
3	CDD	Pre-PD	CNO	Feasibility of KPP/KSA performance at cost.
4	SDS	Preliminary	ASN RDA	Feasibility and cost of sub-system integration.

Alignment with SBD

- Gate 2
  - SBD works well with large design space.
- Gate 3
  - SBD proceeds via feasibility assessment

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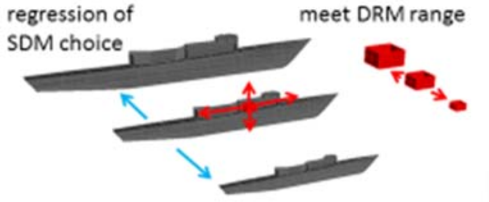
Process Improvement: Gate 2, Analysis of Feasibility (AoF)



Variants for Trade-off		CS 1	CS 2	CS 3	CS 4	CS 5	CS 6
Hull	Beam : (X ↔ Y)						
	Depth:						
	Draft:						
	Cp:						
Propulsion	Type 1						
	Type 2						
	Type 3						
Energy	Type 1						
	Type 2						
	Type 3						
Aux	Type 1						
	Type 2						
Crew	Option 1						
	Option 2						
	Option 3						

Variants are either feasible or in-feasible

Results will produce a "cloud" with a "range" of cost and performance

(1) Split design into Combat System and Ship areas
  - Communicate via SWAP-C and LCG/VCG

(2) Use RSDE to input wide CS range into Ship areas for ASSET.
  - Integrate after CS resolved architectures.

ADVANTAGES

- Parallel effort by Ship and CS = ↓ Design Time and Cost
- More data provides statistical Capability vs Cost trade-off.

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Process Improvement: Gate 3, Cont. AoF

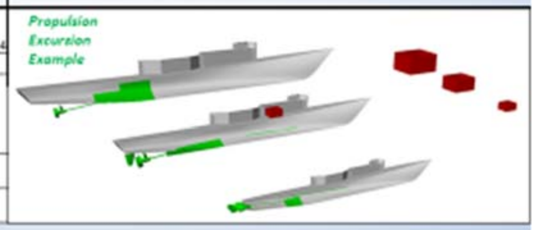
- Feasibility of KPPs/KSAs maintained.
- Build on previous design phase effort.

Gate 3 SBD Process

1) Continue Ship / Combat team segregation
2) Sub-system experts study configurations to identify preferred architectures.
3) Communicate preferred configurations through SWAP-C. Eliminate dominated designs.

Continue process until all areas have technical rigor to support CDD.

Variants for Trade-off			CS 1	CS 2	CS 3	CS 4
Hull						
Propulsion	Type 1	Option 1	Evaluate for dominance			
		Option 2				
		Option 3				
	Type 2					
	Type 3					



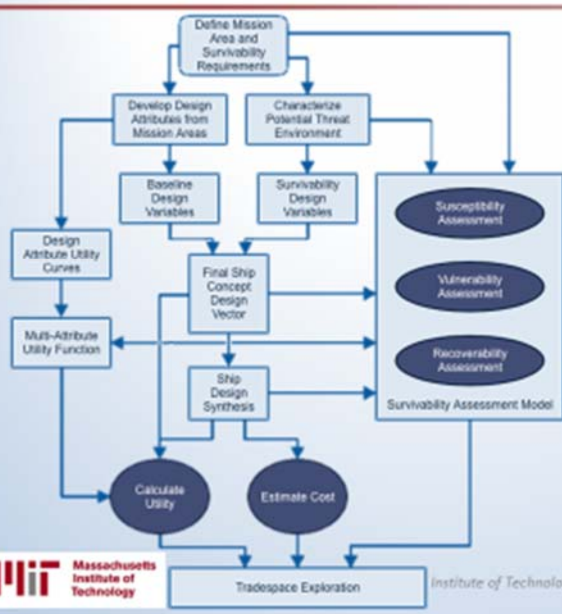
Conclusions

- Findings from USN cases of the use of set–based design:
  - Less cost to design, build, and maintain the product—early but encouraging
  - Reduction of design cycle time—seen in all cases
  - Better design knowledge capture—but still early for some cases
- Navy is moving toward more widespread use of set–based design
  - Pushing into new application domains (e.g., from classic design to CDD, trade studies)
  - Evolution of hybrid approaches employing different design strategies (combining SBD with e.g., tradespace exploration methods)
- 2P/6G process can accommodate SBD (up to a point), but can be improved to benefit more from the additional information provided by SBD
  - Multiple decision-makers in acquisition process—all need to be socialized to the value of SBD analysis and presentation of findings
- Implications for formal ship acquisition process in the USN:
  - Analysis of Feasibility approach as a way to challenge existing acquisition mindsets to encourage greater exploration of the design tradespace
  - Create a temporary TWH position for design process to champion SBD until all SDMs/SIMs have gained familiarity with the process?

TASK 4: TRADEOFFS BETWEEN SHIP SURVIVABILITY AND COST

Develop a generalized model of ship attributes associated with survivability and use that model to explore the tradeoffs between ship survivability and acquisition cost using multi-dimensional and multi-objective optimization/Pareto frontiers methods.

Survivability Analysis Process Overview



1. Generate Ship Requirements
2. Generate Ship Concept Designs
3. Characterize Ship Threat Environment
4. Apply Survivability Variables and Finalize Design Vector
5. Design Synthesis and Ship Baseline Performance
6. Survivability Assessment Model of Naval Ship Concepts
7. Tradespace Exploration

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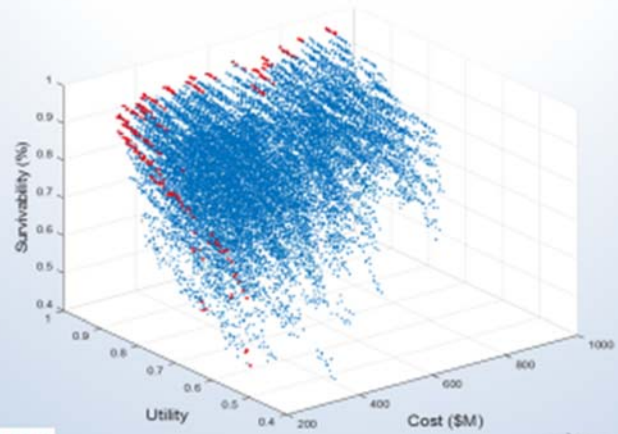
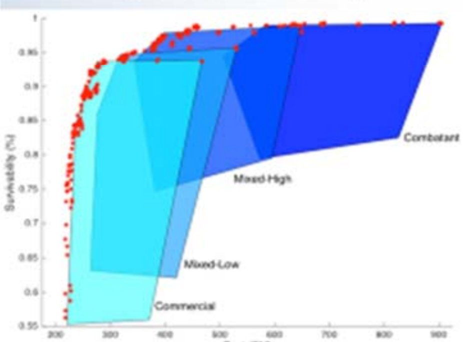
Ship Survivability, Utility, and Cost Trade Space

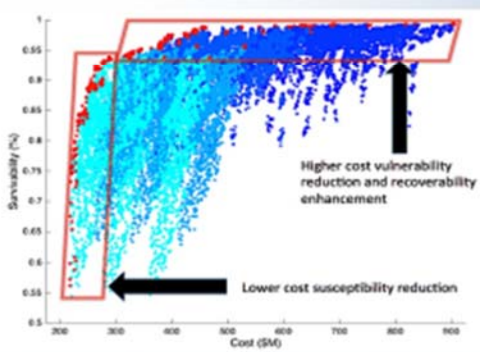
- 3D Pareto surface reveals optimal level of capability and survivability for cost
- Navigation of 3D point designs is problematic



Design Standard Sensitivity (3D Optimized)

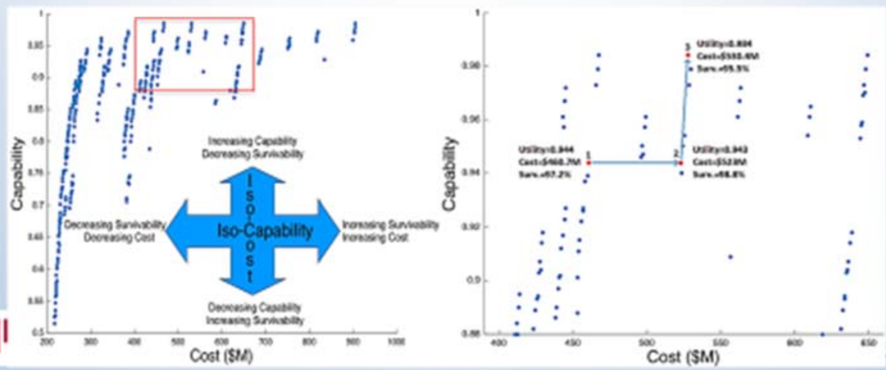
- Pareto surface designs projected on survivability-cost plane
- Pareto surface designs border design standard regions
- Survivability increase in Pareto surface designs characterized by steep rise in survivability with low-cost susceptibility reduction followed by diminishing returns with higher-cost vulnerability reduction and recoverability enhancement.





Analysis Identifies Macro Tradeoffs in Ship Design

- Only optimal designs projected onto capability-cost plane
- Tradespace navigation trends
  - Increased survivability with cost
  - Inverse relationship for capability-survivability tradeoffs (constant cost).
  - Allows path dependent tradespace navigation



Conclusions

- Survivability assessment model:
  - Enables tradeoffs between combat systems, ship design, and design specifications early in the ship design cycle
  - Allows optimization of capability and survivability relative to cost
- Survivability-cost relationship depends on:
  - Desired design capability
  - Threat environment
  - Desired capability after damage
- US Navy lacks concept design survivability assessment tool
  - Need holistic susceptibility assessment method based on projected operating environments.
  - Evaluate large numbers of designs
  - USN develop a concept phase version of Advanced Survivability Assessment Program (ASAP)?

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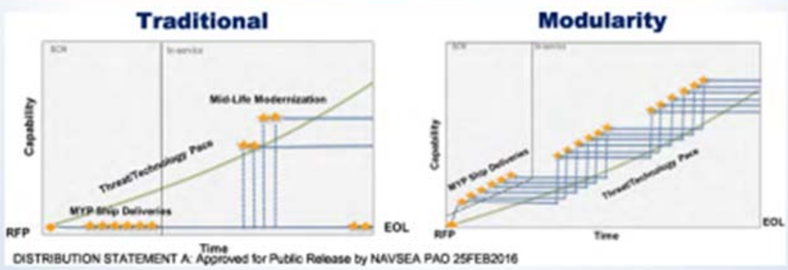
TASK 2: TECHNICAL AND ORGANIZATIONAL STRATEGIES FOR COMMONALITY

Define technical and organizational strategies and approaches to help accelerate the implementation and realization of the full potential benefits of commonality for naval ship platforms.

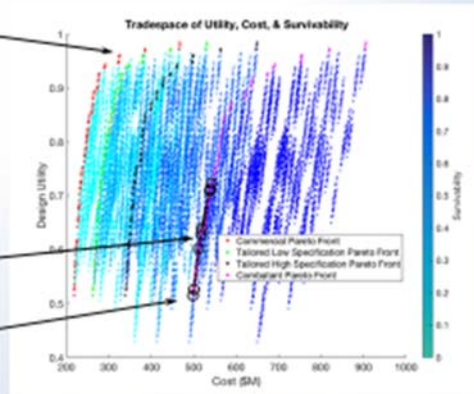
Simulate lifecycle of a ship to understand the possible impacts of flexibility



- Develop a simulation model to assess the benefits of flexibility (e.g., through modular subsystems) in naval ships
- Identify differences between flexible and traditional ship architectures
  - What is the impact of flexibility on lifecycle cost, mission capability, and survivability?
  - Include effects of mission change/uncertainty, upgrades through ship lifecycle, different budget environments

Trade space plot displays upgrade path among many options over the simulated ship lifecycle

- Each dot in the trade space represents a unique ship configuration (2344 displayed)
  - Utility score reflects ability to fulfil mission mix scenario (higher is better)
  - Color of the dot represents a composite of susceptibility, vulnerability, and recoverability (darker is more survivable)
- Ship upgrade path is superimposed over the trade space plot
  - Black circles identify when the ship configuration was changed
  - Starting point is lowest-cost ship with best performance for the design standard
  - Upgrade path follows the Pareto frontier (best utility/value combination) of its design standard—always chooses the most survivable configuration given the mission scenario and the funding level



Adapted from Walker, 2016

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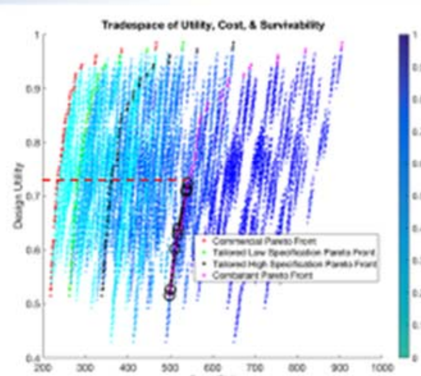
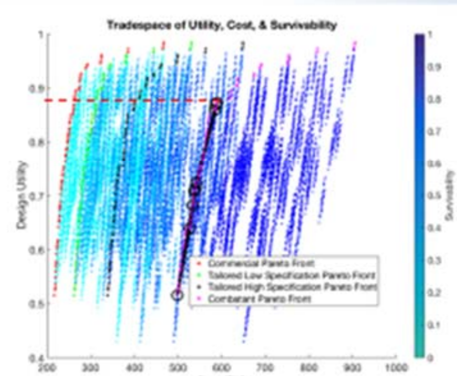
Flexible ships attain higher utility (mission fulfillment) than traditional ships

- Utility of flexible ship is higher than traditional ship in each time step and overall
- Lower reconfiguration costs for flexible ships enable more impactful upgrades





Traditional ship Mission scenario: combatant design standard, high budget **Flexible ship**

Adapted from Walker, 2016

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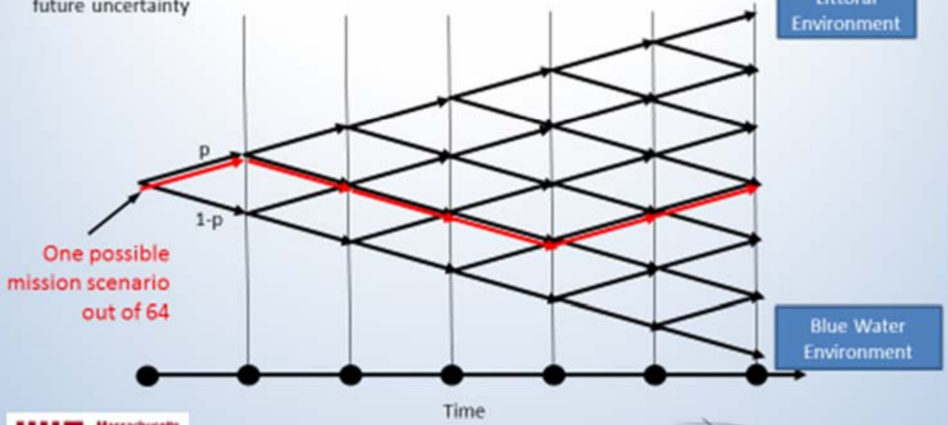
Future missions may change and impact the mission capability and survivability of the design

Real Options Approach: Mission Uncertainty (6 time steps, 64 possible scenarios)

A multi-variate binomial tree with probability of change p in the survivability function represents changing missions with future uncertainty



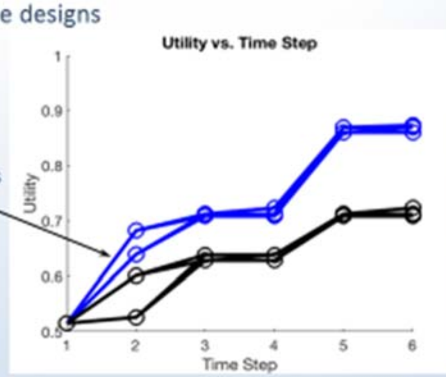
Massachusetts Institute of Technology

Production in the INNOVATION ECONOMY

Flexible ships achieve higher utility (mission fulfillment) in the face of changing missions

- Flexible ship utility exceeds traditional ship utility in all time steps and mission scenarios
- Initial designs (with fewer subsystems) are more diverse and tailored to specific missions, but eventually evolve to become more fully-populated, multi-mission capable designs

- Each line represents a different mission scenario with corresponding optimal ship configurations
- All 64 mission scenarios are superimposed to show the range in performance of possible flexible and traditional ship configurations



Flexible

Traditional

Scenario: combatant design standard, high budget

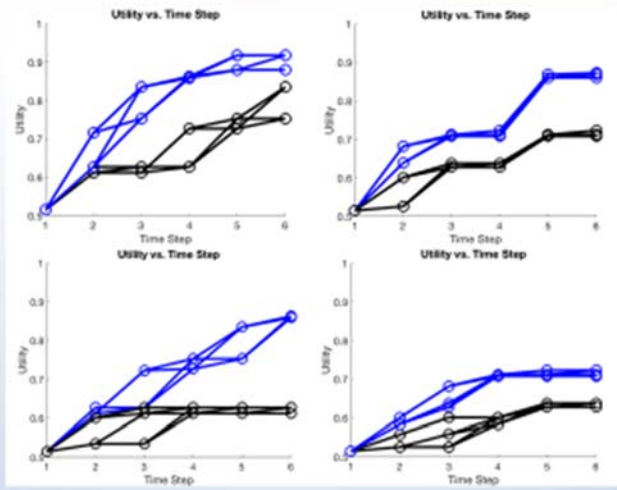
Massachusetts Institute of Technology

Production in the INNOVATION ECONOMY

Flexible ships consistently show higher utility across a variety of mission scenarios and ship configurations

High budget

Low budget



Flexible

Traditional

Flexible

Traditional

Mixed-spec High std.

Combatant std.

Flexible ships also have an overall advantage in expected life cycle survivability

- Simulation in each upgrade always selects the ship configuration with the best survivability for both flexible and traditional ships
- By the end of the 6 upgrade periods, flexible ships have achieved greater overall survivability than traditional ships
  - ~2% increased overall survivability for littoral-only missions (the most challenging mission mix in the model)
  - ~10% increased overall survivability for blue water-only missions
  - ~7% increased overall survivability when mission scenarios randomly move between littoral and blue water mission emphasis
- Primary benefit likely results from flexible ships enabling frequent, high-impact upgrades
- Important caveat: cost of modularity (new construction and upgrades) is based on MEKO experience—a very mature application

TASK 5: HELP INTRODUCE PIE SHIPBUILDING STUDY RESEARCH FINDINGS INTO PRACTICE IN THE NAVY

Develop software and associated methods to interface with the NAVSEA LEAPS ship design database and ship models to extract DSMs and to enable new analyses to take place during ship design.

Current Efforts

- Developed prototype software to extract design information from LEAPS database to create Design Structure Matrices (DSMs)
  - Automatically generate DSMs from USN design tools (e.g., LEAPS, ASSET)
  - Open up use of numerous existing DSM-based analysis methods plus SAAT
  - Testing tolerance across range of FOCUS-compliant models
- Next steps:
  - Combine DSM extractor with SAAT to provide design-to-analysis capability during early design
  - Evaluate use of PIE study-developed design tools using MIT 2N capstone ship design models and course
  - Work with NSWC CD ship design tool developers to introduce capability into ship design toolset
  - Test case: CVN 73 RCOH combat systems architecture analysis and partitioning

PIE Study Phase II Overarching Conclusions

- Research identified the potential application of advanced analysis tools to ship design in order to improve lifecycle performance relative to cost
  - System Architecture Analysis Toolkit (SAAT) to define better ship architecture configurations accounting for complexity and adaptability
  - Set-based design applicability to gates 2 and 3 of USN 2P/6G acquisition process with recommended implementation path forward
  - New approach to include integrated survivability assessment in early ship concept tradeoffs to better balance cost and overall mission-effectiveness
- Helped to shaping future USN leaders through research on ship acquisition with students in the 2N program at MIT
  - PIE shipbuilding study has attracted and enabled researchers at MIT (and beyond) interested in shipbuilding and complex system and acquisition management topics
- Phase II Study period is nearing its conclusion (August 31)—what next?

US Navy Officers and their PIE Study Research

- LCDR John Genta USN—"Using the Principles of Set-Based Design to Realize Ship Design Process Improvement", MIT SM Thesis, June 2016.
- LCDR Johnathan Walker USN—"Multi-Attribute Tradespace Exploration for US Navy Surface Ship Survivability: A Framework for Balancing Capability, Survivability, and Affordability", MIT SM Thesis, June 2016.
- LCDR Kathleen McCoy USN—"Design and Analysis of US Navy Shipbuilding Contract Architecture", MIT SM Thesis, June 2015.
- LT Aaron Dobson USN—"Benchmarking Complexity as a Cost and Schedule Driver in U.S. Navy Shipbuilding", MIT SM Thesis, June 2014.
- LT Ungtae Lee USN—"Using Density to Improve the Parametric Method of Cost Estimating Relationship", MIT SM Thesis, June 2014.
- LT Dominic Alvarran USN—"Realigning Contract Incentives for the Non-Competitive Environment of the US Shipbuilding Industry", MIT SM Thesis, June 2013.
- CDR Terrence Nawara USN—"Resource Constrained Project Scheduling at U.S. Naval Shipyards", MIT SM Thesis, June 2013.

Related Activities

- Related research activities has complemented the PIE study
  - MIT Consortium for Engineering Program Excellence (CEPE) research
    - Complexity management
    - Agile project/program management
    - Project teamwork dynamics
    - Implementing strategic change in complex organizations
  - Joint MIT/PMI/INCOSE book on Integrating Program Management and Systems Engineering
  - Global Shipbuilding Executive Summit (GSES), in support of PEO SHIPS Flexible Ships Initiative
  - University of Tokyo Japan Maritime Sector research collaboration
  - RWTH Aachen (Germany) collaboration on complexity management research

Potential Future Research Topics

- Cost estimating relationships (CER) that account for the cost contribution made by system complexity
- Advanced data analytics to monitor and control acquisition programs and portfolios
- Application of agile and secure software development to large, complex DoD acquisition programs
- Application of advanced additive manufacturing techniques across the ship lifecycle to improve total ownership costs and logistics footprint
- Developing and managing the acquisition workforce
  - Integrating program management and systems engineering disciplines
  - Skill and capabilities development, management, and staffing methods tailored to dynamic strategies (e.g., Agile, rapid prototyping) in acquisition programs
  - Advanced shipbuilding approaches for defense acquisition based on accumulated PIE study findings