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Optimal Selection of Organizational Structuring for Complex System Development and Acquisitions

30 June 2017

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Executive Summary

Background and Approach

Research suggests that product designs tend to reflect the structure of the organization in which they are conceived (i.e., "Conway's Law"). The development and acquisitions of a complex military system is strongly affected by communication mechanisms, resource channels, and the underlying incentives among constituent groups within the acquisition organization. Inefficient setups in this context often result in poor requirements being set, poor understanding of interfaces between elements of the complex systems, and potential failure to achieve the desired return on investment. Prior studies on this topic, especially in the context of acquisitions, have been largely descriptive rather than prescriptive; in other words, they do not provide direct guidance for ways to reduce the inefficiencies resulting from possible misalignments between a product's structure (and ultimate performance) and the structure of the organization that designs/generates the product. While it has been demonstrated that the complexity of a product reflects the complexity of the producing organization's structure, there has been little effort to provide a quantitative support to assist decision-makers in forming organizational structures that best fit the desired complex systems development.

Motivated by this gap, the research conducted under this NPS Acquisition Research Program grant sought to address inefficiencies in the development and acquisition of complex systems by quantitatively modeling the interplay between aspects of an acquisition organization leadership and complex system architecture. Our research combined techniques from operations research and psychological sciences, infused with survey data on program manager competencies, to produce a prototype computational model. Initial exercise of the model targeted ways to improve alignment between organizational performance measures and incentives to accurately reflect the modularization architecture of the systems to be acquired. The model represents a pilot quantitative decision-support framework that, if developed further, could assist acquisition practitioners in determining an optimal modular complex system architecture, and, organizational structure (to include program manager competencies) to support the successful system development.

Key Research Activities

Literature Survey/Collaborative Exchanges

- Our literature survey and collaborative exchanges with subject matter experts on acquisition processes allowed us to construct a "swim lane model" of the defense acquisition lifecycle; this includes the mapping of primary activities and acquisitions relevant documentation required at key decision points along the swim lane timeline, from pre-milestone A to milestone B. The swim lane model provided an organizational construct of required tasks and milestones, upon which we sought to map program manager competencies to. We recognize in particular Dr. Robert Kenley and Mr. Daniel Dumbacher, both Professors of Engineering Practice at Purdue, for their contribution towards this model.

- Our literature survey and collaborative exchanges with subject matter experts on program manager competencies in acquisition organizations allowed us to gather and interpret data to inform our model. Dr. Roy Wood currently at Northeastern State University and formerly on faculty at the Defense Acquisition University, was instrumental in enabling our team to develop the organizational component of our decision-support framework that centers on program manager competencies. Dr. Wood's empirical work using survey method provided a list of 35 (defense) program manager competencies that are regarded as important within the defense community. Building from this list, we surveyed organizational psychology literature to find a well-validated theoretical taxonomy called the "Great Eight" competencies. This taxonomy allowed us to distill Dr. Wood's list of 35 competencies to 8 broad-competency dimensions in order to form a more parsimonious mathematical model for the organizational component of our quantitative decision-support framework.

- Our literature survey of relevant defense acquisition case studies (such as those furnished in prior Government Accountability Office (GAO) reports) informed our assessment of the relative importance of each of the Great Eight competencies at key stages of the defense acquisition lifecycle. The case studies in each report described (among other attributes) programmatic artifacts that related to the program manager tasks identified in literature – these artifacts provided qualitative data that was subsequently then translated into quantitative assessment of the Great Eight competency dimensions.

Developing a quantitative decision-support framework

- For the *organizational component* of our quantitative model, we first mapped the 35 program manager competencies to the Great Eight competencies to reduce dimensionality, and, to promote subsequent parsimonious mapping of competencies to the acquisition lifecycle swim lanes. The availability of details from literature on the relevant acquisition tasks pertaining to each of the 35 program manager competencies, and, high degree of conceptual overlap between the 35 competencies and the Great Eight, allowed for conducive mappings.

- For the *complex system component*, we mathematically described the complex system as a collection of discrete modular systems, where each constituent system is governed by a set of connectivity behaviors. These behaviors can include governing rules on, for example, the exchange of information or resources between systems, compatibility between systems, and, on limits on the number of connections between constituent systems.

- We unify both the *complex system and organizational components*, through use of operations research techniques, to form our quantitative decision-support framework. We leverage prior work and pose our pilot quantitative decision-support framework as highly efficient mathematical optimization problem that is fully domain agnostic and can be applied to government, military and general commercial problems alike.

Demonstrative Example and Results

- We demonstrate our framework using a naval acquisition scenario with the objective of optimally selecting the naval system architecture (collection of modular systems when put together, give rise to a desired capability), and, selecting program manager types (based on program manager competencies) assigned to the development of each system in the chosen architecture.

- The pilot formulation and optimization model proved successful in solving a problem formulated to select the best allocation of program managers based on attributes for a given product feature. Outputs of the model include key information that are of value to decision-makers, including: the specific collection of systems to be acquired, features of each system within the collection, the number of each type of program managers, the assignment of program managers to specific systems being acquired, and, the overall performance index value and level of program manager related risk in the collection.

Recommendations

Based on the success of our pilot computational model, we see the following as key recommendations for potential future work:

- Further research and expansion of the framework to additional organizational dimensions that extend beyond the consideration of program manager competency based allocations. Additional dimensions could include, for example, consideration for various key information that is shared between organizational units, that may vary due to the nature of individual systems being acquired in a complex system.

- Continued development of a quantitative framework for the optimal selection of organizational structuring, and, complex system development, under varied strategic organizational visions – for example, the formulation related to an organization seeking to innovate and evolve its complex system architecture, will be different than say an organization that seeks to improve the reliability and efficiency of its existing complex system architecture.

- Explorations on the use of knowledge management perspectives such as Model Based System Engineering (MBSE), to help provide relevant information to the quantitative framework in this research, in realistic and forward-thinking applications.

Technical Report

Background and Scope of Research

This research investigates the relationship among the physical and functional attributes of 'modular pieces' of a complex system, and, features of organization units assigned to them that correspond to grouping, unit incentive structures measure(s) of performance and corresponding incentives for each unit. The research addressed development and acquisition inefficiencies from misalignments between organizational incentives and system architecture through a developed quantitative framework. Our research is motivated by a need to enable better decision-making on how to objectively select systems that comprise a complex system, and, allocate program managers to each of these selected systems, in a manner that maximizes complex system performance, while minimizing risks associated with mismatches between program manager competencies and system development. More specifically, we refer to organizational structures based on the allocation of program manager types (types based on a spectrum of program management competencies), to manage each of the selected systems in the complex system. We follow Simon's definition of a complex system as being a hierarchical collection of systems and subsystems that are interconnected to provide some desired capability (Simon, 1962). We consider multiple collaborating systems within this definition too since complex systems are typically developed within a collaborative construct of units within and/or across an organization.

Currently, there is a lack of systematic and quantitative modeling framework to assist decision-makers in forming organizational structures that best fit the desired complex systems development and vice versa (Honda, 2015; MacCormack, 2012). This lack is driven in part by difficulties associated with underlying problem of simultaneously selecting a product structure and an organizational structure in an optimal fashion. From a *product* perspective, the task of maximizing a product's (here, complex system) performance may result in a product structure that cannot be well managed, given the population and distribution of program manager types. From an organizational perspective, on the other hand, fixing the selection of an organization’s distribution of program managers will limit the types of products that can be effectively developed. Therefore, there needs to be an objective means of selecting systems in a complex system, and, allocating managers in a quantitatively coherent manner.

Literature Review

A product’s structure is strongly affected by organizational structure, communication mechanisms, and resource channels between organizational units that work together to realize an intended product. Inefficient setup in an organization’s structure often results in poor requirements being set, poor understanding of interfaces between elements of the product, and ultimately, a poor return on investment due to a consequently subpar product being realized. Prior research conducted in software engineering analyzes this relationship and concludes that product designs tend to reflect the structure of an organization in which they are conceived, also known as Conway’s Law (Conway, 1968). Work by Ulrich (1995) and Sinha (2012) explored the question of how the degree of a new product’s novelty affects the structure of an organization. In more recent literature, Honda performed a comparison of information passing strategies in system-level modeling and found that the structure of information coordination, for the case of an example satellite design problem, directly impacts the drive towards an optimal design configuration (Honda, 2015). Austin-Breneman (2016) also explored biases in information passing that impact complex system design due to team structure, types of information between subsystems and how each subsystem explored tradeoffs; the work was exploratory and nature and sought to determine : 1) strategies currently being used when subsystem designers negotiate parametric values for design variables shared between them, 2) the impact that such strategies might have on system design optimality and 3) the impact that such strategies may have on the speed of optimizing each subsystem. Their highly impactful work however is exploratory and explanatory in nature, and, does not provide prescriptive means to deciding how to optimally set up the organizational structure and product architecture. Ioannides (2012) explored how the features of an organization’s structure can impact the ability for the organization's collective screening performance; the paper looks at theoretical foundations on the properties and dynamics of such organizational structures. A recent article, published in Harvard Business Review, presents a case study of how Juniper networks, a company that provides information technology (IT) routing and network solutions, utilized human resources (HR) strategies to improve business processes across its complex organizational structure (Boudreau, 2015). The strategies reduced the number of decision chains involved in product development and sought to identify 'clusters' of employees with the most diverse experience in promoting healthy innovation. Work by Ethiraj & Levinthal (2004) explored a computational model to explore the relationship between bounded rationality and organizational architecture – however, the work did not include explicit consideration for the product architecture as well.

While these prior literatures allude to the coupled nature between a product structure and the structure of the organization that builds it, they are mainly predictive and descriptive in nature. These literatures do not provide prescriptive, quantitative framework to improve decision-making processes related to the product structure (e.g., what collection of modular systems to acquire and connect) and to the organizational structure (e.g., how to allocate human resources such as program managers to the selected constituent systems). Such decision-making processes have significant implications for improving the development and end performance of the product. It is the couplings between organization structure and product architecture, in the context of acquisition, which forms the heart of our research goal.

Methodology

We first define a scope for the 'product' and 'organizational' components of our quantitative framework. For the 'organizational 'structure, we focus on the program manager competencies and how various skillsets and variability can impact product development. On the 'product' side, we adopt a modular perspective on the complex system architecture where the complex system consists of a hierarchical tree of constituent systems that connect via defined interfaces and standards. We illustrate our methodology in the context of defense acquisition; here, the organizational structure is reflected by the distribution of Department of Defense (DoD) program manager types, and, the complex system architecture is reflected by modular systems that are yet-to-be acquired and connected to form a complex defense system.

Our research employs a cross-discipline strategy that seeks to allocate different organizational program manager types, based on program management competency ratings, to the system acquisition life cycle architecture for optimal performance through its phases. For the organizational elements of our framework, we adopt methods and theories from organizational psychology to translate qualitative insights from literature into a quantitative assessment of program manager competency requirements and clarify how they may relate to the execution of the defense acquisition lifecycle. For the complex system architecture, we adopt the mathematical modeling techniques and abstractions as used by Davendralingam (Davendralingam, Mane and DeLaurentis, 2012) and an optimization perspective to enable objective selection of both the complex system architecture and organizational structure.

Problem Formulation and Modeling

We address the problem of how to optimally select systems, from a candidate pool of available modular systems that constitute a complex system, and, allocate program managers to each system, in a manner that maximizes overall performance of the complex system (the "product") while minimizing risks associated with mismatches between program manager competencies and system development ("the organizational structure"). Our problem is based on defense acquisitions and is motivated by availability of data and inputs. We first establish a model for the organizational component and a model of the complex system components of our work. The organizational model reflects the relationship of program manager competencies to defense acquisition processes that need to be executed in developing a constituent system. The product model, on the other hand, reflects how selection of different collections of constituent systems, when combined, provide a desired overarching military capability. In the following sections, we explain our modeling perspective of the organizational and product portions of our framework. We then utilize an optimization based approach to unify both models within a decision-making framework. The data available for this study is derived from studies conducted on program manager competencies by Roy Wood (2010; 2014), and prior case study reports on various defense acquisition programs.

Modeling Organizational Structures (i.e., Program Manager Competency Mapping)

In modeling the "organizational" component of our quantitative framework, we first need to understand the context by which the "organizational" units (here, the program managers) perform. In the case of our concept, defense acquisition problem, the program manager performs a series of required programmatic tasks throughout an acquisition process lifecycle. The ability of the program manager to execute each of the required tasks in the lifecycle, is based on a list of program manager competencies; this naturally has an impact on the end development of each system, and, the complex system as a whole. First, we need to identify/create a life cycle model that allows us to readily map program manager competencies onto it. Second, we need to identify a list of program manager competencies that are relevant to our lifecycle model. Lastly, we need to effectively map these program manager competencies onto the life cycle model by relating relevant subsets of these competencies to each phase of the lifecycle model. In the following sections, we articulate each of the steps in the development of our organizational structure model, beginning with the identification of our life cycle model.

The first step in our organizational structures modeling process was to identify a useful model of the acquisition life cycle. For this purpose, we chose to use a swim lane process model. The decision to create a swim lane model stemmed from a qualitative analysis of life cycle models provided by the Department of Defense and the Defense Acquisition University. There are two prominent models used to describe the system acquisition life cycle of the DoD. Figure 1 is titled "Generic Acquisition Phases and Decision Points" within the literature and is presented in multiple variations throughout the DoD Instruction Number 5000.02 (Department of Defense, 2015).

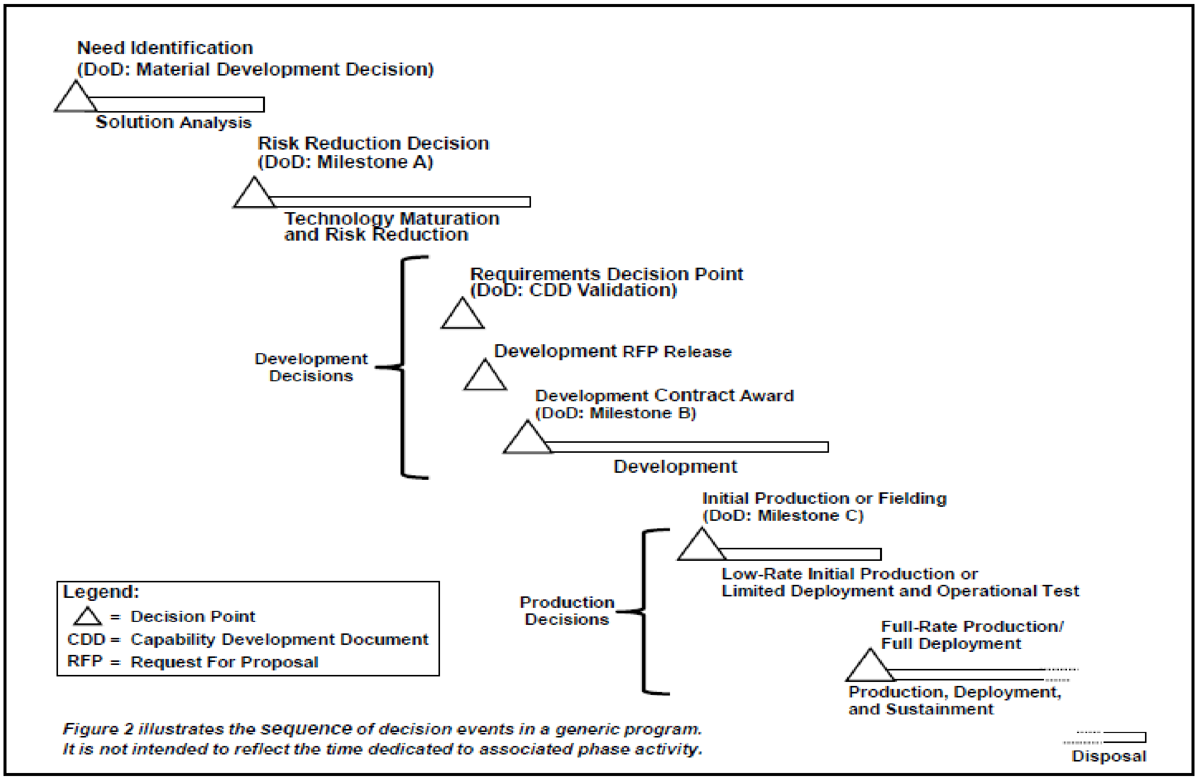

Figure 1: Generic Acquisition Phases and Decision Points (Department of Defense, 2015, *p. 6)*

For our purposes, this model does not provide enough detail to properly distinguish where the competency data would be utilized through the different phases. A significant contribution of the 5000.02 documentation are the descriptions of the phases given with Figure 1 and its ability to provide insight into the DoD program manger's role throughout each step within the life cycle. The second model provided by the Defense Acquisition University presented in Figure 2 provided significantly more visual detail in the processes occurring within each phase.

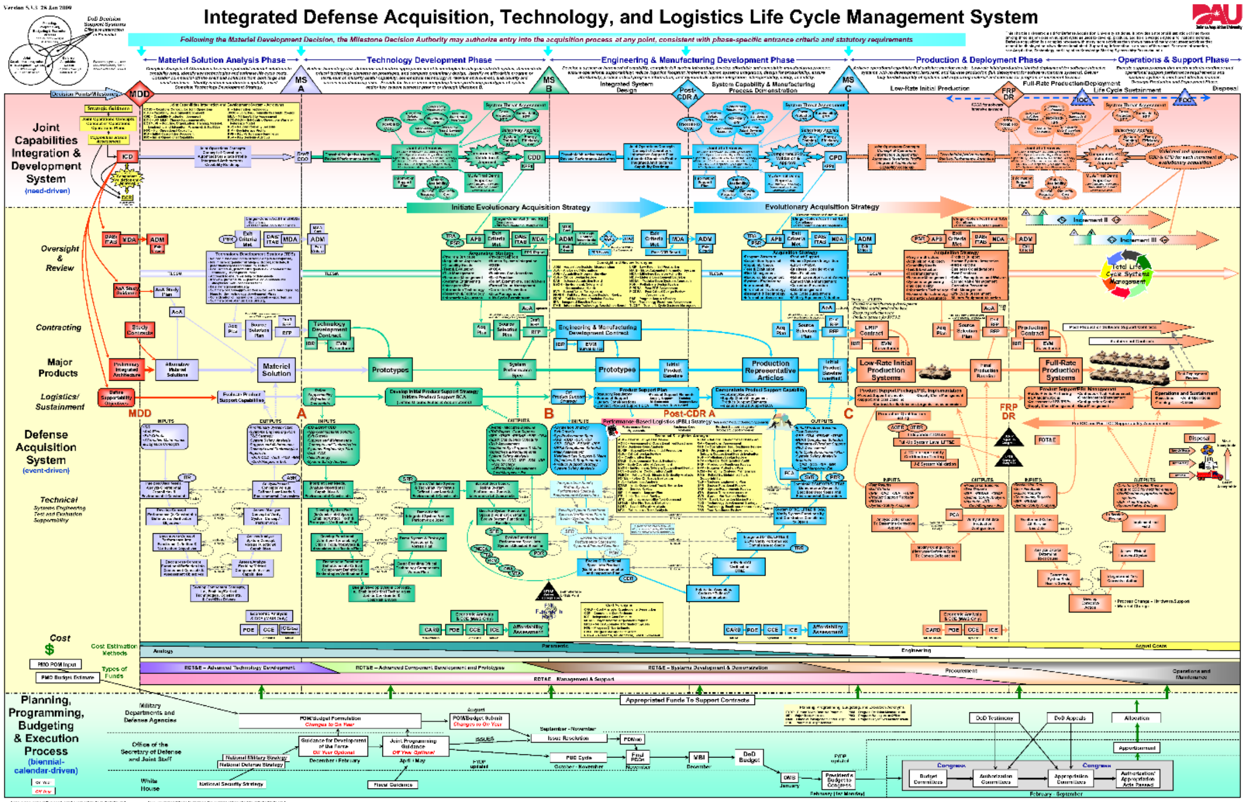

Figure 2: Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System (Defense Acquisition University, 2009)

Due to the scope of this research, this diagram was not ideal for the time frame given to perform our analysis. Thus, we synthesized the information from both existing models forming a new model (swim lane model, Figure 3) that was executable within our given time frame.

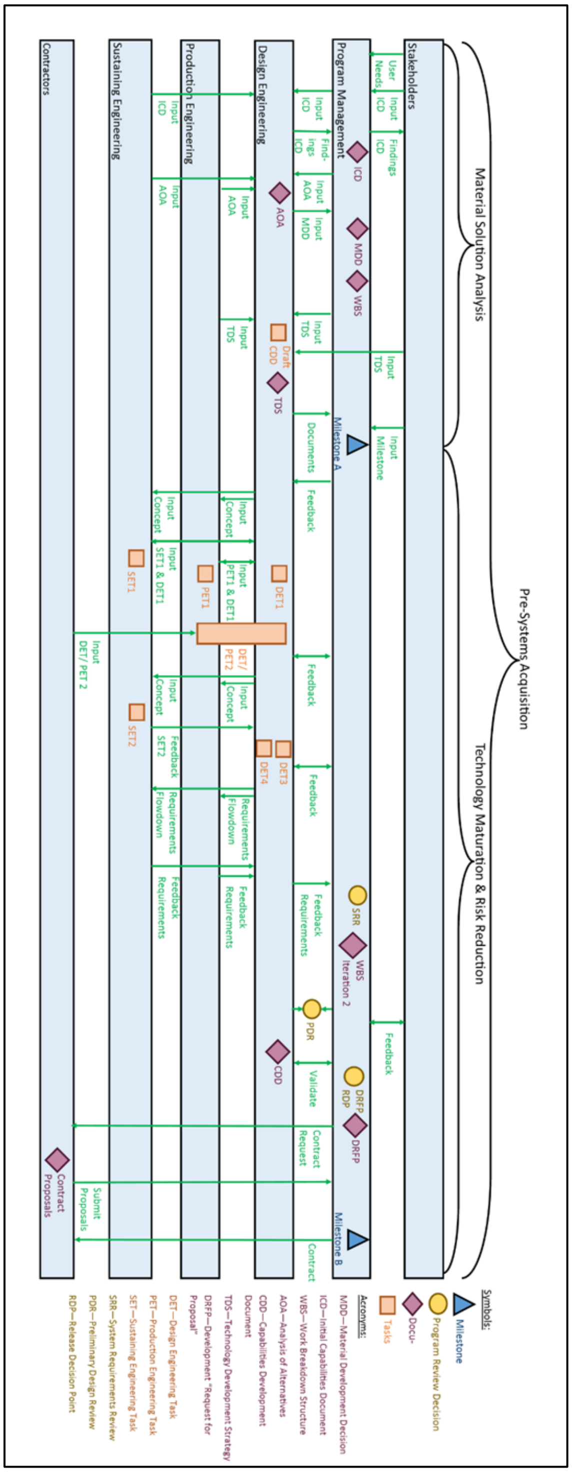

Figure 3: Swim Lane Model Depicting Processes Within the DoD System Acquisition Life Cycle

The swim lane model[1] encompasses DoD System acquisition processes from the inception of acquisition process to Milestone B. To reduce scope for demonstration, the model was furthered reduced to processes between Milestone A and Milestone B for evaluation in the optimization problem of this paper. The swim lanes represent the tasks and interactions between the “Stakeholders”, “Program Management”, “Design Engineering”, “Production Engineering”, “Sustaining Engineering”, and “Contractors”. Each swim lane contains several actors within the DoD which were grouped within these categories based on the functions they are described to perform by the DoD 5000.02 Instruction, Defense Acquisition University’s Integrated Defense Life Cycle Management System visualization, and the DoD Product Support Implementation Roadmap. For example, the “Product Support Management” as stated in the *DoD Integrated Product Support Implementation Roadmap* diagram would fall into the “Product Management” swim lane (Department of Defense, 2012). The elements within the swim lanes are grouped within four major categories: Milestones, Program Review Decisions, Documents, and Tasks. The Milestones, Program Review Decisions, and Documents are referenced in the instructional and GAO literature. We created the Tasks to capture steps within the life cycle that must be accomplished but are not given a formal title within the DoD literature. A description of each of the tasks are provided in Table 1.

Table 1: Swim Lane Model Task Descriptions

Task Label	Task Description
DET1	Evaluate program integration and potential risks based on Milestone A results
PET1	Evaluate potential production needs based on Milestone A results
SET1	Evaluate potential support and maintenance needs based on Milestone A results
DET/PET2	Perform competitive prototyping
SET2	Define support objectives based on competitive prototyping results
DET3	Develop system architecture
DET4	Develop technical architecture

[1] The researchers would like to again acknowledge Dr. Robert Kenley and Mr. Daniel Dumbacher, both Professors of Engineering Practice at Purdue, for their contribution towards the construction of this model.

In this study, we focus on the "Technology Maturation & Risk Reduction" phase. The Technology Maturation & Risk Reduction phase aims to mitigate potential risks and develop a program plan, budget, and schedule. After this phase, a contractor has been selected to pursue the program and the DoD commits its resources to the development, manufacturing, and fielding of the selected solution. The Technology Maturation & Risk Reduction was partitioned into four phases for evaluation within the optimization problem. Phase 1 begins at the conclusion of Milestone A and ends at the start of DET/PET2. Phase 2 begins at DET/PET2 and ends at the start of DET3 and DET4. Phase 3 begins at DET3 and DET4 and ends at the start of SRR. Phase 4 begins at the start of SRR and ends at the conclusion of Milestone B. The competencies addressed in Wood and the availability of qualitative data describing the program manager's role within the life cycle motivated the selection and partitioning of this phase as well as the time frame of this pilot study.

With the components of the swim lane model articulated, we can now move onto the second major phase of our organizational structure modeling – identifying the program manager competencies that can be effectively mapped onto the swim lane model. In the following sections, we articulate the competencies used, as well as the process we used to map them onto the swim lane model.

Identifying Program Manager Competencies

To map program manager competencies onto this swim-lane model, we needed to first obtain a relatively comprehensive initial list of relevant program manager competencies. For this, we utilized data collected by Wood (2010; 2014) that used a set of 35 program manager competencies indicative of the major capabilities that influenced how successful a program manager would be. Specifically, these were designed to assess the program manager competencies that "can be used in drafting project management interviewing questions, developing appraisal models to select the most qualified project managers for promotion, and designing job descriptions for project managers that can be tailored by an organization to clearly outline the roles, duties, and responsibilities of a project manager" (Golob, 2002, p. 7). These competencies were developed based upon a literature review, subject-matter expert reviews, and two surveys of program managers and the managers of program managers. A more detailed explication of these and this process can be found in Golob (2002).

These 35 competencies that resulted from this process were posited to measure 20 technical (or “hard” skills), and 15 behavioral (or “soft” skills). However, as has been posited recently in the program manager literature (Nijhuis, Vrijhoef, & Kessels, 2015) these individual program manager competencies likely are subcomponents that are attributable to more general, higher-order taxonomies of competencies from the general management/organizational psychology literatures. For example, Nijhuis et al., (2015) found that these higher-order taxonomies were effectively able to integrate the diversity of program manager competencies that had been identified in the extant literature. For example, the two “soft skill” competencies of “Project leadership” (i.e., the ability to set a vision, identify the action steps, motivate others to maintain their commitment to program success, and the ability to influence a team to willingly work toward predetermined program objectives) and “Facilitation” (i.e., the ability to facilitate or guide team members through a process that helps them discover answers and overcome barriers to successful program completion) likely map onto the higher-order managerial competency of “Leading and Deciding” that has been well-validated within the general managerial/organizational psychology literatures (Kurz & Bartram, 2002; Bartram, 2005). Thus, while these 35 competencies are a great start, to make them practically useful for our optimization problem, as well as more theoretically parsimonious, it is important for us to map them onto these higher-order managerial competencies.

For this higher-order managerial competency mapping, we used the Great Eight model of managerial competencies (Bartram, 2005; Kurz & Bartram, 2002). These researchers defined competencies as “sets of behaviors that are instrumental in the delivery of desired results or outcomes (Bartram et al., 2002, p. 7). The Great Eight competencies represent a parsimonious representation of the domain of managerial competencies that exist in the extant literature. The Great Eight structure has been extensively validated and refined. This refinement has created not only the broad Great Eight, but 112 component competencies that underlie the eight core dimensions. The eight core dimensions are Leading and Deciding, Supporting and Cooperating, Interacting and Presenting, Analyzing and Interpreting, Creating and Conceptualizing, Organizing and Executing, Adapting and Coping, and Enterprising and Performing.

Due to the high degree of conceptual overlap between our 35 program manager competencies and the Great Eight dimensions, we used the Great Eight as the basis for our higher-order managerial competencies. To link our 35 competencies to the Great Eight dimensions, we engaged in an iterative process of mapping the individual competencies onto the broad Great Eight. Once complete agreement of the mapping was established between all members of the research team, this mapping was finalized. With this mapping in hand, we can parsimoniously integrate these program manager competencies into our swim lane.

Deriving Baseline Great Eight Ratings from Qualitative Data

In this part, we derive a set quantitative ratings for each of Great Eight dimensions where each rating represents the degree to which each Great Eight dimension is important towards accomplishing the acquisition tasks in the swim-lane model; these ratings are considered to be "baseline" as they each represent an aggregate, required rating for each Great Eight dimension, based on the qualitative data from the GAO reports. To accomplish the task of generating these baseline values, it becomes necessary to properly map the program manager competencies from Wood (Wood 2010) onto the swim-lane model, through integrating the qualitative data available from the GAO reports and instructional documentation with the Wood competencies. Specifically, we utilized information regarding the tasks and competencies required at each stage of the swim-lane model to determine the importance of each competency for successful performance of the program manager at that stage in the life cycle. As articulated previously, rather than mapping each of the 35 specific competencies used within the Dr. Wood's research, we use the higher-order Great Eight dimensions that these 35 specific competencies correspond to as depicted in Table 2. This reduces our mapping from 140 ratings (i.e., 35 competencies x 4 phases) to 32 (i.e., 8 competencies x 4 phases) that is more theoretically and empirically parsimonious due to the aggregation of theoretically-redundant competencies.

Table 2: Placement of the Roy Wood Competencies to the Great Eight Dimensions

Great Eight Competencies	Roy Wood Competencies
Leading and Deciding	Document program assumptions; Implement corrective action; Project leadership; Facilitation
Supporting and Cooperating	Trustworthiness; Issue and conflict resolution; Coaching
Interacting and Presenting	Communicated program status; Negotiations; Setting and managing expectations; Communication style; Listening skills; Team building
Analyzing and Interpreting	Document program constraints; Measure program performance; Implement change control; Conduct administrative closure; Problem solving
Creating and Conceptualizing	Define program strategy; Decision making
Organizing and Executing	Determine program goals; Determine program deliverables; Quality assurance; Identify resources requirements; Develop a budget; Create a work breakdown structure (WBS); Develop a resource management plan; Establish program controls; Develop program plan; Organizational Skills
Adapting and Coping	Respond to risk; Flexibility
Enterprising and Performing	Technical ability; Sound business judgement

The process of mapping the Great Eight dimensions onto the swim-lane model was done via a systematic coding process. First, aggregated qualitative data from the GAO reports and instructional documentation were reviewed by a two-person cross-discipline team (an example of this aggregated data can be found in Table 3).

Table 3: Example of the Qualitative Aggregated Data Used to Map the Competencies to the Life Cycle Phases

Phase 3: Requirements Development Qualitative Data	
Instructional Documentation Summary	The Requirement Development effort involves tasks DET3 (develop system architecture) and DET4 (develop technical architecture), as well as, the program review decision SRR (System Requirement Review). The goal is to reduce risk and create a set of requirements which will create a baseline for the program to be presented at the PDR. The resulting requirements are additionally used in the CDD, RFP, and Milestone B.
Instructional Documentation Sources	Department of Defense, Department of Defense Instruction Number 5000.02, 2015; Department of Defense, DoD Integrated Product Support Implementation Roadmap, 2012; Defense Acquisition University, Integrated Defense Life Cycle Management System, 2004
Instructional Documentation Representative Quotes	"The point at which the major cost and performance trades have been completed and enough risk reduction has been completed to support a decision to commit to the set of requirements that will be used for preliminary design activities, development, and production (subject to reconsideration and refinement as knowledge increases)" (Department of Defense, 2015). "Capability requirements are not expected to be static during the product life cycle. As knowledge and circumstances change, consideration of adjustments or changes may be requested by acquisition, budgeting, or requirements officials" (Department of Defense, 2015).
GAO Reports Summary	The Requirements Development phase is hindered by the continual changing of key requirements throughout the acquisition life cycle and the lack of proper requirements development before Milestone B.
GAO Sources	GAO-08-674T, 2008; GAO-06-110, 2005; GAO-16-489T, 2016
GAO Representative Quotes	"we found four factors that have the potential to impact acquisition outcomes on individual programs: (1) unsettled requirements in acquisition programs can create significant turbulence including increased cost growth" (GAO, 2008) "Second, they (users/contractors) cannot veto new requirements. Faced with long development life cycles and promising technology advances, users often ask for new or better capabilities as a program proceeds forward. Program managers themselves are not always empowered to say "no" to demands that may overly stretch their programs, and few senior leaders above them have been willing to" (GAO, 2005). "Because DoD does not yet have approved requirements and is not planning to hold a Milestone B review, its approach for Block 4 modernization will not require the program to have such important cost, schedule, and performance reporting and oversight mechanisms in place" (GAO, 2016).

The two-person coding team consisted of one engineering graduate student with expertise in the intricacies of the program management/engineering life cycle, with the other being a doctoral student in organizational psychology, with expertise in leadership competencies and job performance. During the review of the aggregated GAO reports/instructional documentation, this team discussed each stage of the project life cycle, the tasks involved, how each phase fed into those which followed, and the metrics for successful performance at each phase. Once a similar frame-of-reference was created, the team discussed each of the Great Eight dimensions (considering both the general dimension, as well as the specific Roy Wood competencies underlying it) and its relevance to each phase. After the general relevance was thoroughly articulated by both members of the team, a consensus as to a numeric rating of importance (ranging from 1-10) for each Great Eight dimension was mapped onto each phase of the swim-lane model, for a total of 32 ratings. The team had 100% consensus as to the final ratings. These final ratings were then used as a baseline in the development and execution of the optimization model and are presented in Table 4.

Table 4: Great Eight Mapping to Lifecycle Phases and PM Archetypes

	Acquisition Lifecycle Phase				Program Manager Archetype			
	Loop 1 - Post A Concept Dev	Loop 2 - Prototyping	Loop 3 - Req. Dev.	Loop 4 - SRR to DRFP	PM Type I	PM Type II	PM Type III	PM Type IV
Leading & Deciding	8.0	7.5	9.5	3	9	7	6	6
Supporting & Cooperating	4.5	6.5	6.5	6.5	9	6	7	3
Interacting & Presenting	9.0	9	5.5	10	7	5	4	3
Analyzing & Interpreting	2.5	5	3.5	4	5	6	3	3
Creating & Conceptualizing	2.0	8	8	6.5	5	9	9	2
Organizing & Executing	2.0	4.5	3	7.5	6	9	9	1
Adapting & Coping	2.0	4.5	2	5	3	5	5	4
Enterprising & Performing	7.0	7	8	7.5	5	5	7	3

Table 4 shows both the Great Eight Mapping assessment scores that were ascertained for each of the four studied phases of the total defense acquisition lifecycle; columns (1-4) provide estimated numerical values of required level of competence, in each of the Great Eight dimensions, for the corresponding lifecycle phase. Table 4 also shows a set of notional Great Eight Mapping scores for four classifications (columns 5-8) of program managers (here, we *assume* that there exist four archetypes of program managers, each with a different distribution of Great Eight Mapping strengths). While the values and number of program manager archetypes in this example problem are for illustrative purposes only, we note that there are well known quantitative methods that can be used to solicit such values in real world situations. For example, clustering algorithms such as *hierarchical clustering* can be used to quantitatively determine the number of clusters, and, the values of Great Eight dimensions for program managers in each cluster, given a large survey pool and survey instrument that is executed to extract relevant information.

Modeling Complex System Structures

The complex system is modelled as an interconnected set of systems or 'nodes' that each have a finite set of inputs and outputs. The interconnections characterize how node capabilities (outputs) feed and consequently fulfill requirements (inputs) of any connected compatible node. Figure (4 a & b) show a generalized representation of a complex system which has interdependencies between constituent systems, across multiple layers of the hierarchical structure. Each node (system) is connected to other nodes on the network, in accordance with the set of requirements needed for them to interdependently operate. The connections between nodes are also governed by a set of interaction rules. Interactions between systems are modeled as relatively simple nodal behaviors that are applicable to a wide variety of types of inter-system connections. While not exhaustive, the combinations of these nodal behaviors as modeling rules can cover a large set of real world inter-system interactions.

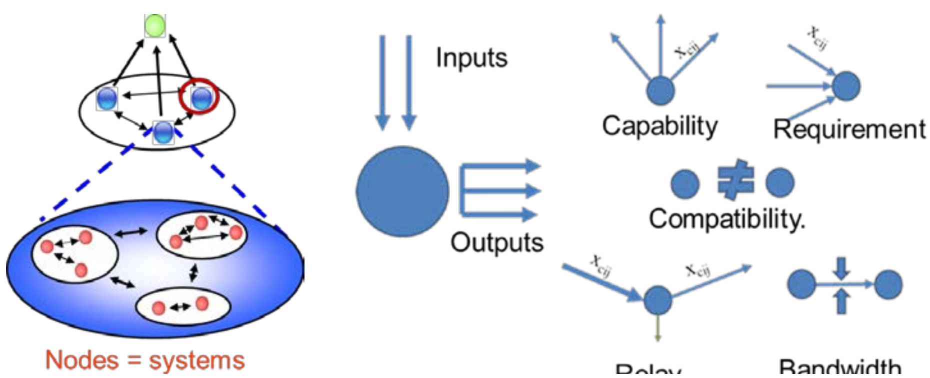

Figure 4 - (a) Complex System hierarchy (b) nodal (system) behaviors

Figure 4 (b) shows the five most intuitive system (node) interactions, consisting of:

- Capability: systems have finite supply of capabilities that limit the number of connections they may form.
- Requirements: System requirements are fulfilled by receiving connections from other nodes that possess a capability to fulfill said requirements.
- Relay: Systems can relay capabilities between adjacent system. This can include excess input of capabilities that are used to fulfill node requirements.
- Bandwidth: Total amount of capabilities and number of connections between systems are bounded by 'bandwidth' of the connection linkages between systems.
- Compatibility: Systems can only connect to other systems based on a pre–established set of connection rules.

The performance of the complex system is related to the ability of the connected network of individual systems to fulfill overarching core objectives. System-wide performance is quantified by the capability of nodes that most directly contribute to the core objectives.

Optimal Organizational Structure and Complex System Structure: An Optimization based Approach

We pose the task of selecting the optimal organizational architecture and complex system architecture as a mathematical optimization problem involving two main segments. The first segment of an optimization problem involves an *objective function* equation that is either maximized or minimized, depending on the metric that is being used. The second segment involves a set of equations called *constraints* that reflect rules as in Fig. 4(b). A simple example of a mathematical program is the maximization of expected stock investment returns, subject to constraints on availability of funds to invest, where the decision variables are, which stocks to buy, and how much to buy of each stock.

The problem of selecting an optimal complex system architecture and its organizational architecture is more specifically posed as a multi-objective optimization problem that addresses both an index that describes the level of performance for a chosen product architecture, and, the uncertainty in program manager performance allocated across the selected architecture. (In the simple case of the stock problem, the notion is tradeoff between expected portfolio returns and risk). The decision variables involve which systems to select in the product architecture and which program manager types to be assigned to systems that need to be developed (we explain 'types' in the subsequent section).

Concept Application: Naval Warfare Scenario Acquisitions

Our naval warfare scenario concept application problem is based on developing a complex military system, through selection of constituent modular systems from a candidate set, and, allocating DoD program managers in a way that maximizes the complex system performance, while minimizing risks associated with mismatches between program manager competencies and individual system development. The performance of the complex system is based on an aggregated performance index of its constituent systems, and, risks of mismatches between program manager competencies and system development are reflected in each program manager's competencies in executing the "Technology Maturation & Risk Reduction" phase of the defense acquisition lifecycle.

Table 5 - Candidate systems or naval warfare scenario

		SoS Capabilities (Outputs)			Capabilities (Outputs)				Cost	Num Power	Num Comm	TRL
No.	System Name	SoS CAP 1	SoS CAP 2	SoS CAP 3	Power.	Comm.	Power Req.	Comm Req.	[$]	Links	Links	
1	Control Station 1	150	0	0	150	0	0	0	$10,000.00	3	3	9
2	Control Station 2	300	0	0	300	0	0	0	$20,000.00	3	3	9
3	Control Station 3	450	0	0	450	0	0	0	$300,000.00	3	3	9
4	Control Station 4	600	0	0	600	0	0	0	$400,000.00	3	3	6
5	Control Station 5	750	0	0	750	0	0	0	$500,000.00	3	3	4
6	First Satellite 1	0	0	100	0	0	75	95	$500,000.00	3	3	9
7	First Satellite 2	0	0	200	0	0	125	150	$650,000.00	3	3	9
8	First Satellite 3	0	0	300	0	0	150	250	$750,000.00	3	3	7
9	First Satellite 4	0	0	400	0	0	175	350	$850,000.00	3	3	5
10	First Satellite 5	0	0	500	0	0	185	450	$900,000.00	3	3	4
11	UAV-1	20	0	0	0	0	100	0	$200,000.00	3	3	9
12	UAV-2	30	0	0	0	0	200	0	$300,000.00	3	3	9
13	UAV-3	40	0	0	0	0	300	0	$400,000.00	3	3	4
14	UAV-4	50	0	0	0	0	120	0	$450,000.00	3	3	3
15	UAV-5	60	0	0	0	0	300	0	$500,000.00	3	3	2
16	Carrier Ship -1	0	5	0	0	0	50	0	$500,000.00	3	3	9
17	Carrier Ship -2	0	10	0	0	0	150	0	$600,000.00	3	3	9
18	Carrier Ship -3	0	20	0	0	0	200	0	$700,000.00	3	3	2
19	Second Satellite 1	0	0	100	0	100	0	0	$50,000.00	3	3	9
20	Second Satellite 2	0	0	200	0	200	0	0	$60,000.00	3	3	9
21	Second Satellite 3	0	0	300	0	300	0	0	$70,000.00	3	3	7
22	Second Satellite 4	0	0	400	0	400	0	0	$80,000.00	3	3	3
23	Second Satellite 5	0	0	500	0	500	0	0	$90,000.00	3	3	3

Table 5 lists a catalogue of modular systems and their hypothetical characteristics. The table shows 23 available systems that can be acquired towards development of an overarching capability, across 5 classes of systems (Control Station, First Satellite, UAV, Carrier Ship, Second Satellite). The first three columns (SoS CAP1, SoS CAP 2, SoS CAP 3) list outputs of system level capabilities that directly contribute to the top-level performance of the overall complex systems. For example, Control Station 1's SoS Cap1 contribution of 150 refers to a capability of 150Mbps of communication bandwidth that contributes directly to the overall performance index of the complex system in general. Columns three and four are capabilities that do not contribute directly to the top-level performance index, but contribute to satisfying constraints at a lower level of abstraction; for example, the same Control Station 1 generates 150 units of power that can be distributed to other systems that connect to it. While power is an output of Control Station 1, it is not a capability that directly contributes to the top-level capabilities of the overall complex system. Columns 5-6 are the requirements of each system. Column 7 reflect acquisition costs. Column 8 and 9 reflect the number of other systems can link to each system; this constraint, for example again in the case of Control Station 1, to be able to provide power to up to 3 other systems that connect to it.

The last column is the Technology Readiness Level (TRL) of each system. We assume that high TRL numbers denote a commercial off the shelf type of system that has relatively straightforward acquisition processes in place, where as a lower TRL level system will require the assignment of a program manager to develop and mature the system towards final acquisition. We assume a finite number of each type of program manager that are available to be assigned to each system listed in Table 5. For simplicity, the measure of performance of each program manager type, in executing acquisition tasks listed in Table 1, is defined as the Euclidean norm of program managers dimensional scores (columns 5-8) that are less than the estimated required values (columns 1-4). The overall performance of the program manager in executing acquisition tasks is taken as simply the average Euclidean norm values across the four loops – here, we term this as an ‘average risk’. Values of the average risk and population of program managers for each type are tabulated in Table 6.

Table 6 - Concept problem program manager population per type

PM Type	Population	Average Risk
I	2	4.1
II	2	5.3
III	2	4.7
IV	2	10.1

Mathematical Formulation: Mixed Integer Programming (MIP)

We model our concept model decision problem as a mixed integer program (MIP). MIP models and methods of solution have been long studied, and, have matured to a point of being widely used across multiple areas of application such as product planning, scheduling, finance and asset management, network design, and even auction mechanisms. While MIPs are generally NP-hard class of mathematical problems (very hard to solve), the great advances in methods of solution has seen the development of many industrial grade solvers and intelligent formulations of problem that enables solution of even very large problems (up to millions of decision-variables). More recent research in MIP such as by Bertsimas (2004,2012, 2014) has included the ability to efficiently account for parametric uncertainty, intransitivity (in the case of decision sciences and marketing), and even preferential data.

We formulate our concept problem of maximizing a complex system's performance while minimizing program manager competency related risks as a multi-objective optimization problem. We adopt a modified version of a prior optimization model by Davendralingam (2012) that views a complex systems architecture as a collection of nodes with interdependency rules that govern their connectivity.

The resulting mathematical program is as follows:

$$\max\left(\frac{\sum_i S_{ic}\cdot w\cdot x_i^B - R_c}{R_c}\right) \quad \textbf{(1)}$$

subject to:

$$\sum_i x_{cij} \geq x_j^B S_{rj} \quad \textbf{(2)}$$

$$\sum_j x_{cij} \leq x_i^B C_{ci} \quad \textbf{(3)}$$

$$x_1^B + \dots + x_n^B = T \quad \textbf{(4)}$$

$$\sum_c x_{cij} - x_{ij}^{c_{bin}} M \leq 0 \quad \textbf{(5)}$$

$$M\sum_{c} x_{cij} - x_{ij}^{c_{bin}} \geq 0 \quad \textbf{(6)}$$

$$\sum_{i} x_{ij}^{c_{bin}} \leq n_{\max} \quad \textbf{(7)}$$

$$\sum_{i} x_{cij} - \sum_{j} x_{cij} - x_{j}^{B} S_{rj} = 0 \quad \textbf{(8)}$$

$$\sum_{i} x_{iq}^{PM} - x_{q\in Q'} M \leq 0 \quad \forall q \in Q_{TRL<8} \quad \textbf{(9)}$$

$$M\sum_{i} x_{iq}^{PM} - x_{q\in Q'} \leq 0 \quad \forall q \in Q_{TRL<8} \quad \textbf{(10)}$$

$$\sum_{t} x_{tq}^{PM} \leq 1 \qquad \forall q \in Q \quad \text{t=1...4} \quad \textbf{(11)}$$

$$C_{req}^{PM} x_{iq}^{PM} \leq C_{cap}^{PM} x_{iq}^{PM} \quad \forall q \in Q_{TRL<4} \quad \textbf{(12)}$$

$$C_{req}^{PM} x_{iq}^{PM} \leq E_{\max} \quad \textbf{(13)}$$

$$x_{cij} \in \text{real, integer}, x_{q}^{B} \in \text{binary}, x_{iq}^{PM} \in \text{binary}, x_{ij} \in \text{binary}$$

where:

S_{ic} - capability (c) of system (i)
w, - weighting factor vector of SoS capabilities (constant)
x_{ib} - binary decision variable for selecting system (i)
R_c - base SoS capability for normalization
x_{cij} - quantity of capability (c) between system (i) and (j)
x_{ij} - adjacency matrix (binary) that indicates connection between systems (i) and (j)
S_{rj} - requirement (r) of system (j)
M - Big-M constant value
Q - set of all possible system choices (q = 1 … 23)

The mathematical model as represented by equations (1-13) represent the formulation of a mixed integer linear programming model. The ‘mixed’ term denotes the existence of both integer and continuous decision variables. Equation 1 is the objective function that represents the maximization of the overall complex system capability index. Here, the capability index is the normalized sum of capabilities of the complex system level capabilities (columns one to three in Table 5), where the normalization is done with respect to some lowest common denominator, R. Equation (2) ensures that for each system type (j) selected, there is sufficient capability type (C) being received from other connecting systems (i) that can satisfy the requirement type (R). Equation (3) ensure that the amount of capability provided by each system, type (i) for each capability type (c) does not exceed the maximum capability of type (c) for the system. Equation (4) generically defines mutual exclusivity rules for systems – for example, if selection of system 1 (x1) and system 2 (x2) is a mutually exclusive condition, then the constraint would be (X1+X2 ==1) where x1 and x2 are binary variables and constant T denotes the condition that the sum of the can only result in 1 system. Equations (5) and (6), more specifically, follow a 'Big-M formulation' that facilitates the calculation of the number of connections that can be made to individual nodes. Equation (7) constraints the number of connections that can exist for each system type (i) and for each capability type (c) for the system. Equation (8) enforces that the total of some capability (q) that is supplied to a node (e.g. power flow or communications bandwidth), combined with its inherent capability (q) is not exceeded by demand for the capability from connected nodes.

Equations (9) and (10) jointly enforce that if a system type (q) is selected from the set of systems that have a TRL level less than 9, then a program manager must be assigned to the system. Equations (9-10), like equations (5-6), employ the use of a Big-M formulation where the pairs of constraints act as logical conditions. Equation (11) set the condition that only up to one program manager from the 4 types (t) can be assigned to each system. Equation (12) imposes the condition that for each system type (q) that belongs to the set of systems with a TRL of level 5 or below, the program manager assigned to the system needs to have a Great Eight competency score that at least meets the score for the requirements of a critical subset of the Great Eight in columns 1-3 of Table 4; these critical subsets are for the top 3 highest scores for the loops (1-2). Equation (13) limits the total performance error, accumulated due to assigning program managers across different systems, to a maximum value of E_{max}; this value is varied to generate an efficiency frontier that trades off the overall complex system performance against the uncertainty in overall program manager performance. It must be noted that while equation (13) is a linear equation and is reflective of the relatively simple model used for our concept problem, it does not detract from more complex forms of modeling for program manager performance. With a richer collection of data, approaches that account for more explicit interdependencies between program manager interactions, when allocated to systems, can be modeled in quadratic forms (Davendralingam 2012) that can be efficiently included in the current modeling framework, even under conditions of data uncertainty. Furthermore, there are a range of robust optimization techniques that can be applied to address data uncertainty as well (Davendralingam 2012).

Concept Application: Results

The resulting optimization model as represented by equations (1-13) is solved in MATLAB 2016b using the YALMIP toolbox with the GNU Linear Programming Kit (GLPK) solver. The problem is solved for a bounded range of values of $E_{\max}$ in equation 13 ($5 \le E_{\max} \le 50$) to generate the Pareto frontier that trades off the overall complex system capability index (optimal values of the objective function) against overall program manager performance risk; this includes Pareto filtering to only include non-dominated solutions on the efficiency frontier. Figure 5 below shows the filtered Pareto frontier generated by solving the optimization model for each range value of $E_{\max}$. Table 7 provides the breakdown of selected modular systems that comprise the portfolio of systems within the overall complex system, and, program manager allocations across each portfolio point on the efficiency frontier.

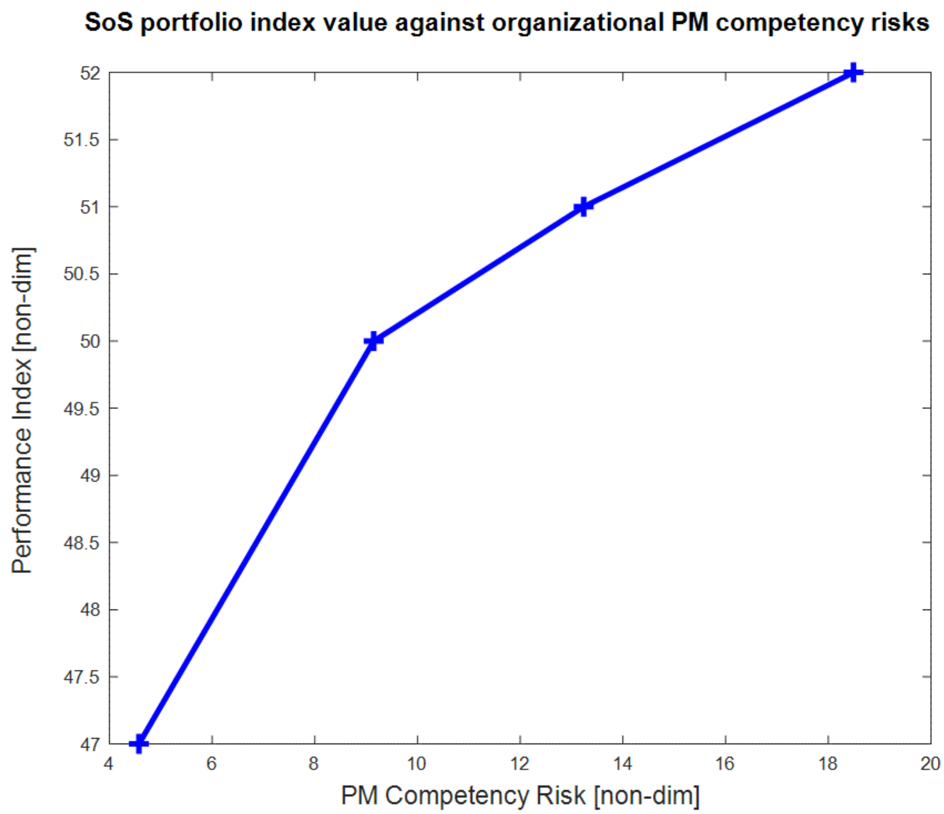

Figure 5 - Efficiency Frontier of Performance against PM competency risk (risk measured as average mean squared error)

Table 7 – Portfolio of systems and program manager allocations

No.	Candidate Systems	Portfolio 1	Portfolio 2	Portfolio 3	Portfolio 4
1	**Control Station 1**	-	-	-	-
2	**Control Station 2**	-	-	-	-
3	**Control Station 3**	-	-	-	-
4	**Control Station 4**	-	-	-	-
5	**Control Station 5**	X	X	X	X
6	**First Satellite 1**	-	-	-	-
7	**First Satellite 2**	X	-	-	-
8	**First Satellite 3**	-	-	-	-
9	**First Satellite 4**	-	-	X	X
10	**First Satellite 5**	-	X	-	-
11	**UAV-1**	-	-	-	-
12	**UAV-2**	X	X	X	X
13	**UAV-3**	-	-	-	-
14	**UAV-4**	-	-	-	-
15	**UAV-5**	-	-	-	-
16	**Carrier Ship -1**	-	-	-	-
17	**Carrier Ship -2**	X	X	X	-
18	**Carrier Ship -3**	-	-	-	X
19	**Second Satellite 1**	-	-	-	-
20	**Second Satellite 2**	X	X	-	-
21	**Second Satellite 3**	-	-	-	X
22	**Second Satellite 4**	-	-	X	-
23	**Second Satellite 5**	X	X	X	X
Program Manager Type		**# of PMs (system # PM allocated to)**			
I		-	-	1 (9)	-
II		-	-	-	2(9,21)
III		1 (23)	2 (23,10)	2(22,23)	2(18,23)
IV		-	-	-	-

The results generated through solving the optimization problem of Equations (1 -13) provides a way for decision-makers to assess potential tradeoffs between selecting different complex system architectures (here, portfolio of interconnected modular systems), and organizational architecture (here, program manager type allocations) by relegating some combinatorial aspects of the problem to the algorithm and delegating decision-making to the practitioner. The results show the progressive levels of complex system performance that can optimally be achieved, given each prescribed acceptable level of risk associated with the program manager performance, for each portfolio. As more capable systems are brought into the picture, to generate a higher performing complex system, program managers are additionally added in an optimized sense, in a manner that bounds risk the sequential increments enforced in equation 13. The program manager allocation also adheres to the rulesets established (for example, the constraints established for allocation of program managers to systems with TRL<9 and TRL<5 as established in prior sections). While an initial instinct may be to first select program managers that are, on average, the 'least risky' following Table 6, we see instead that the optimization selects program manager Type III in Portfolio 1 and Portfolio 2, due to the enabling effect that Type III manager has on developing low TRL systems with a higher potential to improve the complex system performance index. Another useful observation of the results presented, is that the solution generated by the optimization routine, reveals potential pathways for evolving an architecture; for example, when considering portfolios 3 and 4, we observe that a future upgrade from portfolio 3 to 4 will include retirement of Carrier-Ship 2 and a Second Satellite-2 unit, in favor of a Second Satellite-3 unit and a Carrier-Ship 3; this path of system addition and replacement is complemented by the need to replace a Type I program manager with 2 Type II program managers to facilitate the architectural transition. Early stage knowledge on such shifts, can enable the correct requirements to be set on what type of program managers to look for or train for these future updates, thereby minimizing risks and organizational misalignments.

As the number of candidate systems increases, and, the dependencies increase as well, it becomes very difficult to objectively select systems that constitute a complex system, and, program managers that manager each of the constituent systems, without the aid of quantitative means such as that presented in this paper. The mixed integer programming formulation is efficient even for much larger instances of number of systems (and/or number of program manager types), assuming the same problem abstraction being used in this paper. Furthermore, the

MIP perspective lends itself amenable to further formulations of the problem at hand to better account for various forms of interdependencies between product and organization, and, data uncertainty.

Outcomes on Acquisition Decision-making from Concept Problem Demonstration

Results from our concept problem in the naval system acquisition context demonstrate the following contributions of our research:

1. We demonstrated a quantitative approach that can utilize both quantitative and qualitative data (here, the program manager competencies) that relates to both the product architecture (here, the complex system architecture) and organizational structure (here, program manager allocations to selected systems)
2. Outputs of the quantitative framework provide a range of candidate solutions that comprise of both candidate complex system architectures, and, accompanying allocation of program managers for each candidate complex system architecture.
3. The quantitative framework is based on a highly flexible mathematical modeling technique that can incorporate many types of connectivity behaviors between complex system modules (here, individual systems), and, the organizational structure (here, program managers). Furthermore, the complexity of the algorithm does not require the user to manipulate variables or settings that require additional domain knowledge; as evidenced in our concept problem, the only information a user would need to manipulate is input data, and, interpretation of outputs that do not contain any extraneous information unique to the method used.
4. The quantitative approach uses mixed integer programming techniques which are well-known to be able to handle much larger number of decision variables than in the concept problem presented.

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Project Summary and Suggested Next Steps

This research presented an initial quantitative framework that provides acquisition practitioners with the means to optimally determine both the organization's structure and complex system architecture that the organization seeks to develop towards achieving some desired capability. The work explored the status quo on research related to organizational structuring, complex system development, and, algorithmic innovations that can potentially unify decision-making related to both components within a computationally tractable quantitative decision-support framework. We have demonstrated the framework for a conceptual naval acquisition scenario where the objective is to select modular systems that constitute a complex system, and, assign program manager types to each selected system, in a manner that maximizes overall performance.

Our research has led to the following conclusions:

- Further research and expansion of the framework to include the most salient organizational elements considered by practitioners (e.g. explicit system level information threads available to each section of the organization)
- Continued development of a quantitative framework for the optimal selection of organizational structuring, and, complex system development, under varied core strategic organizational visions – for example, an organization seeking to innovate and evolve its complex system architecture, will be different than say an organization that seeks to improve the reliability and efficiency of its existing complex system architecture.
- Explorations on the use of knowledge management perspectives such as Model Based System Engineering (MBSE), to help provide relevant information to the quantitative framework in this research, in realistic and forward-thinking applications.

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