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THESIS

**SYSTEMS DYNAMICS IN PROJECT MANAGEMENT:
SHIFTING THE MENTAL MODEL AND
IMPROVING OUTCOMES**

by

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SHIFTING THE MENTAL MODEL AND IMPROVING OUTCOMES**

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ABSTRACT

As DOD acquisition outcomes continue to fall short on time, cost, and performance benchmarks, it has become evident that project managers need to reevaluate how major defense projects are estimated, managed, and evaluated. This report presents an overview of the Systems Dynamics (SD) theory, process, and application to large engineering and acquisition projects. An SD analysis strives to provide additional context and understanding of system behavior, enabling project managers to better understand the systems under their influence and improve outcomes. The SD theory is applied in a case study of the Remote Minehunting System (RMS) to demonstrate its applicability to the DOD. The analysis uses applied SD theory to move beyond a reconstruction of the RMS' program management. It strives to describe system behavior in relation to outcomes described by the independent analysis, which determined poor acquisition outcomes were the result of changes in procurement quantity, poor performance by the government, and erroneous baseline estimates for cost.

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Actual Cost
ACAT	Acquisition Category
ADM	Advanced Development Model
AMCM	Airborne mine countermeasures
Ao	Operational Availability
APB	Acquisition Program Baseline
APUC	Average Procurement Unit Cost
CDD	Capabilities Development Document
CT	Contractor Testing
DLS	Data Link Subsystem
DOD	Department of Defense
DOT&E	Director of Operational Test and Evaluation
DT	Developmental Testing
EDM	Engineering Development Model
EV	Earned Value
FEED	Front End Engineering Design
GAO	Government Accountability Office
IDA	Institute for Defense Analysis
IOC	Initial Operational Capability
IOT&E	Initial Operational Testing and Evaluation
KPP	Key Performance Parameter
LCS	Littoral Combat Ship
LRIP	Low-rate Initial Production
L&RS	Launch and Recovery Subsystem
MCM	Mine Countermeasures
MIL-STD	Military Standard
MNS	Mission Needs Statement
MTBOMF	Mean Time Between Operational Mission Failure
NAVO	Naval Oceanographic Command
NSWCPCD	Naval Surface Warfare Center Panama City Division

OA	Operational Assessment
ONR	Office of Naval Research
ORD	Operational Requirements Document
OT	Operational Testing
OT&E	Operational Test and Evaluation
PAUC	Program Acquisition Unit Cost
PEO MIW	Program Executive Officer, Mine Warfare
PMBOK	Project Management Body of Knowledge
PV	Planned Value
RDT&E	Research, Development, Test, and Evaluation
RHIB	Rigid-hulled Inflatable Boats
RMFS	Remote Minehunting Functional Segment
RMOP	Remote Minehunting Operational Prototype
RMS	Remote Minehunting System
RMV	Remote Minehunting Vehicle
SAR	Selected Acquisition Report
TECHEVAL	Technical Evaluation
TEMP	Test and Evaluation Master Plan
TOR	Tentative Operational Requirement
VDS	Variable Depth Sensor

EXECUTIVE SUMMARY

The U.S. Government Accountability Office reported in its 2017 assessments of selected weapon programs report that total life cycle costs continue to grow, estimating a total cost growth of \$484 billion in its current portfolio of major defense acquisitions. This report further cites that 49% of programs have declared or intend to declare initial operational capability with little or no operational testing and that 60% of the total cost growth of these programs occurs in late stage engineering or after production starts. The challenges that the U.S. Department of Defense (DOD) faces are not unique to military acquisitions. Dr. Sterman discusses trends that “cost overruns of 100 to 200% are common...Many projects suffer from the ‘90% syndrome’ in which a project is thought to be 90% complete for half the total time required” (Sterman 1992, 2). A more complete, sophisticated, and holistic approach is needed to understand and measure the reality of complex systems in order to allow project managers to gain a better understanding of the consequences of these relationships.

The purpose of this research is to explore the theory and application of system dynamics (SD) and its applicability to the U.S. Department of Defense acquisition projects, program managers, and engineers. This research examines how the application of SD theory can impact a practitioner’s mental model to the benefit of programmatic outcomes. As part of the analysis, the theory of SD is applied to the failed acquisition of Remote Minehunting System (RMS). This research synthesizes research in the application of SD to project management. While the majority of the available research focused on non-DOD applications, the principles are applicable to the management of any large and complex project, to include DOD acquisition projects.

This research begins with a background in the most basic and widely used traditional project management tools used to estimate and evaluate program progress. Each of these techniques relies on an accurate deconstruction of a project into its constituent elements. Decisions on project implementation and resource allocation are reliant on the accuracy of these estimations. The process of estimation is largely informed by the program manager and engineering staff’s mental models. When the underlying

assumptions or situation's change, these tools are unable to provide the decision-maker an accurate understanding of the implications of their decisions. More pointedly, "poor, informal strategic judgement may be the root cause of many project failures" (Rodrigues and Bowers 1996, 125).

SD offers a complementary method to traditional project management techniques in understanding complex and nonlinear behavior within systems. As part of this analysis, the basics of SD theory are provided for background and context to the discussion and analysis. SD is useful for analyzing and communicating how complex interactions cause consequences in non-obvious places at non-linear rates, ultimately impacting the cost, schedule, and performance of a system. Rather than a focus on accurate estimations of an acquisition programs' constituent parts, SD attempts to model the relationships between variables that drive behavior and performance. The process does not replace traditional techniques, but rather seeks to complement them. Additionally, the SD process excels at inclusion of factors that other techniques struggle to capture such as the human (or "soft") characteristics of the system, inclusion of known and unknown rework, and accounting for non-linear relationships. This research analyzes the Department of the Navy's acquisition of the RMS using the concepts of System Dynamics in an attempt to better understand some of the factors that led to the program's poor performance and ultimate cancelation.

The RMS was a key component in the United States Navy's strategic goal of modernizing its mine countermeasures force. The system was "designed to provide off-board mine reconnaissance capability to detect, classify, and localize non-buried bottom and moored mines, and to identify bottom mines in shallow water" (DOD 2016, 309). The program established a Tentative Operational Requirement in 1989, development began in 1998, determined to be in a critical breach of the Nunn-McCurdy act in 2009, and canceled 2016 due to poor reliability. In 2010, the Institute for Defense Analysis (IDA) released a paper outlining the root causes for the Nunn-McCurdy breach as changes in procurement quantity, poor performance by the government, and erroneous baseline estimates for cost.

System characteristics of the RMS, called Program Features in SD terminology, were established for use in the analysis. Seven project features were included in the development of a Casual Loop Diagram (CLD). The CLD provided the framework to look at these project features through the theory of SD. The included project features are: development timeline, changes in scope, subsystem component changes, subsystem component availability, parallel engineering, rework generation, and integration engineering. These project features were linked to programmatic documentation to legitimize them as useful and relevant. Although far from exhaustive, the use of these Program Features allowed for the inclusion of many of the programmatic decisions, circumstances, and outcomes that impacted outcomes.

The CLD was constructed by connecting Program Features using SD theory to establish relationships between features and the system in general. The CLD connects the theory of SD to the RMS' particular behavior and is comprised of three loops, two reinforcing and one balancing. These loops describe individual behaviors observed in the RMS literature in an attempt to give insight to the root causes. These three loops are connected to give a more balanced view or overall system behavior. Finally, the completed CLD was connected to a conceptual model of the rework cycle where conclusions on how system relationships impacted behavior. The interaction between the CLD and the rework cycle allows for the measure of how system behavior results in performance impacts.

This analysis reveals two system characteristics of importance. First, system sub-component updates, specifications changes, or otherwise delayed availability increased the error generation rate and acted in a reinforcing and destabilizing manner on the system; as with many interactions in SD, this relationship is easy to underestimate or overlook entirely. Secondly as the system experienced scope creep, the "Work to be Done" measure within the rework cycle increased; while this finding is non-novel, it is the estimation and understanding of the non-linear impact of scope changes that is of value to the program manager.

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I. INTRODUCTION

A. BACKGROUND

In its 2017 annual review of Defense acquisitions, the U.S. Government Accountability Office (GAO) reports that total life cycle costs for ongoing projects have increased by \$9.4 billion in the past year and \$484 billion in total cost growth. Of note, “60 percent of the total cost growth occurred after programs entered production, when costs should be more stable” (U.S. Government Accountability Office 2017, 2). Additionally, the report cautions that 49% of programs have or intend to declare initial operational capability (IOC) with little or no operational testing (U.S. Government Accountability Office 2017). In its report on knowledge-based approaches to weapons acquisitions, the GAO asserts that the majority of the major DOD acquisitions over the past several decades have underestimated cost and schedules, and programs were committing to “delivering capability without knowing whether technologies being pursued could really work as intended...Problems that surfaced early cascaded throughout development and magnified the risks facing the program” (U.S. Government Accountability Office 2004, 8).

Dr. John Sterman, the current Director of the MIT System Dynamics Group, concisely articulates the challenges facing today’s program managers:

Project management is at once one of the most important and most poorly understood areas of management. Delays and cost overruns are the rule rather than the exception in construction, defense, power generation, aerospace, product development, software, and other areas. Project management suffers from numerous problems of costing and scheduling. Cost overruns of 100 to 200% are common. Projects are often delayed to the point where the market conditions for which they were designed have changed. Many projects suffer from the “90% syndrome” in which a project is thought to be 90% complete for half the total time required. (Sterman 1992, 2)

Solving complex problems requires an iterative and recursive application of effort. A completed task can be acted upon downstream such that work completed previously must be revisited or may be rendered invalid. Even with this knowledge, the predominate view within Department of Defense (DOD) acquisitions is that a linear flow

exists where “one strategic activity is all or the vast majority of what influences the next downstream strategic activity” (Cantwell et al. 2013, 104). System Dynamics (SD) seeks to understand the reality of complex systems, including nonlinear relationships and dynamic feedback loops, in order to allow project managers to gain a better understanding of the consequences of these relationships.

According to a Government Accountability Office Report, 37 DOD acquisition programs have been cited in breach of the Nunn-McCurdy Act since 1997 and 38% of these programs have been in breach more than once. Included in its findings, the GAO report noted that the primary driving factors include engineering and design issues, schedule issues, and quantity changes (Schwartz and O’Conner 2010). Adding to that list, budget pressure, schedule pressure, and changing or undefined requirements are commonly cited as reasons for project failure, both in private and governmental backed enterprises (Meier 2010). Project managers consistently overestimate the amount of work-completed, underestimate the impact of discovered-rework, and functionally ignore the possibility of undiscovered-rework altogether. Although project management in the DOD has existed since its inception, some would assert that as many projects fail as succeed (Cantwell et al. 2013).

The scope and complexity of DOD acquisitions continues to increase as outcomes continue to fall short of initial cost, schedule, and performance estimates. The history of the Remote Minehunting System (RMS) will serve as another example of outcomes falling short of projections. The RMS was a key component in the United States Navy’s strategic goal of modernizing its mine countermeasures (MCM) force. The system was “designed to provide off-board mine reconnaissance capability to detect, classify, and localize non-buried bottom and moored mines, and to identify bottom mines in shallow water” (DOD 2016, 309). The RMS consists of an unmanned semi-submersible vehicle towing a variable depth sensor. The program started in 1989 with a Tentative Operational Requirement (TOR), development began in 1998, it was determined to be in a critical breach of the Nunn-McCurdy act in 2009, and in 2016 the program was cancelled due to poor reliability.

In 2010, the Institute for Defense Analysis (IDA) released a paper outlining the root causes for the Nunn-McCurdy breach: changes in procurement quantity, poor performance by the government, and erroneous baseline estimates for cost. At the time of the Nunn-McCurdy breach, the program office reported to Congress an 85.1% increase of the average procurement unit cost since the acquisition project baseline in 2006 to \$22.4 million per unit. This increase in cost was the result of a reduction of planned procurement quantity from 106 to 52, a reliability growth program initiated in 2009, and unrealistic cost estimation (Bailey et al. 2010). The outcomes in the RMS program are not unique and follow many of the historic trends mentioned above. The factors cited by Schwartz and O'Conner (2016) and Meier (2010) are all underlying factors leading to the root causes of failure in the RMS system and include: immature technology, requirements instability, unrealistic program baselines, high leadership turn over, overreliance on contractors, and blurred accountability lines.

System Dynamics is useful for analyzing and communicating how complex interactions cause consequences in non-obvious places and non-linear rates, ultimately impacting the cost, schedule, and performance of the system. This research analyzes the Department of the Navy's acquisition of the RMS using the concepts of System Dynamics in an attempt to better understand relationships that led to the programs poor performance. First, a background is provided in the most basic and widely used traditional project management tools used to estimate and evaluate program progress. Next, a brief introduction to SD and its application will provide a background on the processes and tools available to the project manager. Lastly, principles of SD are applied in an analysis of the RMS program. This analysis seeks to better understand some of the factors that led to the program's ultimate cancelation.

B. LITERATURE REVIEW

This research synthesizes research in the application of System Dynamics to project management. While the majority of the available research focused on non-DOD applications, the principles are applicable to the management of any large and complex project, to include DOD acquisition projects. Early use of SD in management was pioneered by Professor Jay Forrester in the early 1950s in what was initially called

Industrial Dynamics. Paper-based models were used to seek trends in inventory control systems, allowing for a more analytic approach to their management (Forrester 1996). Dr. Forrester went on to develop management focused computer models based on the emerging idea of feedback-systems that would become the basis for SD. This early work by Dr. Forrester introduced many key concepts that would shape the discipline of system dynamics, including how the theory relates broadly to topics ranging from urban low-income housing to management of business and complex systems.

External forces are often blamed when internal management decisions and processes are at fault. DOD acquisition at the Strategic level occurs in a linear framework, where the predominant view is that a preceding activity is nearly the entirety of what impacts the following activity. The alternative is an approach that focuses on a more inclusive and holistic model where an activity is impacted by many other processes, factors, and activities. The object is not to create a flawlessly accurate description of the system but to “better understand the system and its responses through the use of an empirical model” (Cantwell et al. 2013, 105). Knowledge of the system is gained to empower decision makers to better understand the real impacts and outcomes of their efforts.

The prevailing view in the literature is that project management techniques have not kept up with the complexity of the projects they manage. Traditional techniques rely on a detailed deconstruction of a systems’ constituent parts as a basis for estimating resource allocation. System deconstruction is largely accomplished through informal mental models, based on experience and intuition, and produces “reasonable” estimates of cost, schedule, and performance. The accuracy of these estimates will vary based on experience and judgment (Jalili and Ford 2016). Analysis suggests that “poor, informal strategic judgement may be the root cause of many project failures” (Rodrigues and Bowers 1996, 125).

The SD literature emphasizes a holistic view of the system, including factors both inside and outside of the system itself, where emergent behavior becomes more readily understood and provides insight into how the system as a whole is impacted. SD seeks to include factors that traditional program management do not typically include, but that can

have influence on a system. Concepts found in SD such as ripple effects, undiscovered rework, and managerial pressure on schedule and staffing levels, all build upon the deconstruction work accomplished in many traditional program management techniques. SD build upon program management techniques in several ways: First, SD deals with the notion of perceived versus actual-progress and therefore allowing for more realistic estimations of schedule and cost can be achieved. Secondly, SD acknowledges that there is an amount of work that is categorized as complete yet will need additional effort applied in the future; the principle of undiscovered rework allows for realistic interactions to be simulated (Roberts 1974). Lastly, interactions are assumed to be dynamic, possibility non-linear, and have multiple feedback processes (Rodrigues and Bowers 1996). In attempting to identify the most impactful variable on project duration, analysis revealed that the rework cycle was the most impactful on project duration (Jalili and Ford 2016). These principles exist in abundance in large and complex acquisition projects. By including them in an analytical modeling approach, SD offers to reveal system behavior rather than to measure its constituent parts.

The inclusion of the “soft” or human factors into an SD analysis provides additional context to the factors impacting performance. Research strongly suggests that consequences of managerial decisions impacting system schedule and cost performance are not widely understood or included in empirical models. Schedule compression, information latency, and staffing levels are all examples of “soft” factors that managers can influence and that can have outsized effects on cost, largely as a result of the impact by misunderstood ripple effects (Howick and Eden 2001). The interaction between these “soft” factors and program management decision cycles have been shown to have a significant impact on project performance. The inclusion of these relational factors creates value for SD not only as a forecasting tool, but as a measurement tool to be used mid-project in measuring actual progress and emergent system behavior. By generating a model allowing for inquiry rather than simply performance assessment, managers are given a more complete view of the systems they are charged with keeping on schedule and budget.

Lastly, this research relied on documentation on the RMS to gain an understanding on the approach, performance, outcome of the project. Test and Evaluation Master Plans (TEMP) provided test schedule and evaluation criteria in addition to narratives of individual test events. Selected Acquisition Reports provided baseline and current estimates of schedule, cost, and performance metrics. Reports released from the Inspector General, Government Accountability Office, Institute for Defense Analysis, and various other official memos and reports provided context and analysis of both the RMS and the performance of the acquisition strategy.

C. RESEARCH OBJECTIVES

The primary research question is: **How can the concepts and tools of System Dynamics provide insight into the factors that led to the to the Department of the Navy’s unsuccessful acquisition of the Remote Minehunting System?**

The objective of this research is to focus the methodology of System Dynamics on an analysis of the RMS to better understand the factors that led to poor acquisition outcomes and ultimately the cancelation of the program. The research describes acquisition decisions, interactions between dependent engineering efforts, and poor baseline estimates, that contributed to poor system performance. This research will use program performance data to track how cost, schedule, and scope were impacted.

This research relied on the independent assessments of the Institute for Defense Analysis and Congressional Research Service as well as public records on the RMS to apply the theory of SD. Program outcomes of the RMS were linked to SD theory, suggesting that SD can provide additional context and explanation of system behavior.

The following secondary research questions help to focus this applied project and shape the outline of the research:

- What aspects of System Dynamics are applicable to the DOD’s requirements generation and acquisition process?
- What program features of the RMS’ acquisition is applicable to a SD analysis?
- How did the requirements generation and validation process impact the acquisition performance of the RMS from initial inception to cancelation?

D. METHODOLOGY AND SCOPE

This research project will analyze the acquisition of the RMS using a SD perspective. Its scope will include general knowledge and application of SD, a background study of the history and programmatic decisions of the RMS, and finally application of SD to the RMS program.

As with system engineering generally, the application of SD is dependent on the desired utility of the analysis. That is, the proper level of application is important to optimize its utility without wasting resources. SD can generally be divided into two nonexclusive parts: theory and modeling. First, the application of SD theory provides qualitative concepts and tools to better inform project managers practitioners' mental model in the goal of better understanding and predicting system behavior. As system deconstruction is largely informed by mental models, the accuracy and utility of those mental models are dependent on experience and judgment. "Individual perspectives may be parochial, information incomplete, dated, or biased, and the time available to weigh alternatives insufficient. People, even experts, have great difficulty inferring accurately the behavior of complex dynamic systems" (Sterman 1992, 4). System Dynamics offers an alternative view of a system, taking a holistic approach focusing on system behavior and how managerial strategies can best impact system performance (Rodrigues and Bowers 1996). The second half of SD is the application of its theory in a quantitatively model, applying specific numerical relationship between features resulting in a tool that can measure the impacts of various inputs. These models use can vary widely, but can be applicable as a feasibility estimating tool, a mid-project "what-if" tool, and as a post-completion review tool.

This research will apply the qualitative concepts of SD to the particular circumstances of the RMS. While the creation of a quantitative model would be useful and interesting, especially as applied to the DOD acquisition project, the data necessary to create accurate connection between project features was not available for use in the research. Novel and useful realizations to the project manager can be made with a qualitative application of SD theory. This research will provide a background of RMS development necessary to identify the applicable project features that are applicable.

These program features will then be linked to SD theory to provide insight on contributing factors to the unsuccessful acquisition of the RMS

II. TRADITIONAL PROJECT MANAGEMENT TECHNIQUES

A. TRADITIONAL TECHNIQUE OVERVIEW

Most traditional project management techniques focus on linear open-loop process where each stage of work is completed before the next can be initiated. Figure 1 presents a general project management view, and one that stands true for DOD acquisitions. In the macro view of this general process, there is no allowance for the process to move “backward” between the stages in the process between the problem identification and implementations. This linear flow is useful in communicating phases of work, but poor at planning or measuring progress. Any deviation from the initial plan will require a slip in budget, performance, or schedule. The discussion of these project management techniques will focus on their linear nature in order to later contrast them with the realities of project management.



Figure 1. Problem Solving Methodology. Adapted from Sterman (2014).

A stock-and-flow diagram is a Systems Dynamics method used to depict how work flows through a system in terms of volume of work and effort. Figure 2 is a general form of this problem-solving methodology. The stock labeled “work to be done” consists of a fixed quantity of work that can be measured and planned for. The flow labeled “work being done” acts upon the preceding stock in measured way until all work is transferred to the “work done” stock (Lyneis and Ford 2007). Although stock-and-flow diagram are more focused on the practical measure of work-completed as compared to an open-loop, it is still limited in its description of linear unidirectional movement of work.



Figure 2. Traditional view of stock-and-flow.
Adapted from Cooper (1998).

Many well established and widely adopted techniques exist to take the theory of project management and deal with practical implementation issues. These techniques develop a detailed deconstruction of workflow elements with the goal of tightly controlling the systems' behavior, focusing on the imperatives of cost, schedule and, performance. The interaction of constituent system parts, driven by the detailed deconstruction of inter-relationships, is the basis for estimating resource allocation. These inter-relationships are assumed to interact in clearly defined and understood stages, contrary to the reality of most complex engineering projects (Rodrigues and Bowers 1996). System deconstruction is largely accomplished through informal mental models, based on experience and intuition, and produce “reasonable” estimates of cost, schedule, and performance. The accuracy of these estimates will vary based on experience and judgment (Jalili and Ford 2016).

While not exhaustive, the summary of traditional program management techniques to follow is a brief overview of the most basic and widely used techniques to estimate and evaluate program progress. Each of these techniques relies on an accurate deconstruction of a project into its constituent elements. System-deconstruction, used as an estimate, developed both qualitatively and quantitatively, is the key point this chapter will focus.

1. Work Breakdown Structure

A Work Breakdown structure (WBS) “provides a basis for effective communication throughout the acquisition process. It is a common link, which integrates planning, scheduling, cost estimating, budgeting, contracting, configuration management, and performance reporting disciplines” (DOD 2011). A WBS uses project deliverables as

a starting point, encompassing 100% of the projects assumed scope, deconstructing those deliverables "...into smaller, more manageable components. The key benefit of this process is that it provides a framework of what has to be delivered" (PMBOK guide 2017, 570). The key input to the WBS, according to the PMBOK, is the project management plan that includes statements of project scope and requirements documentation. The output is a deliverable-focused deconstruction of the project into a hierarchal structure of phases, deliverables and work packages. The output is solely dependent on the assumption of scope and accuracy of deconstruction in the project management plan. The level of deconstruction is dependent on the nature of the work, but generally the greater the deconstruction the greater fidelity in understanding of the work to be accomplished and the greater the administrative burden of managing that structure. Budget and schedule are determined at the work package level, then summed into the higher levels to determine the overall estimates. Military Standard (MIL-STD) 881 was established in 1968 and mandates that WBS are used on all Acquisition Category (ACAT) I-III programs (DOD 2011).

2. Gantt Chart

Gantt charts are a category of bar charts used to display the information derived from a WBS. Tasks are organized on the y-axis while schedule is displayed on the x-axis. The width of each task represents the corresponding amount of time required to complete. Preceding dependent relationships are displayed. The key purpose of a Gantt chart is to visually represent and communicate a project schedule. Gantt charts are linear in nature, and do not generally incorporate any allowance for changes in the project requiring effort in previously completed stage of work.

3. Critical Path Method

The Critical Path method (CPM) is a scheduling process used to determine the shortest possible time to complete the series of tasks generated in the WBS and displayed in a Gantt chart. Once dependent relationships are determined and the amount of time required to complete individual tasks is estimated, the longest "path" of activities from project inception to completion is determined and all activities on that path are deemed

“critical.” Any slip in schedule on the critical pathway will result in overall project schedule slip. This process also determines which activities can be delayed without effecting the overall schedule. CPM is a vital step in program evaluation and review technique, discussed below.

CPM provides valuable information on the precedence of dependent tasks, and is a powerful tool in communicating how parallel and series efforts interact. It is a robust visualization tool, but lacks the flexibility to incorporate features such as system interactions and “soft” factors, both of which can heavily influence the system. Schedules are estimated based on the best possible outcomes and can be disrupted by unexpected interactions or missing features of the system. In complex and one of a kind projects, the best possible outcome is rarely the most likely.

4. Program Evaluation and Review Technique

The Program Evaluation and Review Technique (PERT) is a statistics-based project management tool that is used in combination with the WBS and CPM tools to analyze tasks necessary for project completion and evaluate progress. While CPM is task-oriented, PERT is measured in the completion of events. This event-driven orientation allows for uncertainty to be built into the technique, making it well suited for projects where duration of tasks cannot be completely known, especially in complex and large-scale projects. Optimistic, expected, and pessimistic timelines are used to determine an expected time of completion, often using a beta-probability distribution. Uncertainty built into the tool makes it particularly applicable to complex and large-scale projects.

5. Earned Value Management

Earned Value Management (EVM) is a tool to track an “...accurate measurement of the physical work performed against a baseline plan. Most important, it can provide a reliable prediction of the final costs and schedule requirements for a given project” (Fleming and Koppelman 2010, 8). The EVM tool is a unique performance measuring technique in that it accounts for cost and schedule as well as performance. A cumulative budget is estimated as a function of time. This budget, labeled planned value (PV), does not take performance into factor. When a cumulative actual cost (AC) of a project is

compared to the PV, the value of work performed is lost in the assessment. Earned value (EV) is the actual value of the work completed to-date. EV compared to PV allows the project manager to ascertain the true value of the work as compared to the budget and schedule resources expended. This tool, while strictly an evaluation technique, highlights a limitation that progress can only be measured against estimates however accurate they may be.

B. IMPLEMENTATION OF TRADITIONAL TECHNIQUES

The techniques discussed previously in this chapter provide a short discussion of the most widely accepted and implemented system engineering and program management techniques that are applicable to the DOD acquisition life cycle process illustrated in Figure 3. These techniques assume that the constituent system elements are previously known, and can therefore be accurately estimated based on previous experience. Additionally, this linear view requires its clearly defined elements to follow predictable relationship guidelines and progress through time, budget, and performance milestones till completion. This ideal system, one which progresses as planned in clear and completed phases, likely does not exist in complex DOD acquisition projects and traditional project management technique “might not be appropriate to model the more continuous nature of design and development projects” (Rodrigues and Bowers 1996, 121–122).

The DOD acquisition life cycle processes is governed by DOD Instruction 5000.02. This process is event-based where each phase, milestone, or review is required to complete before the next can begin. There are five major phases in the process: materiel solutions analysis, technology maturation and risk reduction, engineering and manufacturing development, production and development, and operations and support. There are three milestone decision points (milestones A, B, C) that must be completed before the program is allowed to move into the production and development phase. This research will focus the information available from the materiel solutions analysis and technology maturation and risk reduction phases, together labeled as pre-systems acquisition. In these two phases, requirements generation is completed and validated, a material solution is selected, and technology risk is reduced to an acceptable level. The

third phase of the DOD acquisition lifestyle, engineering and manufacturing development, will also be discussed; in this phase, integrated system design is completed, a key focus of SD in general and of this research in particular.

Although the process is adaptable and more complex than that pictured in Figure 3, it is apparent that this acquisition process is linear. Any failure in requirements generation or acquisition results in an increase in cost or decrease in schedule or performance. Although the goal of the traditional project management techniques discussed is to provide accurate estimations of performance over this acquisition timeline, they have proven too narrow in scope to meet their intended task.

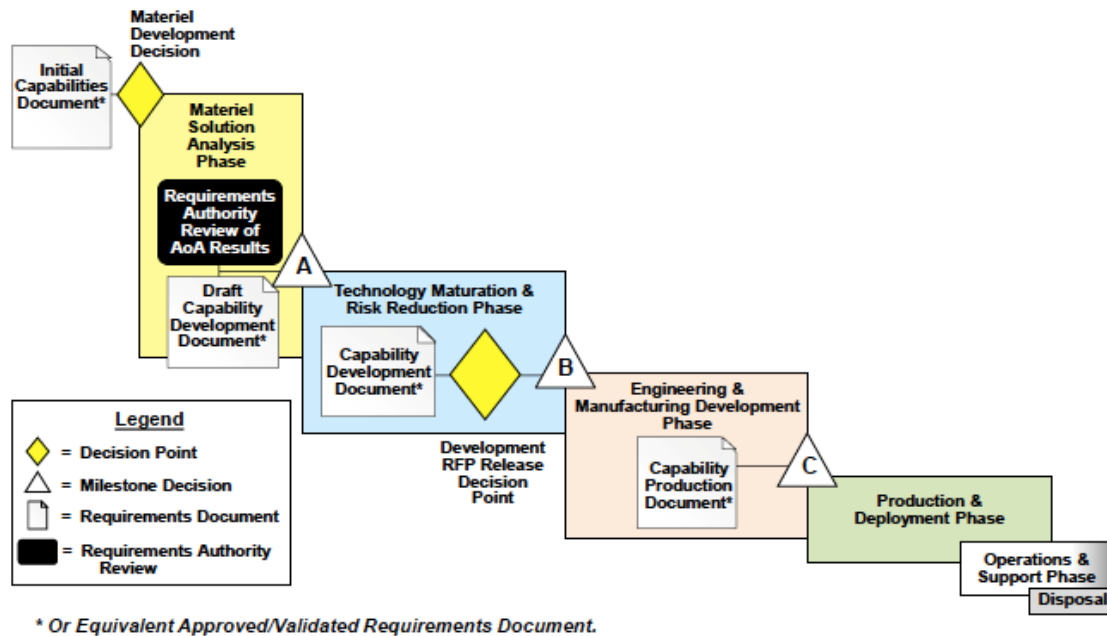


Figure 3. DOD Acquisition Life Cycle Framework. Source: DOD (2020).

C. CHALLENGES OF TRADITIONAL TECHNIQUES

The basis for these traditional techniques is an accurate estimation of schedule, cost, and performance of a system to be developed. Decisions on project implementation and resource allocation are reliant on the accuracy of these estimations. The process of estimation is largely informed by the program manager and engineering staff's mental models; performance of these mental models will be dependent on an individual's

perception, experience, and expertise. Generally, the impact that inter-relationships have on the larger system are minimized and “assumed to work in a linear fashion within a system with clearly defined and understood stages, contrary to the reality of most complex engineering projects” (Rodrigues and Bowers 1996, 125). Dr. John Sterman, again states the problem succinctly:

Though very helpful to schedule the sequence of activities in a project, tools such as Gantt charts, PERT and critical path methods do not solve the problem...the time required for each individual step is estimated by the analyst on the basis of historic data, past experience, or judgment. If customer requirements were to change, or errors necessitating rework were discovered after the project has begun, the analyst can re-estimate the schedule by changing the time required for the small number of individual steps directly affected by the change and then recompute the critical path and time required for completion. The implicit assumption is that the time required to carry out all other steps is unaffected. That is, all other interactions are ignored. But interactions abound. (Sterman 1992, 7–8)

Dr. Sterman highlights the limitations of traditional project management tools. Poor estimations lead to under-resourced (or ill-advised) projects, which often drives costs and schedules well beyond what a more conservative initial estimation might have produced. When the underlying assumptions or situation’s change, these tools are unable to provide the decision-maker an accurate understanding of the implications of their decisions. More pointedly, “... poor, informal strategic judgement may be the root cause of many project failures” (Rodrigues and Bowers 1996, 125).

It is not that organizations or their program managers fail to realize the importance of an accurate project estimation to successful project implementation; the base assumption of this research is that program managers make every effort to produce an accurate plan that they intend to execute as written. Efforts are, however, hampered by project management techniques that do not explicitly allow for the analysis of complex interactions as the basis for their estimations. There is little allowance for revisiting previously “completed” stages of work; any revisit will result in a slip of budget, cost, or performance. Just as important as understanding the complexity of system component interactions is understanding how the human will impact the system’s development. “The impact of human factors is difficult to quantify and traditional management techniques do not allow for explicit examination... the misunderstood and often under reported impact

of local system components or management decisions as trivial to overall system performance has been well documented” (Rodrigues and Bowers 1996, 126). Traditional program management techniques are largely deterministic, disregarding the impacts of the dynamic nature of the person it interacts with. Evidence suggests that disregarding this human nature leaves traditional management techniques insufficient to provide consistent, accurate, and complete understanding of the systems we seek to build.

Unintended consequences originating from complex interactions lead to adverse conditions where long-term outcomes are difficult to link to individual local impacts. This obscurity in outcome origination allows failure to be attributed to uncontrollable external forces while the actual causes are partly within the span of control (or at least understanding) of the development team. An objective approach to handle these factors in a systematic nature, standardized over an entire enterprise, is necessary.

“The complexity of projects and of their environment has increased the disruptive effect of subjective human factors. Personal judgement based on past experience is no longer sufficient to cope with this problem... this can only be achieved through a more formal systemic analysis” (Rodrigues and Bowers 1996, 126). Understanding non-linear and complex interactions will provide a more accurate estimate of performance and lead to better informed decision making. Risk derived from uncertainty will always play a role in complex acquisition projects. Including factors that are known to impact systems into an analysis will lead to better quantitative risk-informed decision making.

This research is not suggesting that traditional program management techniques should be cast aside. They are vital in structuring a project and providing program managers pragmatic methods for managing complex and multidisciplinary engineering efforts. However, there are limitations inherent in these techniques that hinder their ability to include all necessary factors impacting the system.

III. SYSTEM DYNAMICS OVERVIEW

The limitations of traditional management techniques highlighted in Chapter II serve as arguments for how a broader perspective on analyzing system behavior can offer useful insights. Traditional program management techniques are typically held at the operational level, focusing on execution of process through the accurate deconstruction of work flow. “In contrast, the primary objective of a system dynamics model is to capture the major feedback processes responsible for the project system behavior, with less concern about the detailed project components” (Rodrigues and Bowers 1996, 130).

These feedback mechanisms originate from both internal interactions and external influences and can have significant impacts on the system. By operating on a strategic level and focusing on feedback processes, a greater perspective is gained which may lead to insights lost by more operationally focused techniques. The word “dynamic” in system dynamics implies that interactions between sub-components and the environment will change over time, and should therefore be analyzed with time as a variable. These interactions are more complex and change at a higher rate than most project estimation and management techniques are able to cope with. SD is adept at capturing these often non-linear and complex relationships (Lyneis and Ford 2007). Previous research has shown that there is a clear relationship between cost and schedule performance of a project and the deviation from an initial plan. The percentage cost growth caused by late changes has been measured to account for 5–25% of the base cost of a project (Godlewski et al. 2012).

SD is comprised of a methodology (thinking) which informs a set tools (modeling) which is particularly adept at analyzing complex and dynamic systems. The strategic-level view offered in SD considers interactions between system components, managerial structures, and the environment which it operates. The goal of SD is to use a methodical approach to understanding the feedback processes within a system to allow for better estimations and foresee where project managers might mitigate impacts on cost and schedule performance. In his paper regarding SD modeling application in project

management, John Sterman asserts that projects that may gain the greatest benefit from the application of SD typically have similar characteristics:

1. are extremely complex, consisting of multiple interdependent components;
2. are highly dynamic;
3. involve multiple feedback processes;
4. involve nonlinear relationships;
5. involve both “hard” and “soft” data. (Sterman 1992, 5)

These characteristics can be applied to a large percentage of DOD acquisition projects. Projects containing these characteristics are where SD can have considerable advantages to traditional project management techniques used in isolation.

A. COMPONENTS OF SD

In research focused on the application of System Dynamics on modern project management, Dr. James Lyneis and Dr. David Ford describe the structure underlying SD as containing the following components: project features, rework cycle, project control, ripple and knock-on effects (Lyneis and Ford 2007). These four components underpinning the structure of SD provide the framework for analysis.

1. Project Features

As stated previously, SD seeks not an accurate deconstruction of individual components, but to understand system behavior as phases of work are completed (design engineering, methods/industrial engineering, manufacturing, etc.) (Howick and Eden 2001). Analyzing behavior is accomplished through the inclusion of characteristics and process both inherent to and external from the project which have meaningful impact. In SD terminology, these characteristics and processes are called project features. Project features directly affect workflow into the *work completed* bucket. SD specifically seeks to include soft features in its analysis, as they have been shown to dominate the feedback structures (Rodrigues and Bowers 1996). Examples of “soft” project features that have been shown to have measurable impact on progress include addition of manpower, labor deficit, shorting of time horizons in early engineering work, morale, managerial pressure, and extended use of overtime, among others (Howick and Eden 2001).

By incorporating features that impact the system, causality can be traced to origin and action can be taken. Value added is not measured in the completeness of project features included, but in understanding the interactions between features that will meaningfully impact the system. Focusing on features that have a reinforcing characteristic, in where the impact of the feature is destabilizing, allows for a project manager to make more complete risk-based decisions. Ripple effects of these project features can be far reaching. For example, increased managerial pressure and use of extended overtime can be seen as a way to force a project back on timeline. “The effects on fatigue and morale are likely to lead to impacts on both worker productivity and the quality of work carried out, which in turn generates self-sustaining disruption and consequential delay. The delays force new compression of the schedule and so exacerbate the situation. In using either pressure or overtime to compress a project, managers should use caution, as their use is likely to be more costly than most managers envision” (Howick and Eden 2001, 26–34).

“A conventional view of projects breaks them down into their constituent parts—in scope (work breakdown structure), time (critical path networks), cost (budgets), risk (risk registers), and so on.... This, however, is inadequate for complex projects” (Williams 2017, 2). By incorporating features that increase knowledge of causality, a more complete picture of a system is generated and the decision maker is better informed.

2. Project Control

The feedback (or causal) loop is the method as SD analysis describes feedback interactions between the project features and the system. “Diagrams of loops of information feedback and circular causality are tools for conceptualizing the structure of a complex system and for communicating model-based insights” (System Dynamics Society 2018). With the goal of improving project performance outcomes, modeling system behavior through feedback loops provides a tool for project managers to close budget and schedule gaps.

Relationships between project features are described as either positive or negative. If a dependent feature’s value moves in the same direction as an independent feature’s value then it is annotated with a positive polarity (+) sign; if it moves in the

opposite direction it is annotated with a negative polarity (-) sign. Simply put, if both values increase, the relationship is positive; if one value's increase causes a decrease in another value the relationship is negative: causal loops built from these relationships are classified as either reinforcing or balancing. If the elements' relationship to the system enhances the initial tendency, then the loop is reinforcing. A reinforcing loop acts as a destabilizing force, allowing for growth or accelerated collapse. If the relationship opposes the system's tendency, then the loop is balancing. Balancing loops seek to find balance or an equilibrium. As a result of their goal-seeking characteristic, they often result in an oscillating behavior, where the goal is overshoot then a correction is made in the opposite direction (System Dynamics Society 2018).

Figure 4 provides a simple example of a causal loop explaining the relationship between several features. In this example, the temperature of coffee is explained by three features. The relationship between room-temperature and coffee-temperature is described by the feature temperature-difference. As the temperature-difference value increases, as might be explained by drinking a hot cup of coffee on a cold morning, the value of cooling-rate increase, annotated by the positive marking of the relationship. Once the cooling-rate increases, the cup of coffee reduces in temperature (annotated by a negative symbol) leading to a reduction in the value temperature-difference and eventually an increase in the relative coffee-temperature. If one follows the loop twice around, the temperature of the coffee will increase then decrease, indicating a system that attempts to find an equilibrium, known as a balancing loop.

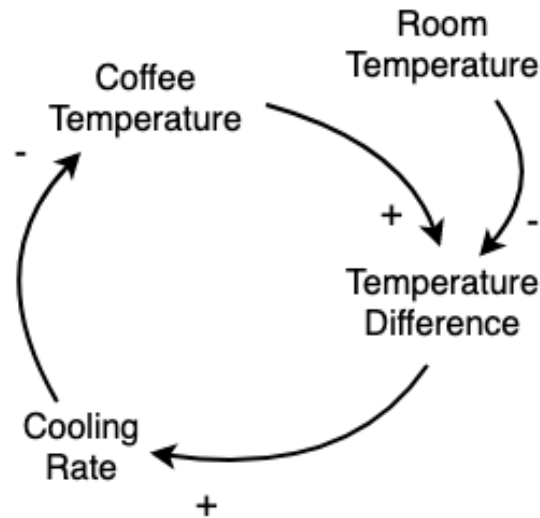


Figure 4. Temperature of Coffee CLD. Adapted from Sterman (2000).

3. Rework Cycle

The rework cycle has been called the most significant feature of a system dynamics model. The cycle describes a recursive nature where system conditions create rework generations that in-turn generates more rework. This recursive behavior can persist through a project's duration and create or exacerbate program management challenges (Lyneis and Ford 2007). The rework cycle was first developed by the Pugh-Roberts/PA Consulting firm in support of a delay and disruption claim; the form of this cycle has been used in almost all dynamic models since (Lyneis et al. 2001).

Effort and resources are applied to buckets of work with the goal of moving all work from the *work to be done* bucket into the *work completed* bucket. However, there is an amount of work that will require additional effort to be considered complete; this concept is referred to as rework. Rework is generated anytime a task has not been completed according to the planned specification or is rendered unsatisfactory due to a dependent relationship. Rework can be discovered immediately, called *known rework*, or remained undiscovered until later, called *undiscovered rework*.

The rate that *work to be done* is converted to either *work complete* or *undiscovered rework* is measured by the rate *progress*. The rate that rework is generated is measured by the rate *error rate*. During the time between rework generation and discovery, that work is incorrectly deemed complete; the rate that *undiscovered rework* is identified is measured by the *discovery rate*. As parallel or dependent efforts precede, additional rework is generated, impacting project schedule and budget performance. Figure 5 provides an example of how a rework cycle is depicted using a stock and flow diagram.

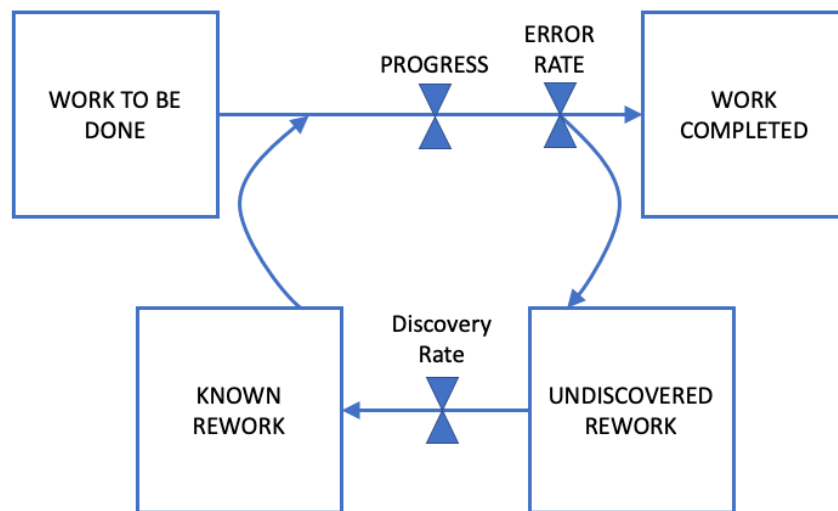


Figure 5. The Rework Cycle. Adapted from Lyneis and Ford (2007).

4. Ripple and Knock-On Effects

Often unintended consequences, unexpected behavior, or defective work will generate additional unanticipated work downstream from its origin; this phenomenon is known as a “knock-on” or “ripple” effect. “The rework cycle’s recursive nature in which rework generates more rework that generates more rework, etc., creates problematic behavior that often stretch out over most of a project’s duration and are the source of many project management challenges” (Lyneis and Ford 2007, 160). The impact of rework has been observed to be as much as the initial cost of change, and (Cooper and

Lee 2009) Both project estimating and management benefit from understanding how emergent behavior will impact system performance.

B. APPLICATION OF SYSTEMS DYNAMICS

As stated in the discussion on traditional techniques, SD's usefulness is not in the deconstruction of a project into measurable constituent elements but in its ability to inform decision makers on the impacts of their decisions. Better understanding how managerial decisions impact performance leads to better outcomes, especially in complex project where new technology is being developed. Lyneis and Ford discuss SD usefulness in four general categories of project management: post-mortem assessments for disputes and learning, project estimating and risk assessment, change management, and project control (Lyneis and Ford 2007). The level of deconstruction to be analyzed in a SD analysis is highly project dependent and should focus where the maximum insight to be gained.

A SD analysis should first seek out the project features which are thought to impact or interact with the system. The scope of included project features will enable or limit the usefulness of the analysis. A key goal of a SD analysis is to reveal unknown or under-estimated integrations within the system. As such, as many project features should be included as feasible. Next a CLD will be built, linking project features and their interactions within the system. The CLD is then linked to the rework cycle, seeking to link individual project features to the creation of rework. In an analysis linking SD theory to system behavior, this CLD is used complement traditional project management techniques, to inform mental models, and apply effort and interventions in areas of concern. Figure 6 is an example of a rework cycle being interacting with project features, whose impacts are described with causal loops. In this CLD, the types of interactions are color coded for further investigation. Once the interactions are investigated and understood, emergent system behavior will begin to become apparent in the interactions. In the example provided in Figure 6, changes in the project (depicted by the plus or delta sign) are shown to have effects through the system; increased staffing and budgetary constraints are linked to staff fatigue and turnover rates, hiring of new staff members impacts training requirements and overall density of knowledge on the team (Cooper and

Lee 2009). The diagram is a tool to establish interaction between project features and facilitate a discussion on where, and to what degree, primary and secondary impacts will be manifested.

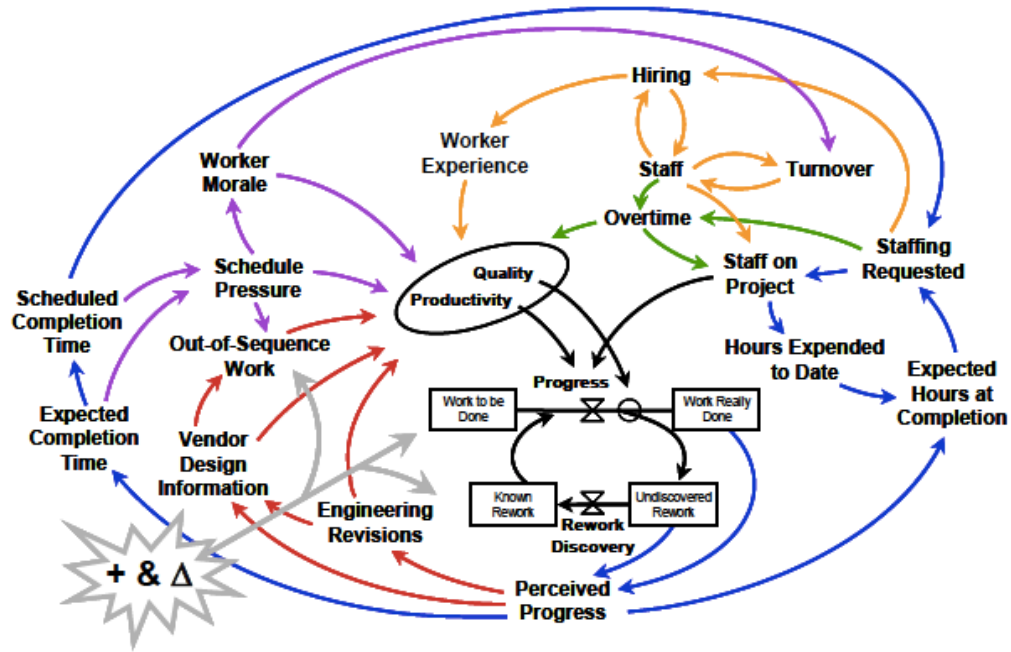


Figure 6. General CLD Example. Source: Cooper and Lee (2009).

IV. REMOTE MINEHUNTING SYSTEM

The RMS was proposed to modernize the U.S. Navy's mine countermeasures capability and counter the growing sea mine threat in the Persian Gulf. The RMS is a remotely operated semisubmersible mine-reconnaissance system designed to detect and identify bottom and moored sea mines. While legacy MCM assets required a manned asset be present in the minefield to conduct countermeasure operations, presenting a hazard to both the person and MCM asset, the RMS was designed to combat the sea mine threat at a distance, keeping the sailor out of the minefield. Under the traditional or "legacy" construct, MCM assets are made available on as-needed basis. Part of a system-of-systems approach to mine countermeasures, the Littoral Combat Ship (LCS) MCM mission package was designed to provide an organic MCM capability within the carrier or amphibious strike group. The organic MCM construct was intended to provide commanders "in-stride" naval mine detection capability without relying on assets outside the task group.

A. PHYSICAL OVERVIEW

The RMS' official nomenclature is the AN/WLD-1, with several variants having been developed. A graphical overview is provided in Figure 7. The major subcomponents include:

- Remote Minehunting Vehicle (RMV)
- Variable Depth Sensor (VDS)
- Launch and Recovery Subsystem (L&RS)
- Data Link Subsystem (DLS)
- Remote Minehunting Functional Segment (RMFS)

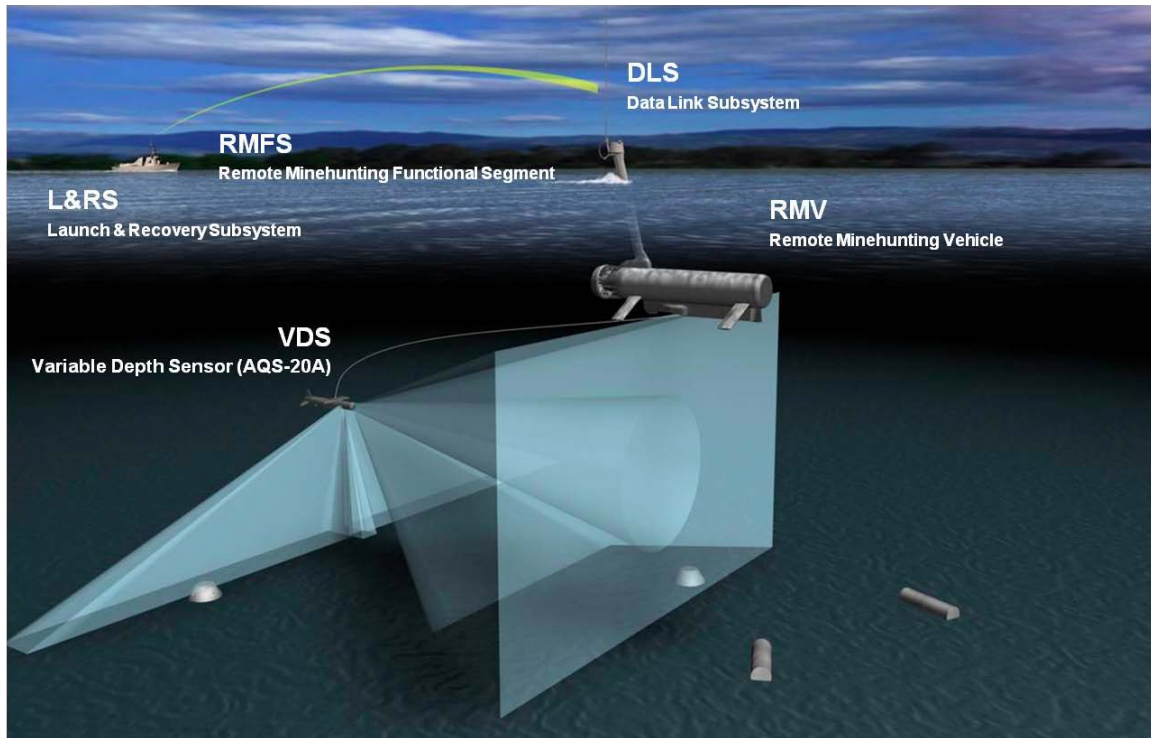


Figure 7. RMS Overview. Source: Bailey et al. (2010).

The RMV is a 23-foot unmanned radio-controlled semi-submersible vessel that can operate at extended distances from its host ship. The RMS is designed to maneuver over a predetermined space of water where mines are expected, pull (or tow) the VDS behind the RMV (also referred to as the RMV in program documentation) over predetermined tracks, and host the DLS equipment. A mast protrudes through the surface of the water from the RMV to provide air induction and exhaust for the engine and to allow data transmissions between the DLS and the RMFS. The AQS-20A minehunting sonar comprises the VDS in the systems' final configuration. The sonar is actively controlled and maneuvers independently of the RMV to improve navigational accuracy and the quality of data collected by the onboard sonar equipment. The AQS-20A sensors are capable of detecting, localizing, and identifying mine like objects.

The L&RS comprises a collection of hardware which allows for the safe deployment of RMV from host ship into the water, recovery of the RMV following mission completion, as well as facilitating ship-board maintenance (Bailey et al. 2010). The DLS provides all communication functions allowing for "Line-Of-Sight and Over-

The-Horizon radio telemetry functions between the RMV and LCS” (Bailey et al. 2010, 3). The RMFS is located on the host ship, the LCS, and provides monitoring and control functions of the RMV to include “receive, process, and display mission data; conduct post-mission analysis; monitor performance, fault detection, and fault location; and provide network communications to the DLS” (Bailey et al. 2010, 3).

B. DEVELOPMENT OVERVIEW

The overview on RMS’ development will focus on major acquisition events, changes in scope and material solution, as well as delays in development for use in the analysis of the system. A Tentative Operational Requirement (TOR) was signed June of 1989 to allow for “an organic capability to allow ships to employ a minehunting capability to provide a measure of protection in environments and situations like those encountered during Persian Gulf conflicts” (Martin 2009, 1). A Cost Analysis of Alternatives (AoA) was delivered in June of 1991, concluding that a semi-submersible system would best address the threat, resulting in the issuance of Mission Need Statement (MNS) #MO42-85-93 in October of 1993. The MNS directed the procurement of a system to allow for an organic mine detection capability for the Carrier Battle Group, Surface Action Group, Amphibious Task Force, and Amphibious Readiness Group assets and resulted in the development of a Remote Minehunting Operational Prototype (RMOP), dubbed RMS(V)1 (Martin 2009).

RMS(V)1 was developed on commercially available semisubmersible vehicle towing the Navy’s AQS-14 side scan sonar and a commercial forward-looking sonar. The ROMP demonstrated successful employment in 1994 and 1995 during developmental trials and in Exercise Kernel Blitz deployed off of a Spruance-class destroyer via rigid-hulled inflatable boats (RHIB). Following these trials, development of a modular L&RS was approved. With the L&RS integrated onto a Spruance-class destroyer the system was updated to the RMS(V)2.

RMS Operational Requirements Document (ORD) 432–85-96, TEMP 1520, and Milestone I decision were approved and signed in 1996, ending the Concept Exploration portion of the acquisition cycle as an ACAT II program. Initial ORD requirements were expressed as a rate of search while achieving a given rate of clearance for mine detection

(95%) and classification (50%). Most relevant to this research was the establishment of a Mean Time Between Operational Mission Failure (MTBOMF) requirement, 150 hours between failures that would cause mission stoppage. The initial system MTBOMF requirement was based on a single components' expected value (the AQS-20 VDS), however the ORD requirement was for a modular multi-platform system where availability and reliability of system components would impact the overall system performance (Office of the Secretary of Defense 2014).

The commercial semisubmersible used in testing the RMS(V)1 and (V)2 was found insufficient to meet requirements set forth in the ORD. At the same time the Naval Oceanographic Command (NAVO), in conjunction with the Office of Naval Intelligence, was interested in a joint procurement specification of a semi-submersible of modular design would allow for use in hydrographic surveys, replacing the MCM sonar with a hydrographic sensor. This modular design would also allow for the RMV to be utilized as part of the LCS' anti-submarine mission package in addition to the anti-mine mission package.

After a competitive solicitation process, Lockheed Martin was awarded the procurement contract in 1996 to develop a new semi-submersible for the program, designated the RMS(V)3 and later renamed the AN/WLD-1(V)1. Builder trials commenced in 1998 and revealed performance, maintenance, and corrosion issues of the newly developed RMV, largely attributed to the modular design required to support secondary hydrographic survey and anti-submarine missions. Development issues with the RMV prevented the L&RS from being used in trials, further delaying the overall acquisition timeline. The U.S. Navy shifted priority from the L&RS being rapidly available to the Spruance class of ships to delivery of a full capacity to the Arleigh Burke-class guided missile destroyers (PMS 495 2006). This decision further delayed installation, integration, and testing of the L&RS and resulted in RMV testing evolutions being conducted without the L&RS. As a result of a sensor tradeoff study by U.S. Navy and industry partners, the AQS-14A sonar was replaced by the AQS-20A sonar in December 1999 (Martin 2009).

The System Specification and Statement of Work was updated in June of 1999 to reflect the substantial system requirement changes. Revision 1 of the RMS ORD 528–85-99, approved in October 1999, required the RMS to integrate into the ship’s AN/SQQ-89(V)15 Undersea Warfare System. The change required the program to outfit, out of Research, Development, Test, and Evaluation (RDT&E) funds, all eleven DD 51 Arleigh Burke class ships currently built or in production. Additionally, the revised ORD altered the specification for the L&RS to a non-modular DDG 51-only design. At the same time, a re-examination of requirements and mission analysis revealed that the previous MTBOMF requirements were “grossly short of what would be required to be confident of completing a single sortie... resulting in less than a fifty percent probability of completing a single sortie” (Martin 2009, 12).

In December of 1999 Lockheed Martin was awarded a \$77.9M modification to a previously awarded contract for the development of the AN/WLD-1(V)1 up to Critical Design Review (CDR) (Martin 2009). Milestone B decision was achieved in December of 1999 ending the Demonstration and Validation Phase as an acquisition category (ACAT) II program (Director, Operational Test and Evaluation 2006). By December of 2001 the CDR was completed and a contract for three AN/WLD-1(V)1 Engineering Development Models (EDM) was issued. In July of 2005 Milestone Decision C was approved, ending the Engineering and Manufacturing Development Phase (later rescinded in June 2010); By April of 2006, the RMS program was upgraded to an ACAT 1C program due to an extended development timeline resulting in increased spending (Bailey et al. 2010).

In September of 2006 Lockheed Martin was awarded an additional \$34M contract for four additional low-rate initial production (LRIP) RMV units, in addition to the three EDM units previously approved for testing. August 2006 through September 2008 Developmental and Operational testing events were completed. “During that time, the Operational Availability (Ao) Key Performance Parameter (KPP) and MTBOMF reliability parameters were not successfully achieved” (PMS 403 2015, 9). Additionally, an Initial Operational Testing and Evaluation (IOT&E) event was downgraded to an Operational Assessment (OA) in September 2008 due to low reliability and availability of

the RMV (Bailey et al. 2010). While these events were largely conducted aboard surrogate vessels and the ORD had stated that the RMS will operate from DDG-51 class ships, the Navy had signaled at this time that it intended to operate the RMS solely on the LCS (Director, Operational Test and Evaluation 2006).

In January 2009 the Navy reduced its planned buy of RMS systems from 106 to 52 as a result of “reliability problems in nearly all periods of developmental and operational testing between 2005 and 2008 and twice failed to complete a planned IOT&E. By late 2009, schedule delays, costs associated with improving reliability, and an increase in the unit cost caused by the Navy’s decision to acquire fewer vehicles” (Office of the Secretary of Defense 2014, 4). The reduction in procurement of RMS was directly linked to the LCS’ anti-submarine mission package and Naval Oceanographic Command (NAVO) missions seeking unique material solutions for the RMV (Bailey et al. 2010). At the same time a Reliability Growth program (RGP) was initiated in response to low system performance, requiring an additional \$120 million in RDT&E and 5-year gap in procurement to execute (Inouye 2010). In December of 2009 the Navy notified Congress of a critical Nunn-McCurdy breach in both the Program Acquisition Unit Cost (PAUC) and Average Procurement Unit Cost (APUC). The root causes cited include decrease in procurement quantity, unrealistic cost estimate in the 2006 APB, and “poor performance of the government program management and governance” (Inouye 2010, 9).

In June of 2010 following the Nunn-McCurdy breach, the program was restructured to an ACAD 1D and the Milestone Decision C was rescinded. During a review of the program to support the Nunn-McCurdy decision, the Navy reported that the reliability of the system was 44.4 hours MTBOMF, well short of the stated KPP threshold requirement (Office of the Secretary of Defense 2014). November 2011 through March 2015 developmental and contractor testing in compliance with the first phase of the RGP was executed with the goal of addressing observed RMV failure modes and assess vehicle reliability. At the conclusion of 40 months of testing, the RMV reliability was reported to have increased, yet still short of reliability and availability KPP requirements.

Following upgrades to the RMV in the first phase of the RGP, the Navy reported that reliability had grown to 213 hours MTBOMF. An independent DOD review

concluded that “these tests were not conducted in an operationally realistic manner and the resultant MTBOMF estimate was not representative of what would be expected in more realistic stressing operations” (Office of the Secretary of Defense 2014, 5).

Additionally, the review challenged an updated reliability definition as not operationally relevant, asserting that contractor testing had artificially inflated the measurement by a factor of two or more (Office of the Secretary of Defense 2014).

Compounding the issue, the Navy choose to forego its own developmental testing, relying on the contractor testing to validate the KPP requirements. The Director of the Operational Test and Evaluation Directorate stated in a memorandum to the Under Secretary of Defense for Acquisition and Sustainment that “I will not approve the Navy’s test plan because the version of the system available for this OA...is incompatible with the Littoral Combat Ship (LCS) and will never be used operationally” (Office of the Secretary of Defense 2014, 1). Additionally, the director rejected the plan to conduct an operational assessment of the RMS until the system in test is one that “will actually be used in conjunction with the LCS MCM package...” (Office of the Secretary of Defense 2014, 15).

Following a letter from members of the Senate Committee on Armed Forces, Senators John McCain and Jack Reed, citing concern for the program’s performance and management, the Navy initiated a formal review of the program. “In October 2015, the Navy delayed operational testing of the Independence-variant LCS equipped with the first increment of the MCM mission package pending the outcome of an independent program review, including an evaluation of potential alternatives to the RMS” (DOD 2016, ix).

In August of 2015 a Technical Evaluation (TECHEVAL) of the Increment 1 mine countermeasures (MCM) mission package was completed. Although the system met some of its KPP requirements, significant reliability issues were noted with the RMV and associated subsystems. Following the results of the TECHEVAL, The Chief of Naval Operations and Under Secretary of Defense, Acquisition, Technology, and Logistics ordered an independent review of the program. By February 2016, the Independent Review Team (IRT) released findings on the RMS program and recommended that the

Navy halt all procurement of the RMV and dedicate resources to other near-term technologies to accomplish the MCM mission (O'Rourke 2017). "In early 2016...the Navy canceled the RMS program, halted further RMV procurement, abandoned plans to conduct operational testing of individual MCM mission package increments, and delayed the start of LCS MCM mission package IOT&E until at least FY20" (DOD 2016, ix). Figure 8 summarizes the RMS' development from the signing of the original ORD till program cancelation.

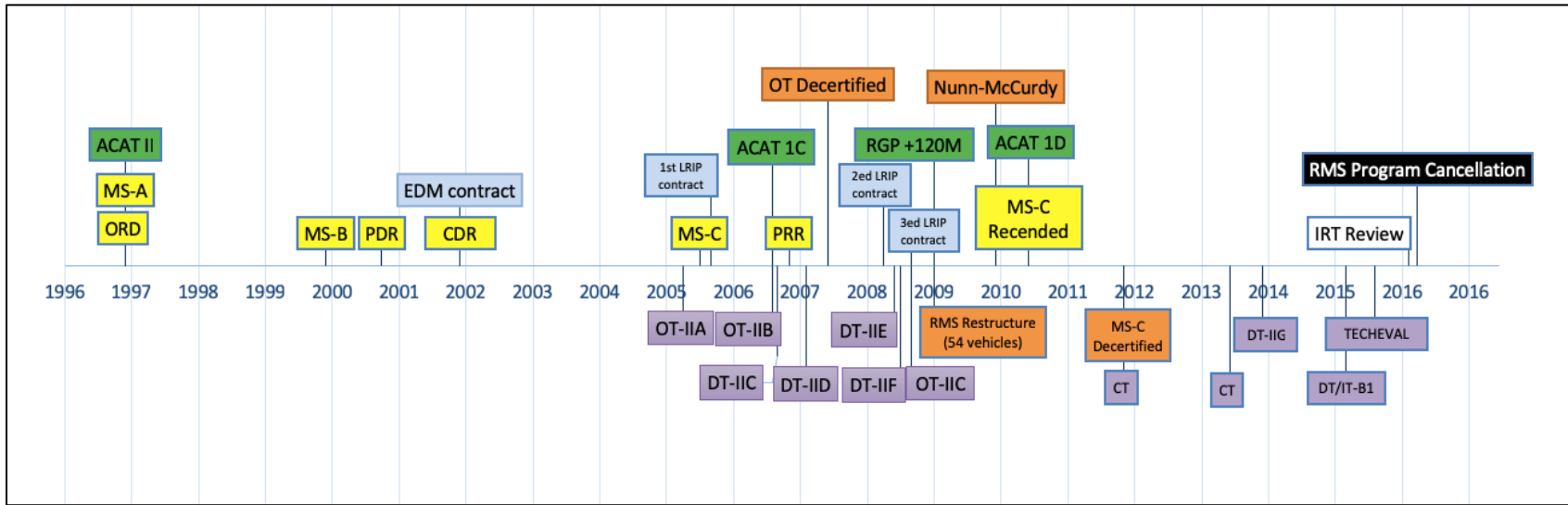


Figure 8. Timeline of Major RMS Acquisition Events. Adapted from Bailey et al. (2010).

C. PERFORMANCE OVERVIEW

System and programmatic performance will use the IDA's conclusions (Bailey et al. 2010) as a basis for a SD analysis. The timeline of this analysis will encompass program inception until Nunn-McCurdy breach in late 2009. The use of IDA's analysis as a starting point has two practical functions: First, the IDA had a greater access to the program and its associated data than was available for this research. Second, the timeline utilized by the IDA allows for the comparison utilizing the same number of planned RMS units, thus isolating program performance from procurement decisions exogenous to the system. Although lack of detailed programmatic data precludes the assignment of numerical or relative impact of SD principles to the cost, schedule, and performance outcomes discussed below, it is important to establish an overview of project performance which may be used to assert the follow-on SD analysis.

1. Cost

The factors listed as proximate causes for cost growth by the IDA include a planned reduction in procurement quantity from 106 to 52 RMS units, availability and reliability shortcomings, and an incorrect program acquisition baseline. These factors led to increase in RDT&E spending from \$418M at the 2006 APB to \$548M by 2009 (all values reported in fiscal-year 2006 dollars). Figure 9 provides program spending increases between the original 2006 APB and estimated post-2009 SAR (labeled "Current Navy Estimate") which include the fully funded RGP. The IDA's analysis attributes system reliability and unrealistic costs estimations accounting for 36% growth of the PAUC beyond the baseline estimate.

These three factors, while accounted for independently in the report, acted upon each other in a destabilizing manner. Poor system performance resulted in the adoption of a \$120M RGP and a 5-year delay in production. Indirectly, poor performance resulted in a change in procurement profile, extending the planned production run from 13 to 16 years, and likely impacted the decision to peruse a different anti-submarine warfare module resulting in a reduction in procurement quantity.

In \$M BY FY 2006	Original APB	Current Navy Estimate	Delta	% Growth
PAUC	12.1	22.4	+10.3	85.1%
	Qty Reduction & Profile Change		+ 5.17	43%
		<i>Quantity Reduction</i>	+ 4.24	35%
		<i>Reduced Production Rate</i>	+ 0.93	8%
	Reliability Issues		+ 2.71	22%
		<i>Reliability Growth Program</i>	+ 2.22	18%
		<i>Five-year Gap</i>	+ 0.49	4%
	Unrealistic unit cost estimation		+ 1.68	14%
	Other		+ 0.74	6%
APUC	8.4	12.7	+ 4.3	51.2%
	Qty Reduction & Profile Change		+ 1.52	18%
		<i>Quantity Reduction</i>	+ 0.54	6%
		<i>Reduced Production Rate</i>	+ 0.98	12%
	Reliability Issues: Five-year Gap		+ 0.51	6%
	Unrealistic unit cost estimation		+ 1.74	21%
	Other		+ 0.53	6%

Figure 9. Nunn-McCurdy Reported Cost Growth.
Source: Bailey et al. (2010).

At program cancellation, the total program acquisition cost is reported in the 2006 SAR as \$739.1M (FY2006). While the revised baseline was \$1279.6M, this included all development costs and the planned procurement of 52 RMS units. Starting with the initial baseline PAUC of \$12.1M, then 2009 McCurdy cost growth reported PAUC of \$22.4M, the final estimate of PAUC at program cancellation in 2016 is reported as \$74.46M (DOD 2016). Of the planned 52 RMS units only 10 LRIP units were eventually purchases, to remain in the Navy's inventory as test platforms for future technologies.

2. Schedule

It is difficult to determine exactly how far behind the development schedule the RMS was by the programs' cancellation in 2016. The program reported that it was largely on track from 1999 until 2009 when the program came under the scrutiny of the Nunn-McCurdy program review. Milestone-C decision was planned to be completed in FY2005, ending the engineering and manufacturing development phase and starting the production and deployment phase (PMS 495 2006). In July of 2005 MS-C was approved, however it was later rescinded in June 2010. In 2016 the last SAR was released for the program and the MS-C threshold was still estimated at 2014 with no updated estimate provided.

Figure 10 provides the final reported schedule of RMS events. If the RMS had achieved MS-C in the same year as its final report the program would have been 11 years behind its original baseline estimate. However, the program was far from receiving a MS-C decision in 2014. Another indication of program delay is provided in the 2016 TEMP documentation where IOC for the system was estimated to be completed in 2007 (PMS 495 2006, II-4). At program cancelation in 2016, IOC was estimated by to be completed in 2018. Again, the difference is 11 years.

Schedule Events				
Events	SAR Baseline Development Estimate	Current APB Development Objective/Threshold		Current Estimate
Milestone II	Dec 1999	Dec 1999	Jun 2000	Dec 1999
OA (Shallow)	Apr 2005	Apr 2005	Oct 2005	Apr 2005
Milestone C/LRIP	Jul 2005	Jul 2005	Jan 2006	Jul 2005
Operational Assessment	Aug 2006	Aug 2006	Feb 2007	Aug 2006
Second LRIP Decision	Sep 2006	Sep 2006	Mar 2007	Sep 2006
DT/OA Increment 1	Feb 2014	Feb 2014	Aug 2014	Dec 2013
Milestone C	May 2014	May 2014	Nov 2014	N/A ¹
LRIP Contract Award w/Options for FRP	Sep 2014	Sep 2014	Mar 2015	N/A ¹
Initial Operational Capability	Jan 2015	Jan 2015	Jul 2015	Aug 2018 ¹
TECHEVAL	Mar 2017	Mar 2017	Sep 2017	N/A ¹
OPEVAL	Jun 2017	Jun 2017	Dec 2017	N/A ¹
Full Rate Production	Jul 2017	Jul 2017	Jan 2018	N/A ¹
Excercise FRP Contract Options under LRIP Contract	Oct 2017	Oct 2017	Apr 2018	N/A ¹

¹ APB Branch

Figure 10. 2016 SAR Scheduled Events. Source: DOD (2016).

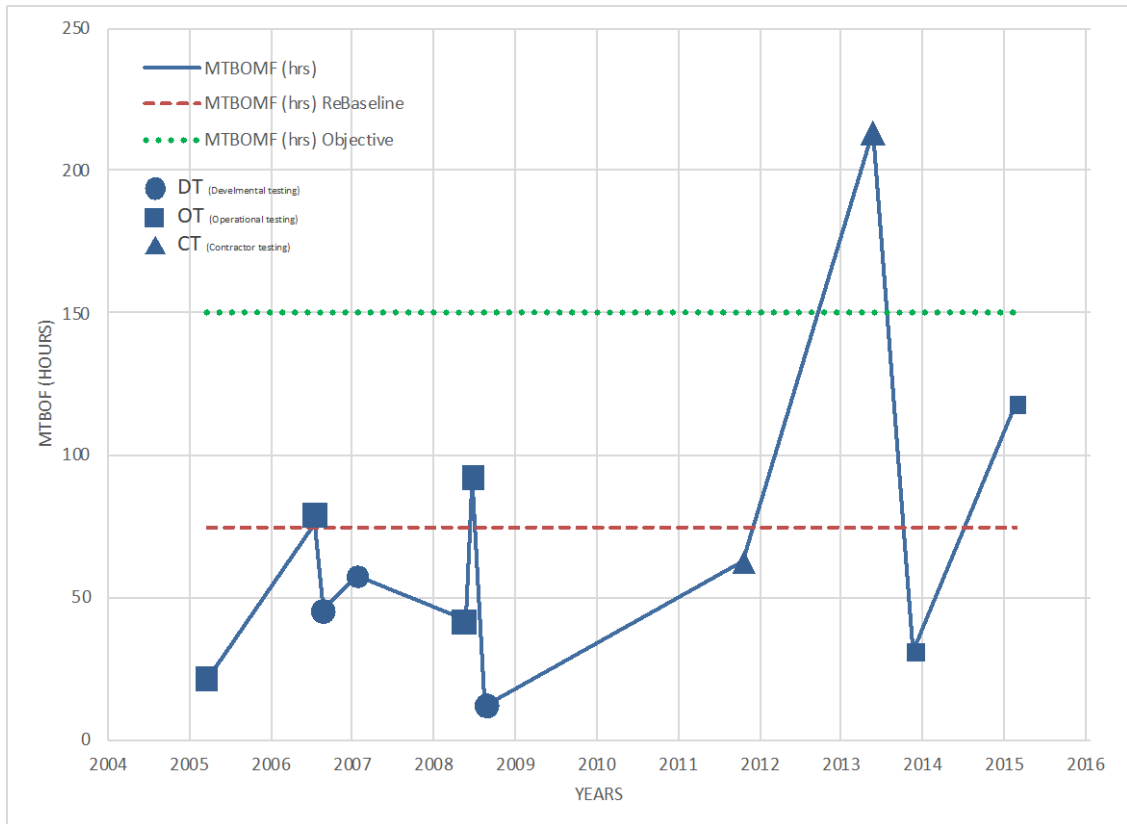
3. Performance

MTBOMF is the primary Key System Attribute (KSA) used to measure system performance for this analysis; it is defined as the time between failures which would cause mission stoppage. The attribute allows for a direct measure of RMS availability and reliability, two factors cited in the programs failure to achieve a Milestone C decision. (Office of the Secretary of Defense 2014).

By 2013, the Capabilities Development Document (CDD) had been updated to contain two definitions for MTBOMF. The first is defined as the reliability KSA, derived

from standard reliability definitions and found by dividing the total operating time by the number of operational mission hardware failures and operational mission software faults for any component of the RMS. In this definition, mission time is measured from vehicle release to capture and its threshold was set at 150 hours between mission failure. The second definition of MTBOMF in the CDD, added during the Nunn-McCurdy process, is largely the same as defined in the CDD with four important distinctions: First, any operational level maintenance action that corrects an operational mission failure or operational mission fault within two hours is not recorded as a fault or failure. Second, MTBOMF would only consider reliability of the RMV, not the system-of-systems that comprises the RMS. Third, the measure of operating time was expanded to include the time between RMV pre-release from its host-ship till the completion of post-mission analysis (which occurs after the vehicle is recovered). This post-mission analysis time, where the vehicle has been recovered and its recorded data is being processed by personnel, greatly inflates the measure of MTBOMF as compared to the reliability KSA definition by at least a factor of 2 (Office of the Secretary of Defense 2014). Fourth, this definition decreases threshold from 150 to 75 hours between mission failures (DOD 2012). “The Navy validated these new lower requirements after several studies suggested that clearance objectives could be achieved when reliability met this threshold. However, these studies often treat RMV and RMS reliability as the same and assume that an unacceptably large number of replacement vehicles will be available to continue operations after other vehicles fail” (Office of the Secretary of Defense 2014, 5).

Figure 11 is a graphical overview of MTBOMF reported for the majority of the Contractor (CT), Developmental (DT), and Operational (OT) Testing events as recorded in the IDA’s analysis and various programmatic documentation. Only a single event was reported to meet the ORD KSA requirement, a CT event in June of 2013 reporting MTBOMF as 213 hours. An independent review found this testing was “not conducted in an operationally realistic manner and the resultant MTBOMF estimate was not representative of what would be expected in more realistic stressing operations” (Office of the Secretary of Defense 2014, 5).



Adapted from Bailey (2010); PMS 403 (2015); DOD (2013); Office of the Secretary of Defense (2014).

Figure 11. RMS Performance Summary

A statistical analysis of RMS reliability was included in the Director of Operational Test and Evaluation (DOT&E) 2016 annual report. The analysis shows a comparison of reliability over time as reported by the Navy and as independently assessed by the Director of Operational Test and Evaluation (DOT&E) from June 2010 through September 2015. This report, summarized in Figure 12, finds a disparity between the two assessments of RMS performance and asserts. Contrary to the Navy's narrative that reliability was steadily improving, the statistical analysis revealed no improvement in reliability (IOT&E 2016).

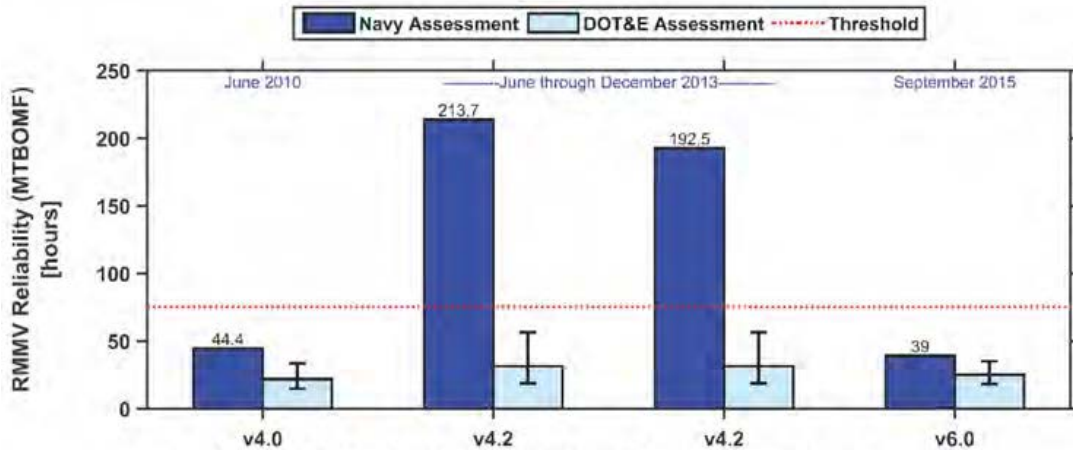


Figure 12. Statistical Comparison of RMV Reliability.
Source: DOT&E (2016).

In a separate memo, the DOT&E stated that “results of recent developmental testing have convinced me that RMS, including the RMV, is not yet sufficiently mature to perform effectively... Years of testing have highlighted a variety of system performance problems that will unacceptably degrade LCS MCM effectiveness if not corrected” (Office of the Secretary of Defense 2014, 1). The IDA’s analysis is consistent with DOT&E conclusions. Reliability improvement was assessed by the IDA utilizing a Duane plot, shown in Figure 13. The dashed and solid red lines represent the original ORD’s MTBOMF threshold of 150 hours and the updated post-Nunn Mcurdy’s value of 75 hours respectively. The solid blue line represents the trend of reliability as a function of cumulative RMV operating time since testing began in 2005. The trend line has two noteworthy characteristics. First, the growth of reliability is slow. Second, the reliability of the system is below the 75-hour threshold (Bailey et al. 2010). Comparing Figure 12 with Figure 13, it is apparent that the data reported by the Navy and the IDA differ significantly.

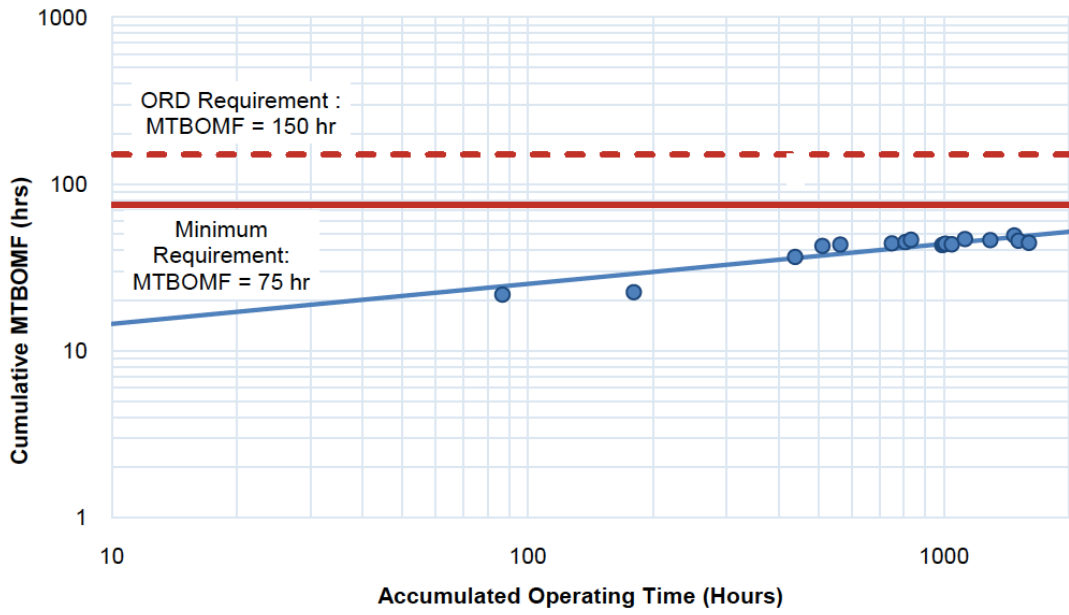


Figure 13. Duane Plot of RMS Test Data since 2005.
 Source: Bailey et al. (2010).

V. SYSTEM DYNAMICS APPLIED

The SD analysis of the RMS will relate project features with system behavior through a CLD to help provide context to programmatic outcomes. This analysis will not restate details established in previous sections, but will highlight points to provide clarity on their relation to the CLD. An SD analysis need only to be as detailed as useful. This analysis will focus on the major project features of which information was available and who's impacts were significant to the performance of the program.

The following analysis will first give a general overview of the project features of the RMS to be included in the analysis. Next, a CLD will be built linking project features to their interactions within the system. Finally, the rework cycle and CLD will be related in order to draw conclusions from those interactions.

A. PROJECT FEATURES OF THE RMS

Seven project features were included in the development of the CLD. These project features, although far from exhaustive, allow for the inclusion of many of the programmatic decisions, circumstances, and outcomes which impacted outcomes. The CLD will provide the framework to look at these project features through the theory of SD.

1. Development Timeline

The increase in developmental timeline had both direct and knock-on effects. As such, it is a good candidate for examination. Generally, an increase in development timeline is a knock-on effect of programmatic decisions or unforeseen occurrences; as an example, unrealistic baselines and early adoption of immature technology were directly linked to schedule overruns in the RMS program (Meier 2010, 34).

The RMS development timeline presented previously allows for a detailed review of engineering efforts over time. The development of the RMS, from validation of the Urgent Needs Statement in 1998 to the program's cancelation in 2016, stretched 18 years. The extended development timeline heavily impacted the program by allowing for other project features to interact and influence the system over an increased time. "Projects are

often delayed to the point where the market conditions for which they were designed have changed” (Sterman 1992, 2). The timeline over which the RMS was developed allowed for technology to become increasingly obsolete as timelines extend, leading to an increased rate of component changes that in turn create additional integration engineering work resulting in longer development timelines; the cascading effects of these interactions were far reaching for the RMS program.

2. Changes in Scope

“There is a clear, unambiguous relation between the level of changes and the cost and schedule performance of projects” (Godlewski et al. 2012, 20). The reinforcing action an increase in project scope, or “scope creep,” can have destabilizing effects resulting in both direct and indirect consequences. Increasing scope can originate from project management decisions, inclusion of additional features or capabilities not previously accounted for, or as the indirect result of other project features. The latter, second-order effects, is where scope creep acts in a reinforcing manner where a change in scope can result in additional change in scope. Identifying where and how scope creep can be impactful can be difficult to foresee and mitigate.

The RMS experienced project scope change as the result of poor requirements generation and validation as noted in the IDA’s analysis (Bailey et al. 2010, 8). An example of this scope creep includes the added requirement to integrate the RMS with the Arleigh Burke class ships’ AN/SQQ-89(V)15 Undersea Warfare System, efforts that would be rendered fruitless after the RMS’ host ship would change eventually to the LCS. Additional requirements were not accompanied by additional funding, but was funded out of the existing IOT&E budget. Additionally, the RMV initially adopted a modular design to accommodate secondary hydrographic survey and anti-submarine missions that were later abandoned. This modular design, which was later rendered unnecessary, introduced performance, maintenance, and corrosion issues discovered in OT and DT events.

Although changes in scope are almost always implied as an increase, the RMS experienced a decrease in scope, not in capability but in procurement quantity. The reduction of the planned buy of 106 RMS units down to 52 was directly linked to the

Navy's decision to seek a "different, more advanced system for anti-submarine warfare modules" (Bailey et al. 2010, 6). The decrease in scope resulted in the programs' Nunn-McCurdy breach and subsequent TECHEVAL and IRT evaluation. The failure in requirements generation is cited as a leading example of the reduced purchase (Bailey et al. 2010, 9).

3. Subsystem Component Changes

Changes of subsystem components in system-of-systems can have far reaching effects. The RMS requires all five of its major subsystems to function in an operationally effective manner. As subsystem components' form or function are modified, impacts can be realized both in the singular component and other subsystems with which it interacts. The following subsystem components created a clear relationship to negative programmatic outcomes: The change from a commercially available and proven RMV platform to a proprietary and modular platform. Multiple VDSs used in development and testing. The host ship for the system changed three times during development. The RMS was envisioned to be a modular and platform independent in its initial 1998 urgent needs statement. Initial development efforts were focused on Spruance class destroyers, continued on Arleigh Burke-class destroyers, and then finally on the LCS.

Both the slow rate of technology maturation and the long development timeline of the program increased the number of subsystem component changes thought the lifespan of the development. There were many other component changes recorded in the documentation, but these examples highlight how programmatic decisions leading to changes in a subsystem component had impacts on both schedule and budget which can be difficult to forecast.

4. Subsystem Component Availability

In a complex system of systems, an individual component's development is highly dependent on the availability of the other components. Even when individual components can be developed in isolation, the integration of these components can prove to be instrumental to the project's success. Such is the case with the development of the RMS.

Delays in the development of the LCS class of ship caused a reduction in availability for RMS testing and development, resulting in schedule delays of the LCS' subsystem, RMS included. The most obvious example of material availability impacting scheduling is the interaction between the LCS and the L&RS. The L&RS is the physical connection between the RMS and its host ship; development never reached full operational capacity, largely due to the lack of host platform availability (DOD 2013). Impacts of the L&RS being unavailable for integration include forcing the RMS development to be continued on ships of opportunity (PMS 403 2015). The deployment, operation, and recovery of the RMS from these ships of opportunity differed enough from that of the planned employment from the LCS that problem discovery was delayed to a point it became a major contributor to the programs' cancellation; these two examples highlight how components that function as expected in isolation can fail to meet expectations when operating as part of a system-of-systems.

5. Parallel Engineering

The inclusion of the Project Feature "parallel engineering" allows for the examination of how multiple technology development efforts interacted and impact each other. It is intuitive that the development of interdependent technologies will cause unpredictable and sometimes unfavorable interactions. It is also studied that technology maturation occurs at a slower rate than expected. However, the impact of these factors, both isolated and in combination, are underestimated and underreported (Jalili and Ford 2016, 90). When multiple complex components are developed at the same time, the consequence of localized setbacks are felt in places within the larger system that can be hard to recognize and isolate. This project feature focuses on the impact of technology maturation on parallel development efforts and the system as a whole.

The major engineering efforts that interacted and impact each other were the simulations developments of the RMV and the systems' host, the LCS. The LCS was both a new type of platform and a new concept of employing combat capability in littoral waters. As the LCS development, and its accompanying concept of employment, was delayed the development of the RMV itself was hindered (DOD 2010).

6. Rework Generation

Widely studied and a key concept in System Dynamics theory, rework generation can have far reaching and unforeseen impacts that have shown to make the largest contribution in a CLD (Jalili and Ford 2016, 89). The relative impact of rework generation will depend heavily on the volume of unforeseen rework generation and when in the acquisition process that rework is acted upon. As this analysis strives to understand outcomes through the SD theory, examining the extent to which rework generation impacted this system is vital to tracing the sources of those impacts and better understanding system behavior.

The impact of late or changing preliminary engineering, also referred to as Front-End Engineering Development (FEED), is of particular interest in the development of the RMS. Figure 14 summarizes research into the impact that late stage technology maturation can have on the final cost of a project (Cooper and Lee 2009). As the overall percentage of preliminary engineering work is delayed until later stages of engineering, overall cost of the project is observed to rise. It is apparent by the facts presented in the documentation that the amount of rework was heavily impacted by changing preliminary engineering and continued technology maturation in the later development stages; this notion is not unique to the acquisition of the RMS. In its 2006 annual report, the director of DOD Operational Test and Evaluation (OT&E) commented that “OT&E is too often the place where performance shortcomings and new failure modes are discovered. When problems are found late in the acquisition process, the cost to fix these problems is much higher than if they were discovered earlier” (Director, Operational Test and Evaluation 2006, i).

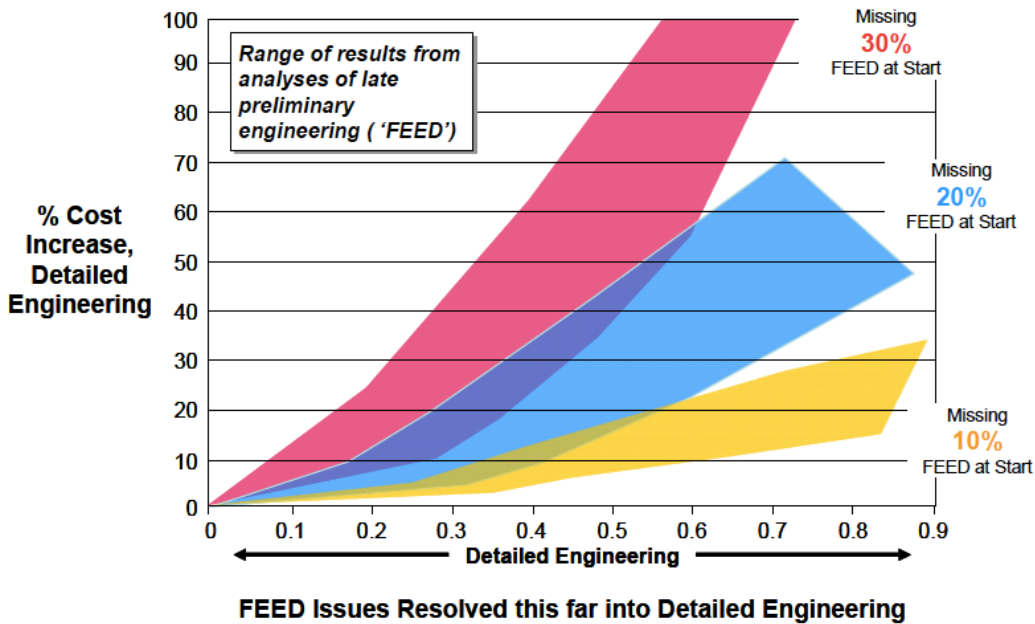


Figure 14. Impact of FEED. Source: Cooper and Lee (2009).

7. Integration Engineering

A system-of-systems depends on the successful integrations of its components as much as it does the performance of those components. “The MCM mission package operates as an integrated family of systems. Each of the seven systems needs to provide full capability and operate in conjunction with each other in order to accomplish MCM missions” (Meyer 2009, 8). The goal of including “Integration Engineering” into the project features is to examine how the integration of components effects the system overall performance.

Once the RMS and LCS were both available for testing, the programmatic documentation contains many examples of integration and implementation issues:

- “Early integration testing determined the AN/AQS-20B was not ready to support LCS MCM MP IOT&E and RMV v6.0 presented parts reliability issues. The test halted for a six-week fix and repair period” (DOD 2016, 12).
- The LCS and its physical connections to the LCS, the L&RS and RMFS, were not integrated and tested until late in the development

of the RMS. The failure to make these connections lead to a DOT&E recommended re-engineering an RMV recovery solution (Schwartz and O’Conner 2016).

- The RMV and mission package communications interfaces failed to meet communications range requirements and would have required re-engineering to meet performance thresholds (Director, Operational Test and Evaluation 2016).
- “Current Navy plans for developing, integrating, and testing mine hunting and mine sweeping systems in the LCS MCM mission package are not adequately funded to mature the MCM capabilities to meet mission requirements” (Director, Operational Test and Evaluation 2016, 274).

While not an exhaustive list, the examples of integration and implementation issues are emblematic of the challenges that faced the RMS program. Unfortunately, many of these issues were “baked into” the system by under-accounting for Front-End engineering development necessary prior to integration and testing (Godlewski et al. 2012, 19). Parallel engineering efforts and component availability created component compatibility issues which were only realized in late stage development.

B. RMS CASUAL LOOP DIAGRAM

The RMS CLD’s use casual loops to describe relationships within the system that can result in complex, unexpected, and outsized impacts thought the system. The program feature relationships have a synergistic effect so that their combine impact is greater that their individual feature impacts The loops within the diagram act as either reinforcing (or positive) or balancing (or negative) relationship. Although the interactions presented in this CLD are not exhaustive, they do attempt to address major factors cited in the IDA’s analysis (erroneous or unrealistic baseline estimates) and Nunn Mcurdy root causes (unrealistic cost estimates and poor government management)

Figure 15 presents a CLD utilizing the project features established in this chapter. The CLD will be discussed with the use of the following loops: “Errors build errors,” “Slip in Deadline,” and “Oversight Failure” (Lyneis and Ford 2007). These three

constituent loops comprise the RMS CLD and connect project features with the IDA's outcomes that the diagram will help describe. While discussion of how project features describe the RMS system in particular is useful, it is the understanding of the interactions between specific project features where System Dynamics adds value.

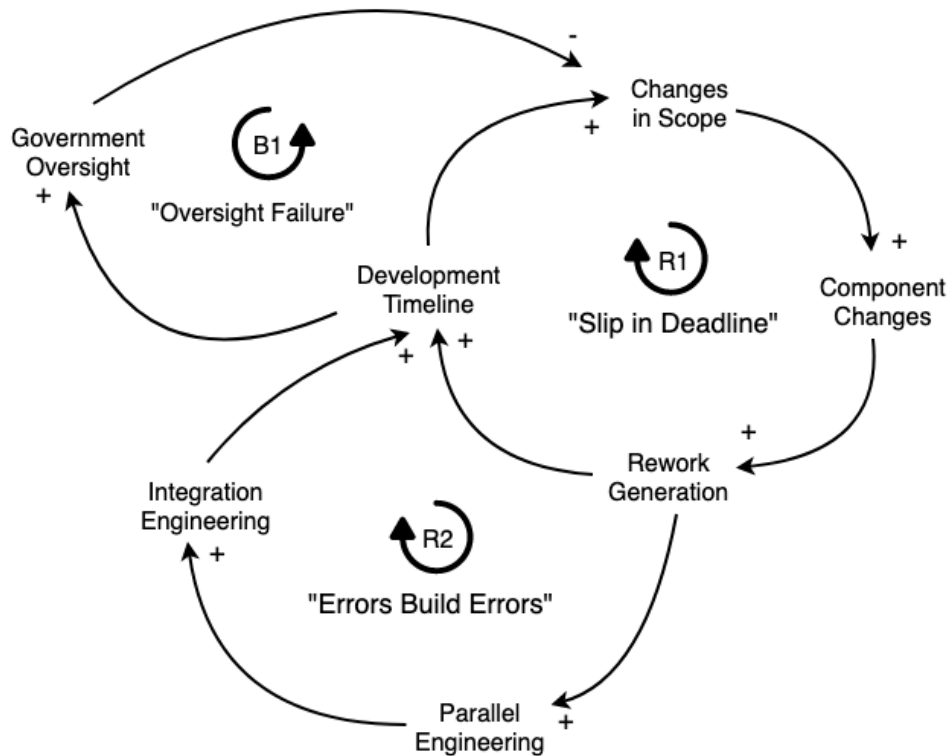


Figure 15. RMS CLD

1. Slip in Deadline Loop

Figure 16 depicts the loop “Slip in Deadline,” labeled “R1.” As with any SD analysis, the individual interactions within a loop are generally simple, however mapping and understanding the cumulative interactions combined with unrealized or underappreciated relationships within the system that provide novel insight. The “Slip in Deadline” loop considers four project features: “Changes in Scope,” “Component Changes,” “Rework Generation,” and “Development Timeline.”

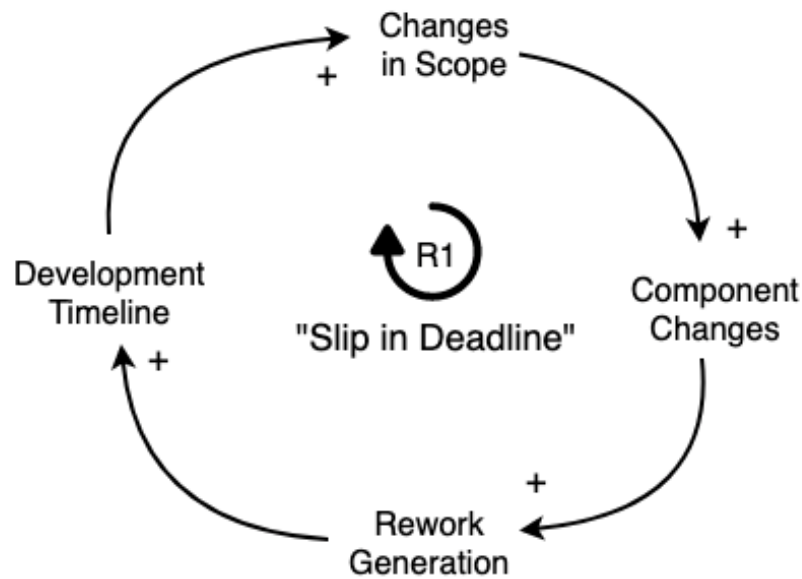


Figure 16. "Slip in Deadline" Loop

As captured in the summary of the RMS development, development timelines were significantly increased from the baseline estimates. The 1993 MNS released directed the procurement of system to allow for an organic mine detection capability for the Carrier Battle Group, Surface Action Group, Amphibious Task Force, and Amphibious Readiness Group assets. By 1999 a revision to the ORD reflected substantial system requirement changes including a change in specification for the L&RS to a non-modular DDG 51-only design. By 2006 the Navy had signaled at this time that it intended to operate the RMS solely on the LCS (Director, Operational Test and Evaluation 2006, 104). From 1993 to 2006 there were no less than four host-platform changes for the RMS. This shift in RMS hosting platform is represented by the positive relationship between "Changes in Scope" and "Component Changes"; as the scope of the project increased, the number of overall material solution also increased.

Material solution changes invariably lead to previous effort being rendered ineffective, work previously completed will need to be revisited, and the creation of additional work. The "R1" loop depicts the positive relationship between "Component

Changes” and “Rework Generation”; revisiting of previously completed work is obliged as material solutions change. As changing requirements, material solution, and rework generation increased the overall schedule is impacted (assuming no additional labor is applied). By viewing a system using SD, we see the program feature “Development Timeline” not only as being impacted by the preceding project features, by also as impacting follow-on project features. The length of the RMS’ development, 13-years between initial MNS and final host platform selection and 23 years between the initial MNS and program cancelation, was a direct contributor to the “Changes-in-Scope” feature and the remainder of the loop indirectly.

By tracing the loop, is it evident that “Development-Timeline” eventually acted upon itself in a reinforcing manner. The “Slip in Deadline” loop provides context on one of the major factors cited in both the program review supporting the Nunn Mcurdy decision and IDA’s analysis, erroneous or unrealistic baseline estimates for cost.

2. Errors Build Errors Loop

Figure 17 depicts the loop “Error Build Errors,” labeled “R2.” The loop describes the reinforcing interaction between project features “Rework-Generation,” “Parallel Engineering,” “Integration Engineering,” and “Development Timelines.” The casual loop focuses on programmatic decisions and performance outcomes that cause “Rework-Generation” to increase resulting in an increase in “Development Timeline.” As the nature of SD is cyclic and connective, the point at which a CLD is entered is not essential to its function. Additionally, as R2 is discussed in context of R1, it is natural to start the discussion with a program feature that is included in both loops, “Rework Generation.”

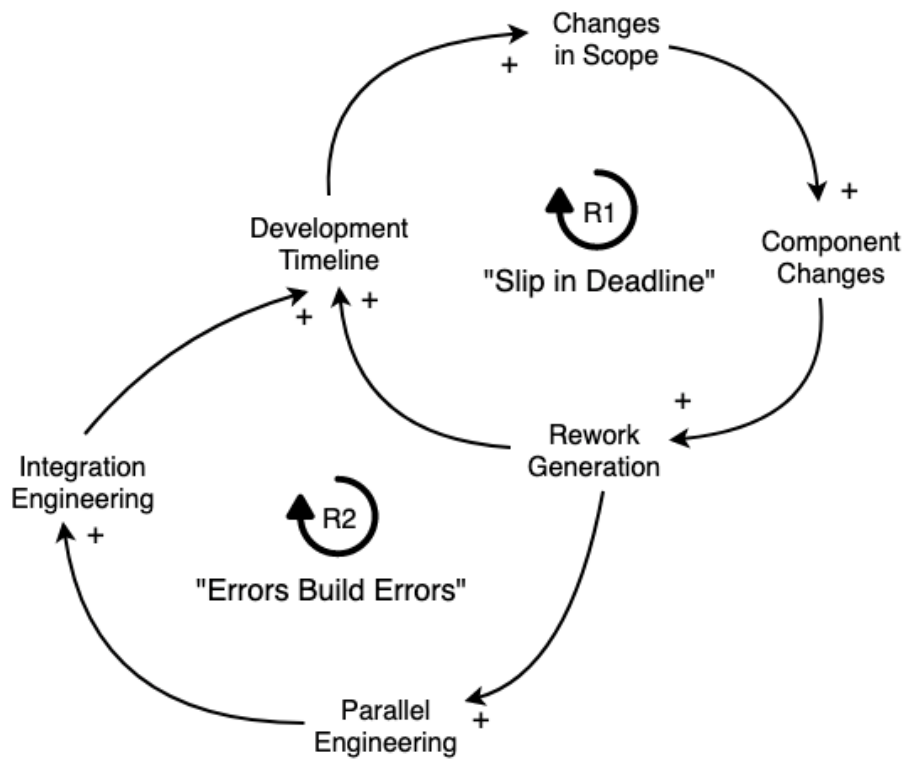


Figure 17. “Error Build Errors” Loop

The generation of rework can be tracked from RMV subsystem scope creep. The RMV was additionally required to allow for a joint procurement specification that could accommodate both a NAVO and anti-submarine mission, in addition to its anti-mine mission. RMV component changes added complexity as a result of the joint procurement specification and contributed to initially low performance and persistently low reliability in the system (DOD 2016). The integration of subcomponents, RMV included, was a major contributor to failed testing events and was ultimately cited as posing a “significant risk to the planned operational test of the Independence-variant LCS and the Increment 1 mine countermeasures (MCM) mission package” (Director, Operational Test and Evaluation 2016, ix). The amount of rework was increased, as previous development on the RMV and integration work with the other subsystems needed to be revisited, notably the RMV chassis and the L&RS; as the program feature “Component Changes”

increased, its positive relationship with “Rework Generation” resulted in a large amount of total work that needed to be completed.

Loop R1 now starts to interact with loop R2; subcomponent development and systems integration work was never completed before work halted on the RMS in 2016 after the IRT released its findings, some 12 years after the EDM contract was awarded. The delay in technology maturation and testing created by rework generation increased the percentage of RMS’ constituent components that needed to be developed at the same time, labeled as “Parallel Engineering” in the R2 loop. As subcomponents were changed, previous integration efforts are rendered invalid and the overall volume of “Integration Engineering” is increased. Specifically, delays in RMV development and VDS selection led directly to delays in the integration of these components with the L&RS, a direct contributor to CT event failures and changes in the definitions of KPP’s (Director, Operational Test and Evaluation 2006) (Martin 2009). Increases in the “Rework Generation” project feature led directly to increases in “Parallel Engineering” and “Integration Engineering.” By tracing the localized impacts of an error in requirement generation to capture and freeze the specification of the RMS, it is shown that the cumulative effect of interacting project features effected systems performance directly measurable by the measure of “Development Timeline.”

The discussion of the loop R2 helps to understand how SD can increase the understanding of system behavior. Loop R1 describes the simple interaction between “Rework Generation” and “Development Timeline,” an increase in work leads to an increase in timeline. However, when the R2 loop is considered, the discussion now includes not only the additional rework (such as the development of a new subcomponent), but the secondary impacts (such as the integration and mutual-interference effects) that affected program performance; the simple acknowledgment of these system behaviors will lead to better informed program management.

This example serves to trace a specific example through a causal loop to highlight impact of a programmatic decision in various locations in a system, ultimately having performance impacts. In the loop “Error build errors” an erroneous initial requirement generation process led to increased work and rework, effecting performance metrics

negatively and interacting with the rework cycle by increasing “Development Timeline.” Put simply, errors created additional errors, a finding made clear by the IDA’s findings that “inadequate contract planning, due to schedule pressures and personnel shortages” and a key contributor to two of the three Nunn Mcurdy root causes (unrealistic cost estimates and poor government management) (Bailey et al. 2010).

3. Oversight Failure Loop

Figure 18 depicts the loop “Oversight Failure,” labeled B1. The loop describes the balancing interaction that the project feature “Government Oversight” had, or should have had, on the RMS program. Although “Oversight Failure” can and did have impacts thought the system (such as in the “Error Build Errors” loop), by viewing this interaction as independent of other loops its impacts can be isolated and traced with the goal of creating actionable insight. Linking poor government management and governance, cited as a major factor by the IDA and as a root cause in the Nunn McCurdy program review, to the CLD requires specific and in-depth knowledge of individual programmatic decisions. Due to lack of knowledge in specific managerial decisions and processes in this RMS’ acquisition, impacts of specific programmatic decisions on the system cannot be included in this analysis. However, if taken as fact that “poor government management and governance” was a feature of the RMS program, then this feature has obvious interactions with the CLD and can be included in this analysis using general terms and highlight SD’s utility in including the “soft” elements of project management (Inouye 2010).

“Oversight Failure” is a balancing feedback loop, where the loop acts upon an input in a stabilizing manner. In this example, as the program feature “Development Timeline” increases “Government Oversight” should also increase. As oversight increases the desired behavior is a decrease to the following program features, starting with “Changes in Scope.” This feedback structure was built into the acquisition of the RMS, as it is with all Major Defense Acquisition Programs, through the Nunn-McCurdy Act which requires reporting past certain cost thresholds. A Nunn-McCurdy program review was triggered in 2009, but the oversight was not enough to overcome the programs failures. As an input into the loop, the result of the Nunn-McCurdy program

review did result in an increase in “Government Oversight” and the desired decrease in “Changes in Scope”.

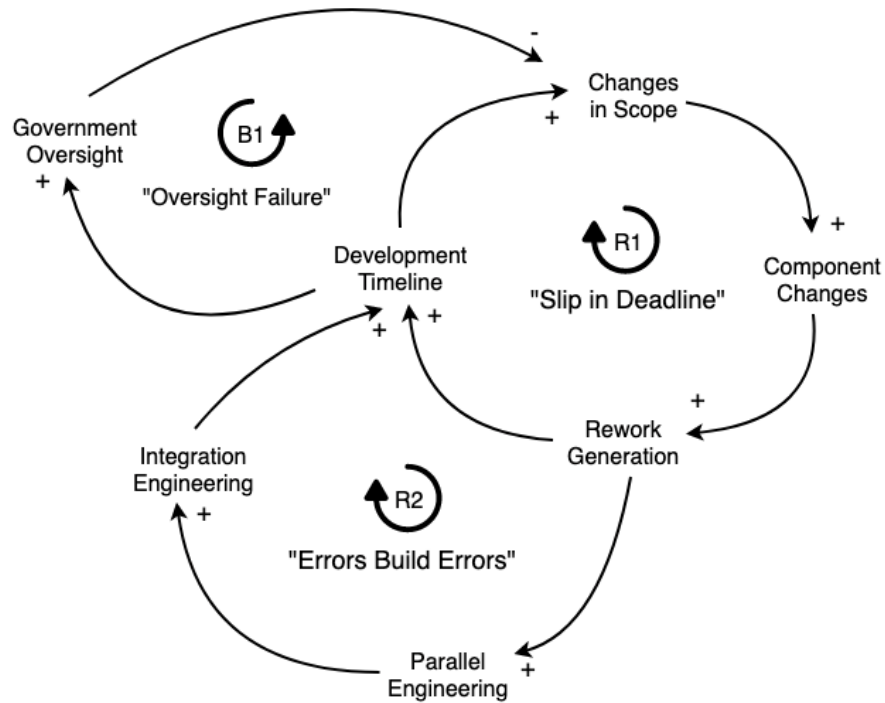


Figure 18. “Oversight Failure” Loop

Although there was an eventual increase in oversight, several examples are cited in the documentation of persistent inadequate oversight and management of the program. First, the U.S. Navy was sighted by the IDA as awarding an initial production contract “without adequately reviewing the contractor drawings, resulting in subsequent engineering change proposals and delays at government expense...the program office individually approved and signed less than 10% of the drawings that composed the data package” (Bailey et al. 2010, 9). Inadequate review of documentation led directly to “Changes in Scope” and follow-on interactions accordingly. The second example cited in the documentation of inadequate management of the RMS system is an immature design becoming a leading cause for “early developmental and production units falling short of the system’s performance thresholds for availability and reliability during testing. Although the reliability issues became apparent as early as 2005, the program office did not sufficiently address them before awarding any of the three LRIP contracts” (Bailey et

al. 2010, 9). As technologies and subcomponents failed to meet time and performance thresholds, adequate controls and mitigating actions were not taken in time to prevent an increase in the project features “Changes in Scope” and ultimately “Development Timeline.” These are examples where the loop “Oversight Failure” was not valid as the behavior of the system was not accurately represented by the CLD.

The inclusion of human interaction within a system is an area where SD has significant advantages to traditional project management techniques in providing useful insight. Both of the examples presented, while less useful to SD process than detailed programmatic decisions (addition of labor, prioritizing scheduling over other metrics, freezing designs, schedule buffers), are valid and useful to the CLD and in a SD analysis. Soft project features have wide reaching effects that are often under accounted in SE managers’ mental models (Rodrigues and Bowers 1996). The discussion of the casual loop diagram “Oversight Failure” provides two examples of how soft project features impact the performance of the system through interaction with the program features “Changes in Scope” and ultimately “Development Timeline” in the CLD and support the IDA’s findings that the system suffered from “inadequate contract planning” and the Nunn McCurdy root cause of “poor government management and governance” (Inouye 2010, 9).

4. CLD and the Rework Cycle

The impacts of dynamic behavior in systems can be difficult to understand or mitigate when the system is viewed in the traditional linear action/reaction-style model. Through a System Dynamics’ perspective, the impacts of programmatic decisions and outcomes can be better traced to origin, and their effects better understood through a relationship-based approach. Figure 19 connects the 3 constituent loops into the RMS CLD to components of the rework cycle, annotated in green. The interactions within a CLD are only of particular interest where they effect the rework cycle. The rework cycle, as discussed in context of Figure 5, provides a framework to quantify where system behavior translates to an amount of work to be completed for a given task.

Although an analysis can point to each part of the rework cycle as being impacted, this analysis will focus on two obvious interactions between the RMS CLD and

the rework cycle. First, the increased volume of “Integration engineering” impacted the “Error Generation rate” negatively. As discussed extensively, many factors within the “Errors Build Errors” loop led to an increased amount of “Integration Engineering” which directly impacted the error generation rate. As system sub-components were updated, specifications changed, or otherwise delayed the increased error generation rate acted in a reinforcing manner on the system; an increased error generation rate in-turn results in additional integration engineering work (along with many other impacts). As with many interactions in SD, this relationship is easy to underestimate or overlook entirely. Secondly, as the feature “Changes in Scope” increased, unsurprisingly the “Work to be done” bucket within the rework cycle increased. It is not the fact that changes in scope results in an increase in overall work to be completed that novel, is the estimation and understanding of the non-linear impact that scope changes that is of value. The RMS experienced many changes in scope, both in capability and material solution thought the span of the project. If project managers or oversight officials had better understood the consequences of scope changes, outcomes for the RMS may have been different.

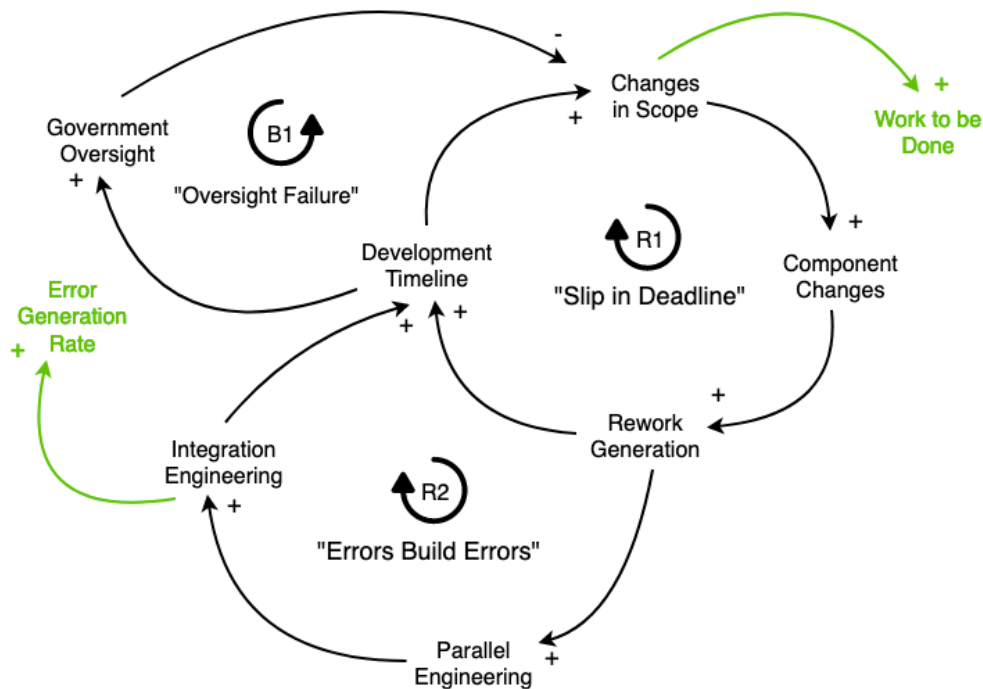


Figure 19. RMS CLD and the Rework Cycle

C. SD ANALYSIS SUMMARY

This SD analysis of the RMS strived to relate seven project features to system behavior through the context of a CLD. Although this analysis was limited to making strictly qualitative connections using project features of which information was available and who's impacts were significant to the performance of the program, all assertions were linked to previous works that did have access to the program and detailed data. Connections between project features provided context and understanding to the behavior of the RMS' acquisition in a novel way as compared to traditional project management techniques.

First project features of the RMS to be included in the analysis were discussed in general SD terms then with specific implications to the system. These project features were linked to programmatic documentation to legitimize them as useful and relevant. Next, a CLD was built into three distinct loops, two reinforcing and one balancing, using the discussed project features and defined relationships. These loops were discussed in context of the IDA findings and Nunn McCurdy Root causes reinforcing their conclusions. Finally, the CLD was related to the rework cycle in order to draw conclusions from those interactions and identify where system behavior impacted performance. This SD analysis highlighted the impacts of the "Error Generation Rate" and the volume of "Work to be Done" within the CLD as being novel insights of the SD process and useful to a management of the program.

As asserted previously, a SD analysis need only to be as detailed as useful. This analysis used the available documentation on a program of record in a post-mortem look at the applicability of the SD process to DOD program acquisitions in the goal of answering this research' primary research question: **How can the concepts and tools of System Dynamics provide insight into the factors that led to the to the Department of the Navy's unsuccessful acquisition of the Remote Minehunting System?** This analysis has revealed two useful insights into how SD's tools and approach are applicable to the DOD acquisition system in general and the RMS in specific: education of the SD theory and approach has great potential to better manage DOD acquisitions, and that

relationships established in this analysis are widely applicable to complex engineering and acquisition system.

To the first insight, a basic understanding of the principles of the rework cycle, the CLD, and the concepts and principles within SD provide context and understanding that do not require the extensive resources that would be needed for a complete quantitative SD analysis. An application of SD academic knowledge could have far reaching effects by shaping mental models to better understand and forecast the behavior of systems. With additional context, better estimations of a project's performance can be made before inception and impacts of decisions can be better understood once that project has begun. To the second insight, I assert that the relationships within the CLD existed in the RMS program from its inception, and are broadly applicable to program development and acquisition as a whole. By understanding these relationships from the beginning, the outcomes of the RMS acquisition may have been improved. Broadly, if these relationships exist in the general context of large program development then an understanding of these relationships could provide valuable understanding of the relative impacts of individual program features. The DOD could benefit greatly from an empirical understanding and application of how these project features interact with each other and impacted the system as a whole. Although there is much value to be gained from the application of SD theory, the use of that theory in the building of an qualitative SD model has the potential to more completely inform decision making, better understand risk, and ultimately improve acquisition outcomes.

VI. CONCLUSION

A. SUMMARY

This research provides a case study to demonstrate how the application of System Dynamics theory can provide a unique and valuable tool to the DOD acquisition process. This research relied on the independent assessments from the Institute for Defense Analysis and Congressional Research Service as well as public records on the RMS to apply the theory of SD. Both the Nunn McCurdy's stated root-causes and the IDA's findings provided context on how program management and acquisition decisions effected both acquisition and system performance. Program outcomes of the RMS were linked to SD theory, suggesting that SD can provide additional context and explanation of system behavior.

The analysis focused on seven major project features that information was available and who's impacts were significant to the performance of the program. The interactions between program features were described in a CLD and then connected to the rework cycle. Conclusions were drawn between the interactions between the CLD and rework cycle, and the RMS literature. Although data was unavailable to quantify many of the connections within the CLD, the acknowledgment and discussion of their interdependences allows for useful insights and the expansion of mental models. System Dynamics provided insight into the factors leading to the unsuccessful acquisition of the RMS but highlighting the complexity and non-obvious nature of the various interacting features of the program.

By focusing on the modeling of behavior, inclusion of non-linear and complex interactions, as well as treating the human-element as a part of the system, the theory and practice of SD modeling allows for a more holistic, complete, and true representation of a system. When emergent behavior becomes more readily understood, insight is gained into how the system as a whole is impacted. As Dr. Forrester, System Dynamics' earliest practitioner and champion states it: "System dynamics modeling can organize the descriptive information, retain the richness of the real processes, build on the experiential knowledge of managers, and reveal the variety of dynamic behaviors that follow from

different choices of policies” (Forester 1995, 14). This analysis of the Remote Minehunting System stresses the need for the DOD’s acquisition system to use all the tools available to best understand how an acquisition system will behave in the reality of a complex, non-linear, and human driven environment.

B. FUTURE RESEARCH

This analysis was centered on a retrospective look at the cancelled RMS program using largely qualitative statements derived from qualitative analysis’ unavailable for use in this report. While an analysis of an unsuccessful program is vital to learning from failure, SD’s true value is in its application thought the acquisition process. Given the time and data availability, the next step in this line of research would be the creation of an analytical model to generate the values of interactions within the SD model. Eventually, with a large enough sample size in SD models, patterns of interactions will emerge and prove useful in the creation and use of a risk-based decision-making tool for a project in early acquisition stages. Models should focus on the measure and inclusion of the external human factors to best complement and add value to traditional program management techniques.

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