

LAWRENCE TECHNOLOGICAL UNIVERSITY

A. Leon Linton Department of Mechanical Engineering

Model-Based Systems Engineering Application to Analyze the Ground

Vehicle and Robotics Sustainment Support Strategy

Presented in partial fulfillment of the requirements for the degree of

Doctor of Engineering in Manufacturing Systems (DEMS)

by

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Doctor of Engineering in Manufacturing Systems (DEMS)

This dissertation has been reviewed and accepted by the examination committee.

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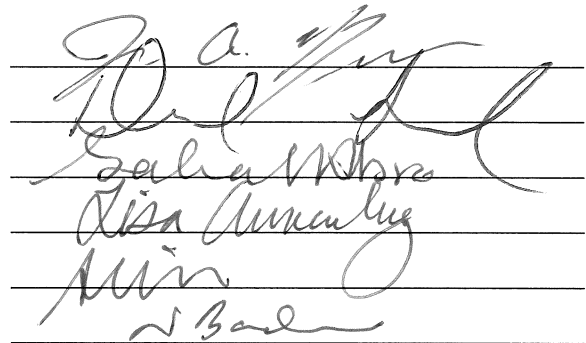
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ABSTRACT

Model-Based Systems Engineering and Logistics Engineering are emerging disciplines that offer a synergy for integrating the proactive modeling of prototype R&D acquisition and industrial base sustainment support into a framework that characterizes the most influential phases of the Department of Defense ground vehicle and robotics equipment life cycle. This research enhances situational awareness of upstream factors that drive the capability and capacity constraints to leveraging new technology for sustainment risk mitigation. These capability and capacity constraints include sub-optimal supply chain coordination and limited collaboration between government R&D centers. This research also demonstrates how a new business model called the Defense Mobility Enterprise solves these problems, while offering an incubator for Model-Based Systems Engineering experimentation and continuous productivity improvement. Through the successful application of SysML, the modeling language of systems engineering, this research concludes with multi-model orchestration, using the momentum of commercial-off-the-shelf tools, providing a strategic lens with which to specify, analyze, design, and verify Department of Defense ground vehicle and robotics technology transition opportunities.

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NOMENCLATURE

2D	Two Dimensional
3D	Three Dimensional
AAC	Acquisition Advice Code
AD	Axiomatic Design
AHP	Analytic Hierarchy Process
AL&T	Acquisition, Logistics, and Technology
AMC	Army Materiel Command
AMDF	Army Master Data File
AMRDEC	Aviation and Missile Research, Development, and Engineering Center
AMSAA	Army Materiel Systems Analysis Agency
AMUC	Average Manufacturing Unit Cost
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
Ao	Operational Availability
AoA	Analysis of Alternatives
APICS	American Production and Inventory Control Society
APS	Advanced Planning and Scheduling
AR	Augmented Reality
AR	Army Regulation
ARC	Automotive Research Center
ARCIC	Army Capabilities Integration Center
ASAALT	Assistant Secretary of the Army for Acquisition, Logistics, and Technology
ASEC	Advanced Systems Engineering Capability
ASME	American Society of Mechanical Engineers
ATK	Andrew Thomas Kearney
ATP	Advanced Technology Program
AutoSoft	Journal of Intelligent Automation and Soft Computing
AUVSI	Association for Unmanned Vehicle Systems International

AV	Augmented Virtuality
BAH	Booz Allen Hamilton
BCITs	Brain-Computer Interaction Technologies
BOB	Best-of-the-Best
BOM	Bill of Material
C2	Command and Control
C3V	Cortically-Coupled Computer Vision
CAC	Common Access Card
CAD	Computer Aided Design
CAPS	Center for Advanced Purchasing Studies
CERDEC	Communications and Electronics Research, Development, and Engineering Center
CFAR	Collaborative Forecasting and Replenishment
CHASM	Collaborative High Speed Adaptive Supply Chain Model
CCIMPLEX	Consortium for Intelligent Integrated Manufacturing Planning-Execution
CCR	Contracting Control Registry
CM	Configuration Management
COA	Course of Action
COTS	Commercial-off-the-Shelf
CPAT	Capability Portfolio Analysis Tool
CPFR	Collaborative Planning, Forecasting, and Replenishment
CPS	Cyber-Physical System
CSCMP	Council of Supply Chain Management Professionals
CTMA	Commercial Technologies for Maintenance Activities
CY	Calendar Year
DA	Department of the Army
DBS	Decision Breakdown Structure
DME	Defense Mobility Enterprise
DEMS	Doctorate of Engineering in Manufacturing Systems
DFL	Design for Logistics
DFM	Design for Manufacturing

DFS	Design for Supportability
DFS	Design for Sustainment
DLIS	Defense Logistics Information Service
DM	Decision Management
DMSMS	Diminishing Manufacturing Sources and Material Shortages
DoC	Department of Commerce
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DOE	Design of Experiments
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities
DS	Distributed Simulation
DSM	Design Structure Matrix
DSPO	Defense Standardization Program Office
ECP	Enterprise Collaborative Portal
EDA	Equipment Downtime Analyzer
EECOMS	Extended Enterprise Coalition for Integrated Collaborative Manufacturing Systems
EEG	Electroencephalography
EEP	Enterprise Expertise Portal
EIA	Electronics Industry Alliance
EIP	Enterprise Information Portal
EKP	Enterprise Knowledge Portals
EJOR	European Journal of Operational Research
EOL	End of Life
ER&D	Engineering, Research, and Development
ERP	Event-Related Potential
EUABs	Equivalent Uniform Annual Benefits
FBD	Free Body Diagram
FCS	Future Combat Systems
FMEA	Failure Mode and Effects Analysis

FMS	Foreign Military Sales
FOUO	For Official Use Only
FR	Functional Requirement
FSC	Federal Supply Class
GCS	Ground Combat Systems
GUI	Graphical User Interface
GV	Ground Vehicle
GVR	Ground Vehicle Robotics
GVS	Ground Vehicle Systems
GVSETS	Ground Vehicle Systems Engineering Technology Symposium
HC	Human Capital
HEMTT	Heavy Equipment Medium Tactical Truck
HIIT	Helsinki Institute of Information Technology
HLA	High Level Architecture
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
IB	Industrial Base
IBAT	Industrial Base Analysis Tool
IBBA	Industrial Base Baseline Assessment
IBET	Industrial Base Engineering Team
IBHD	Industrial Base Health Directorate
IEEE	Institute of Electrical and Electronics Engineers
IFPSM	International Federation of Purchasing and Supply Chain Management
IJSI	International Journal of Social Inquiry
ILAP	Integrated Logistics Analysis Program
ILSC	Integrated Logistics Support Center
INCOSE	International Council on Systems Engineering
INFORMS	Institute for Operations Research and the Management Sciences
I/O	Input and/or output
IPSERA	International Purchasing and Supply Education and Research Association
IRSP	International Research Study of Public Procurement
ISCMS	Logistics and Supply Chain Management Society

ISM	Institute for Supply Chain Management
ISO	International Organization for Standardization
IT	Information Technology
JCIDS	Joint Capabilities Integration Development System
JMTM	Journal of Manufacturing Technology Management
JOM	Journal of Operations Management
JOSCM	Journal of Operations and Supply Chain Management
KT	Kepner Tregoe
LCMC	Life Cycle Management Command
LE	Logistics Engineering
LHS	Latin Hypercube Sampling
LSS	Lean Six Sigma
LTV	Light Tactical Vehicles
LMP	Logistics Modernization Program
M&S	Modeling & Simulation
MARCORSYSCOM	Marine Corps Systems Command
MBE	Model-Based Engineering
MBSE	Model-Based Systems Engineering
MDSD	Model-Driven System Design
METP	Materiel Enterprise Transformation Plan
MIT	Massachusetts Institute of Technology
MODAF	Ministry of Defense Architectural Framework
MOM	Model of Models
MR	Mixed Reality
MSR	Minimum Sustainment Rate
NAF	North Atlantic Treaty Organization Architectural Framework
NAMC	National Advanced Mobility Consortium
NAPA	National Association of Purchasing Agents
NASA	National Aeronautics and Space Administration
NCMS	National Center for Manufacturing Sciences
NDIA	National Defense Industrial Association

NIGP	National Institute of Governmental Purchasing
NIIN	National Item Identification Number
NIST	National Institute of Standards and Technology
NMCM	Non-Mission Capable for Maintenance
NMCS	Non-Mission Capable for Supply
NPI	Non-Procurement Item
NPR	NASA Procedural Requirement
NSF	National Science Foundation
NSRDEC	Natick Soldier Research, Development, and Engineering Center
NVA	Non Value Add
O&S	Operations & Support
OBSE	Object-Based Systems Engineering
OEM	Original Equipment Manufacturer
Op Tempo	Operating Hours
ORSA	Operations Research Society of America
OSMIS	Operating and Support Management Information System
OTA	Other Transaction Agreement
P&IM	Production & Inventory Management
PAT	Process Analytical Technology
PBD	Platform-Based Design
PBOM	Provisioning Bill of Materials
PCM	Pacific Conference on Manufacturing
PDS	Parallel and Distributed Simulation
PEO	Program Executive Office
PM	Program Manager
PMAC	Purchasing Management Association of Canada
PMR	Provisioning Master Record
P/N	Part Number
Pro/E	Pro Engineer
PS	Parallel Discrete-Event Simulation
PSM	Product Support Manager

PTC	Parametric Technologies Corporation
QbD	Quality by Design
QbI	Quality by Inspection
QbT	Quality by Testing
QFD	Quality Function Deployment
RFP	Request for Proposal
RPI	Risk Priority Indicator
RPSTL	Repair Parts and Special Tools List
RSVP	Rapid Serial Visual Presentation
RTC	Robotics Technology Consortium
RTI	Run Time Infrastructure
S&T	Science & Technology
S2T2	Sector-by-Sector-Tier-by-Tier
SA	Situational Awareness
SA	State Analysis
SAMS-E	Standard Army Maintenance System – Enhanced
SARSS	Standard Army Retail Supply System
SB	Sequential Bifurcation
SC	Supply Chain
SCC	Supply Chain Council
SCM	Supply Chain Management
SCOR	Supply Chain Operations Reference
SCRM	Supply Chain Risk Management
SD	System Dynamics
SE	Sustainment Engineering
SE	Systems Engineering
SERA	Sustainment Engineering Risk Assessment
SME	Subject Matter Expert
SMEs	Small and Medium Enterprises
SMO	State Model Object
S/N	Signal-to-Noise

SOP	Standard Operating Procedure
SoSAT	System of Systems Analysis Toolset
SOW	Statement of Work or Scope of Work
SPRDE	Systems, Planning, Research, Development, and Engineering
SQL	Structured Query Language
SSSS	Sustainment Support Strategy State
STEM	Science, Technology, Engineering, and Mathematics
SUSV	Small Unit Support Vehicle
SWA	South West Asia
SWaP+C	Space, Weight, Power, and Cooling
SWaP+C+L	Space, Weight, Power, Cooling, and Logistics
SysML	Systems Modeling Language
TACOM	Tank Automotive Command
TARDEC	Tank Automotive Research Development and Engineering Center
TDP	Technical Data Package
TIMS	The Institute of Management Sciences
TKK	Teknillinen Korkeakoulu (Finnish for Helsinki University of Technology)
TM	Technical Manual
TOGAF	The Open Group Architecture Framework
TRANSNAV	International Journal of Marine Navigation and Safety of Sea Transportation (a.k.a. Transportation Navigation)
TRIZ	teorija rezhenija izobretalenskikh zadach (Russian for theory of inventive problem solving)
UML	Unified Modeling Language
UNCTAD	United Nations Conference on Trade and Development
UPDM	Unified Profile for DoDAF and MODAF
USD	U.S. Dollars
VIICSO	Voluntary Inter-Industry Commerce Standards Organization
VRA	Vehicle and Robotics Alliance
VRA PO	Vehicle and Robotics Alliance Program Office
VSM	Value Stream Mapping

VSR	Virtual Situation Room
VTT	Valtion teknillinen tutkimuskeskus (Finnish for Technical Research Centre of Finland)
WBS	Work Breakdown Structure
WCCI	World Congress on Computational Intelligence
WILD	Web Integrated Logistics Designer
WIP	Work in Process
WOW	Worst-of-the-Worst
WSC	Winter Simulation Conference
WSTAT	Whole Systems Trade Analysis Tool
WTO	World Trade Organization

1. INTRODUCTION

1.1 Motivation

A sustainment support strategy for a piece of equipment encompasses the nature by which the piece of equipment is to be acquired by its users, once the equipment has been initially fielded. This post-fielding phase of the lifecycle is commonly known as the sustainment phase. A sustainment support strategy includes the reasons behind how equipment is to be made and fielded. It also includes the legal conditions, batch size, and frequency by which equipment will be procured, how equipment is to be introduced into the system, who is authorized to remove, install, or dispose of it, and many other facets. Equipment is either routinely operationally available during the sustainment phase, or it experiences degrees of unavailability based on its underlying support strategy.

When they are created, sustainment support strategies are fixed, while the manufacturing technology and economic forces that influenced the strategy evolve. Sustainment support strategies are often only modernized after problems occur in the field (i.e. reactive), as opposed to being modernized based on the technological capabilities of industry and academia (i.e. proactive). As an example, the 6.2L diesel engine High Mobility Multi-Purpose Wheeled Vehicle variant experienced a reactive field issue in 2011. The issue stemmed from fuel lines being out of production. To justify the effort of the supplier rebuilding the fuel line production tooling and demanding a high piece price, multiple sustainment support strategies were generated reactively to provide alternate options to save money. Inefficient effort was spent setting up a reverse engineering initiative for the

fuel lines, before the critical discovery was made that the strategy (as defined by a previous executive office) was to cancel the sustainment of the High Mobility Multi-Purpose Wheeled Vehicle with the 6.2L variant. In other words, the fuel lines had been deemed obsolete by a separate government organization a year BEFORE the field issue arose.

A solution is needed to help codify the practice of systems engineering in the logistics and acquisition domains. No framework exists that integrates ground vehicle and robotics sustainment strategies with technology transition opportunities. Model-based frameworks will enable communities of analysts to interact within a common environment that mitigates the risk of making conflicting decisions. The Department of Defense should integrate more developed frameworks and working models into everyday practice, because there is an “undercapitalization of business systems, IT systems and design and modeling tools, all of which should be modernized” to sustain the organization of the future [1, 2, 3, p. 118, 4]. Exercising modeling & simulation, this work integrates the structure, behavior, and requirements of ground vehicle and robotics sustainment support strategies in conjunction with technology transition opportunities.

1.2 Background

The U.S. industrial base is a vital asset that needs to be effectively managed so it can supply equipment over a product life cycle [2, 5]. Currently, the U.S. Army obligates billions of dollars of resources towards the sustainment of equipment based on support strategies that are often outdated. Diminishing Manufacturing Sources and Material Shortages (DMSMS) are market forces that negatively affect product availability [6, p. 1]. A military sustainment support strategy for any particular system is encoded in its list of repair equipment and the industrial base that provides it. After a system is fielded, it is maintained throughout the entire sustainment phase, through the ordering spare parts from an industrial base that is expected to be on call, regardless of economic conditions. At worst, suppliers may go out of business and analysts become aware at the same time the public does [7]. When a list of repair parts and corresponding supply chain is initially devised, the current economic conditions influence decisions to choose between parts, suppliers, and levels of repair that offer the best business case. As economic conditions change, repair part support strategies become sub-optimal if they are not updated periodically. Even if the repair parts strategies are sub-optimal, being aware of new technology can still prepare strategists for changes. Therefore, “it is imperative for program managers to adopt and fund a robust DMSMS management strategy and plan, in concert with proactive technology management, early in the life cycle” [8, p. iii].

For example, Figure 1 depicts how Beta video equipment became obsolete, due to the onset of the VHS format. Let t_i be the initial time a new technology begins to emerge and

t_f represent the final time when the emerging technology is destined to overcome the outdated technology.

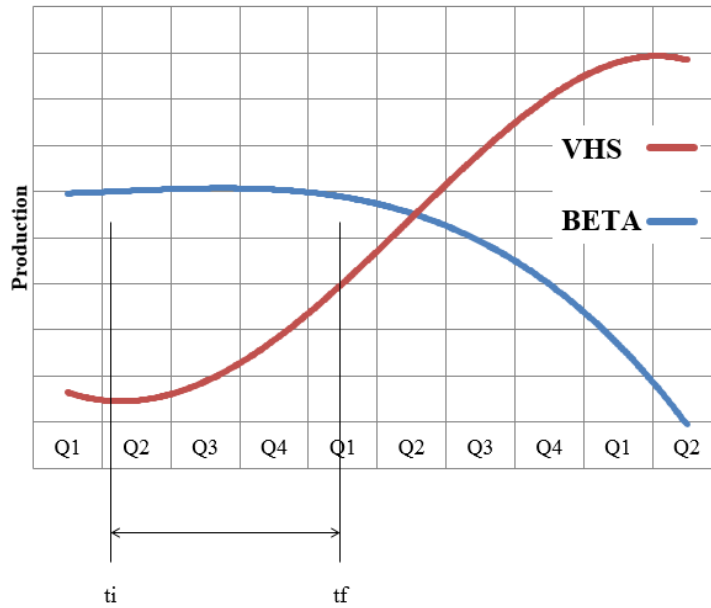


Figure 1. Notional example of obsolescence indicators in R&D domain, using VHS and Beta video formats

For example, if the Beta line (blue) represents the status quo repair part managed in the logistics realm and the VHS line (red) represents the new technology or capability managed in the R&D realm, the influences on one another may go unnoticed until it is too late. In this example, VHS takes over, leaving Beta obsolete and unavailable.

Analogous to the renter versus consumer enigma [9], the Beta versus VHS depiction can result in the Department of Defense (DoD) getting stuck trying to acquire and maintain sub-optimal equipment, forcing the warfighter to have only “second best”, at outdated prices. This is why major DoD Original Equipment Manufacturers (OEMs) often invite their R&D, or “tech transfer team”, to their obsolescence reviews. In these reviews, equipment obsolescence is studied in conjunction with technology readiness. Decisions

are then made whether to pull ahead new technology to replace the aging equipment or wait until the technology matures further. These practices “emphasize technology insertion and refresh in program planning” [10].

The Technology Readiness Level (TRL) scale of assessment is one way to associate formal stages of readiness to technology insertion trigger points [11]. First, a numeric value is assigned to nine stages of the technology development lifecycle, ranging from “Basic Principles observed and noted” (TRL1) through “Actual system “flight proven” through successful mission operations” (TRL9), as listed below:

TRL 1: Basic Principles observed and noted

TRL 2: Technology concept or application formulated

TRL 3: Experimental and analytical critical function and characteristic proof of concept

TRL 4: Component or breadboard validation in a laboratory environment

TRL 5: Component or breadboard validation in a relevant environment

TRL 6: System or subsystem model or prototype demonstrated in a relevant environment

TRL 7: System prototype demonstration in an operational environment

TRL 8: Actual system completed and “flight qualified” through test and demonstration

TRL 9: Actual system “flight proven” through successful mission operations

Then, the TRL scale can be superimposed over lifecycle decision points, as shown in Figure 2.

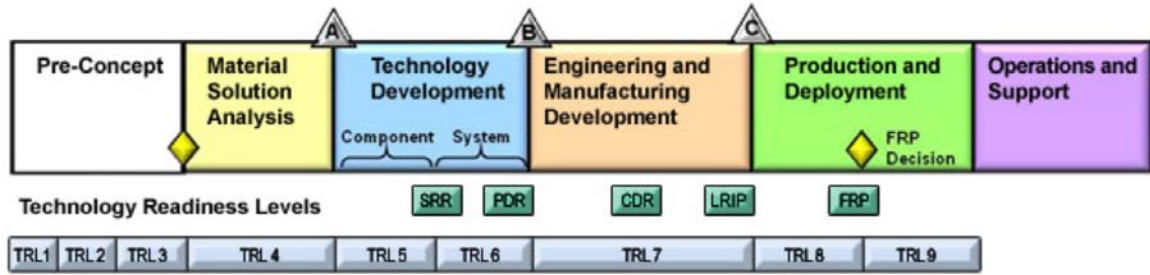


Figure 2. Technology Readiness Levels [11]

For example, t_i could be assigned to the level called “System Prototype Demonstration in an Operational Environment” (TRL7), whereas t_f could be assigned to the level called “Actual System Completed and Flight Qualified Through Test and Demonstration” (TRL8). The interval between t_f and t_i in Figure 1 is a strategic resource that often goes to waste in organizations that lack awareness and proactive modeling & simulation (M&S) fluency between the R&D and logistics/sustainment realms. In terms of Figure 2, “DMSMS mitigation should be planned even before Material Solution Analysis” [12].

1.2.1 U.S. Military DMSMS Trends

The defense workforce is experiencing information overload, staff attrition, old-fashioned office tools, and defense spending cuts. Together, these lead to poor collaboration and low productivity among sustainment analysts and strategic planners [13]. With many Vietnam-era professionals leaving the workforce, a new generation of analysts must quickly learn unfamiliar jargon, industries, and even resources that cut across the doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) elements of DoD processes. Legacy information technology

systems and the need to establish networks of colleagues adds difficulty to the already steep, next generation federal employee learning curve.

Groups of analysts researching individual aspects of the industrial base (IB) are spread over multiple hierarchies, locations, and agencies; each with their own history, culture, and mission. For example, although the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) Systems Engineers (SEs) are beginning to work on more sustainment-related tasks, the Integrated Logistics Support Center (ILSC) houses the core logisticians who work on Tank Automotive Command (TACOM) sustainment support. However, according to DoD policy, the Product Support Managers (PSMs) are solely responsible for sustaining operations over the equipment life cycle and consequently report directly to the equipment Program Manager (PM) [14]. As a result, the U.S. Army Research, Development, and Engineering Centers (RDECs) have acknowledged a need for more collaborative analysis between these disparate roles and responsibilities. In the defense industry, logistics engulfs most of the domains that contribute to the make-up of existing equipment sustainment support strategies. In fact, logistics data includes many features of the acquisition and contracting domains as well. Cross-domain logistics data is underutilized in the realm of supportability analyses and sustainment modeling & simulation, partly due to the fact that engineering is not a typical career field within the logistics discipline. However, varying connotations of job classifications and office location cultures often cloud roles and responsibilities (i.e. mission requirements). “For example, a supportability integrated product team (IPT) should have representatives from the disciplines that will influence the supportability of

the item. In other words, a supportability IPT should not be simply a relabeled logistics management team comprised solely of logisticians” [15, pp. 9-3]. Since the majority of a system’s life-cycle cost is accrued in the sustainment phase, a high potential exists for identifying key relationships through the virtual experimentation of logistics factors and their corresponding ramifications during the sustainment phase.

As part of a workforce culture rejuvenation, the Logistics Engineering (LE) discipline and accompanying curriculum was created within TARDEC to help bridge the gap between the multiple groups and processes within TACOM that influence the sustainment of existing equipment, as shown in Figure 3 [16].

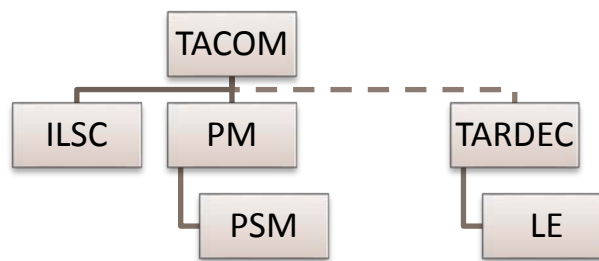


Figure 3. Logistics Engineering Discipline

This is in line with the supportability analyses activities that are part of any robust systems engineering strategy and that product support analysis be “an integral part of the systems engineering process” [15, pp. 5-12, 17]. In terms of importance, Logistics Engineering adds a new dimension to the Payload-Protection-Performance tradeoff paradigm of Figure 4, below.

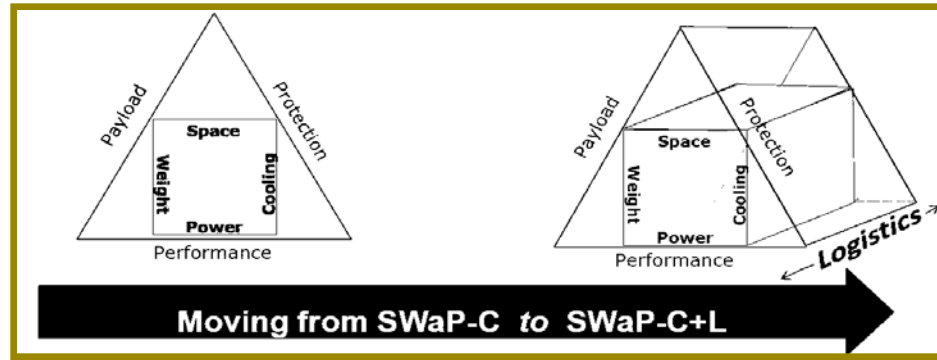


Figure 4. Paradigm change to a logistics frame of mind [18]

The word logistics includes “planning and executing the sustainment of forces and equipment in support of military operations” [13]. As illustrated in Figure 4, senior leadership is emphasizing that equal consideration be given to the logistics ramifications of equipment design decisions. The major focus of sustainment logistics is to ensure that fielded systems are maintainable and ready for operations.

Army Regulation AR 70-1 states that supportability analyses must be conducted as an integral part of the SE process [19]. Because the IB provides the instruments of sustainment and supportability, IB M&S should also be considered integral to success. Army Regulation AR 70-1 also states that “the use of M&S should be considered throughout all modifications and upgrade efforts, as well as measuring supportability and military worth”. Therefore, LE practices are being incorporated throughout TACOM, in an effort to better understand the biggest culprit of life-cycle costs, as portrayed in Figure 5 below. Synonymous to Figure 2, Figure 5 superimposes equipment life-cycle cost over six generalized phases: 1) Concept Exploration/Definition, 2) Demonstration/Validation, 3) Engineering/Manufacturing Development, 4) Production and Deployment, 5)

Operations and Support (O&S), and 6) Disposal. Most analysts new to the defense industry do not realize the amount of time and money associated with sustaining equipment from the time it is fielded to the time of its demilitarization. Stereotypical technology analysis and engineering activities often disappear after the Production and Deployment Phase, as depicted by the placement of TRL 9 in Figure 2. However, the Operations and Support (O&S) Phase, oftentimes referred to as the heart of the Sustainment Phase, accounts for approximately 70% of an equipment's life-cycle cost with "95% of the O&S costs locked in before a system goes into production" [20, 21].

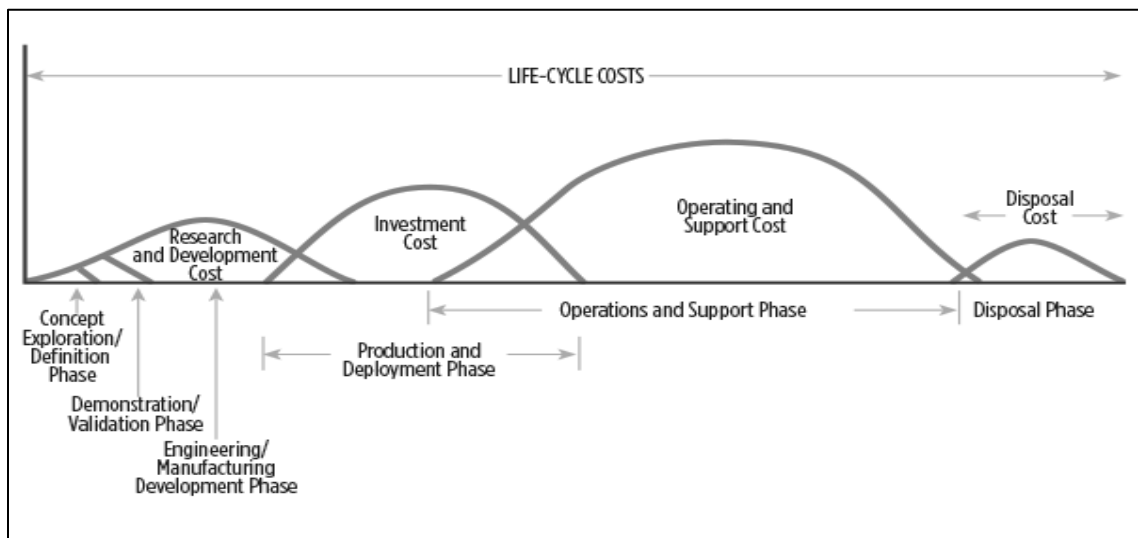


Figure 5. Constituents of life-cycle cost [22]

TARDEC sponsored an offshoot Design for Sustainment (DFS) movement, through the execution of key portions of the Human Capital (HC) initiative. The HC initiative weighed the short and long term skills needs of TARDEC with the current and future staff, respectively [23]. The lessons learned from the HC initiative revealed that improved capabilities in information technology (IT), communication, and strategic thinking are in higher demand than the traditional skill sets of the past (e.g. mechanical engineering).

Uncovering new M&S techniques for analyzing strategic IB information is a research area that answers the call for IB analysis, while fulfilling the gaps identified in the HC initiative. Therefore, a collaborative IT design solution that solves problems for the modern acquisition workforce is considered to be high value.

1.2.1.1 Case Study: HMMWV Fuel Lines

For most platforms, over 90% of the platform's repair parts are managed by the Defense Logistics Agency (DLA). In Chapter 4, this percentage will be calculated for a specific platform. DLA management of the majority of platform repair parts is an economies-of-scale logistics strategy stemming from WWII to promote commonality and price reduction [24]. Many times, DLA attempts to purchase a batch of repair parts, but cannot. For example, a part may no longer be in production, prices have increased, a producer may have gone out of business, or a producer may have been acquired by a foreign source. In most of these cases, DLA issues a "Form 339" requesting engineering support which includes actions such as identifying an alternative source of supply, reverse engineering, or forcing a next higher assembly purchase strategy. Form 339s are usually reactive DMSMS instances. In other words, engineering analysis is usually only brought into logistics affairs when a sustainment support strategy has failed. Figure 6 illustrates a common repair environment for the High Mobility Multi-Purpose Wheeled Vehicle (HMMWV) that experienced DMSMS issues in 2011 on the fuel lines for the 6.2L diesel engine.



Figure 6. High Mobility Multi-Purpose Wheeled Vehicle 6.2L repair environment

Figure 7 shows a Form 339 that was issued in 2011 for one of the fuel lines (cylinder #2) that was out of production and demanded a high piece price, in order to justify the cost of the supplier choosing to run another batch.

Request For Engineering Support				
Case Number: DSCC-FM-11-49540		Start date: 05/18/2011		Due date: 08/16/2011
Revision letter:		Revision date:		Required Award Date:
Suffix letter: A		ECD:		Need Arrival Date:
SICA: AZ		ECD reason:		
Army: AJ ☒ AZ BD BF BG CL CT	Navy CIMCOS: CH CP JX LH NI PX			
Navy: GA ☒ HD HX KE				
USAF: GT SG ST SU ☒ SX TG	USMC: ☒ PA NSA: XN			
USCG: XF XG XH XK				
Requesting office: DSCC-FMDB		Point of contact:		
Address:		Phone:	DSN:	Comm:
		Fax:	DSN:	Comm:
		Email Address:		
DSC engineer/Technician reviewer name:				
Email address:		Phone:	DSN:	Comm:
ESA Response Time Required: F 90 Days				
Nomenclature	NSN	CAGE	Part Number	Reason for Sending
TUBE ASSEMBLY METAL	4710011489580	7X677	14033912	ALT
Critical Application Item(CAI): YES	AMC/AMSC: 1B		Is this a CIT Item? NO	
Critical Safety Item(CSI):			LIM:	
SPC:			ETD:	
DLA Request for Engineering Support (check all that apply (Describe in DLA Text)) ☒ A. Alternate method of support 1. Contractor advises item obsolete without replacement 2. Contractor/Manufacturer does not recognize part number 3. NSN: CAGE: P/N: is recommended as a replacement 4. Contractor out of business or moved without forwarding address ☒ 5. Product line discontinued 6. Technical data required for open competition B. Alternate Offer Manufacturer: CAGE: Point of contact: Phone: Category: 4 N/A 1. To manufacture IAW OEM drawing No: Rev: Encl: 2. To supply CAGE: P/N: IAW technical data encl: 3. Potential cost savings/Improved delivery description: C. Item non-conformance(waiver/deviation)/ECP/VECP: N/A ☒ D. Request technical data package development or validation ☒ 1. Development ☒ 2. Validation ☒ 3. Screening				

Figure 7: Example Form 339 from fuel line case [25]

DLA Form 339s are issued for reasons such as this and include basic information (e.g. part number, agent contact information, description) necessary for an engineer to investigate the case and devise a sustainment support solution for the DLA analyst. The total number of engineering hours spent working the case is sometimes logged into a database and is considered to be only a fraction of the total time spent on the case, since multiple organizations are often consulted, prior to closing the Form 339 with a path forward. Discovering the many stakeholders for a piece of equipment as simple as a fuel line requires hours of coordination, if a case is to be properly worked. A systemic understanding of the Work Breakdown Structure (WBS), or even the hierarchy of replacement part-to-system options as can be acquired through Technical Manual illustrations (such as the ones shown in Figure 8), is usually a good first step.

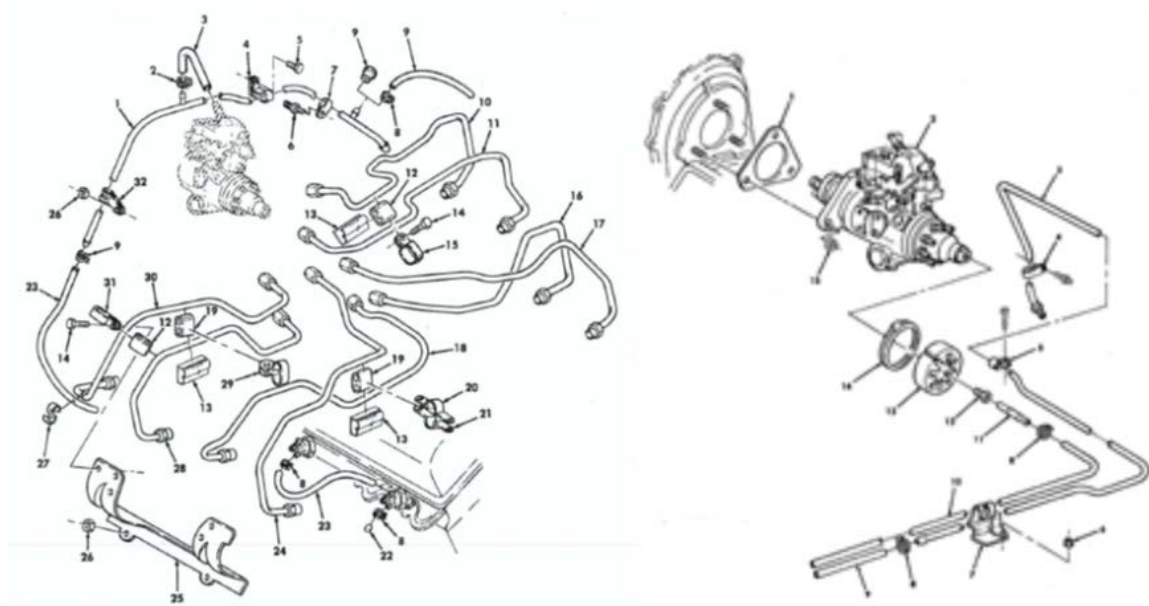


Figure 8. Fuel line parts exploded view [26]

Since the many pieces of information that get patched together to build the sustainment support strategy for a piece of equipment are not properly connected, document-based

diaries, like the one shown in Figure 9, are often created by engineers and stored in isolated locations, like hard drives and local share drives. However, oftentimes the information gathered in the document-based diaries critically affects the course of action.

(Pump DB2829-4523 Config.)		(Pump DB2829-4879 Config.)	
NSN	QTY	NSN	QTY
4710011495075	3200	4710013144489	3200
4710011489580	3200	4710013144483	3200
4710011489581	3200	4710013144488	3200
4710011495076	3200	4710013160222	3200
4710011531636	3200	4710013144487	3200
4710011500971	3200	4710013144485	3200
4710011495077	3200	4710013144486	3200
4710011489582	3200	4710013144484	3200
- GM guy says these are CUCV, TM says HMMWV - original 339 references only the cyl#2 line - Brad wants all 8 for both pump configs - Greg got 6 lines on 7/28: -075, 4710013144484, 5, 6, 7, -9581)			

Figure 9. Working diary for fuel line case

For example, the Form 339 of Figure 7 was only issued for one fuel line (i.e. 471001489580) listed in Figure 9, yet, the fuel lines pertaining to the remaining seven cylinders of the 6.2L diesel engine, as well as the lines pertaining to other fuel pump configurations, have the same underlying DMSMS issue. In addition, the first hyphenated note at the bottom of Figure 9 suggests that there might be a possible National Stock Number (NSN) versus vehicle (e.g. CUCV versus HMMWV) association misunderstanding. Uncertainties like this need to be resolved and possibly communicated outside of a local spreadsheet, before proceeding with courses of action that involve the transfer of funds.

In this particular case study, a reverse engineering effort was initiated, since the technical data for the fuel lines was unavailable. As shown in Figure 10, precious resources were spent acquiring sample fuel lines from the field, analyzing geometry and material, and gathering quotes for creating prints and 3D models of the fuel lines, in preparation for manufacturing bid solicitation.



Figure 10. Fuel line reverse engineering and dimensional analysis

Not until the fleet planning organization was consulted was the critical discovery was made that the sustainment support strategy for the entire HMMWV did not include the 6.2L diesel, nor any of its fuel lines. In other words, the fuel line being pursued so diligently by a handful of collaborating organizations had been deemed obsolete and was even published in a field maintenance bulletin a year prior to the Form 339 [27]. This uncoordinated waste of resources happened because a community of analysts were working independently of one another with little awareness of each other's computer

databases and personal notes pertaining to the sustainment support strategy for the same piece of equipment. The lesson learned is: a more sophisticated model-based infrastructure is needed. This will give a diverse group of analysts the ability to communicate the attributes of a sustainment support strategy in a live, multi-faceted modeling environment, similar to how a Computer Aided Design (CAD) model is layered and accessed throughout a product lifecycle.

1.2.1.2 Case Study: IB Metrics

A list of 225 IB metrics was gathered in 2010, by TARDEC, including minimum sustainment rates (MSRs), critical skills, and production lead times, among others [28]. In an effort to distribute workload among organic (i.e. government-owned) depots, these metrics, along with the upkeep of data mining and updating them, were scrutinized to no avail. The effort struggled with conflicting requirements from management paradigm flux and eventually morphed into a “similar-but-different” project title under a new team with a renewed obligation target. Many transient logistics and contracting activities associated with repair parts and their suppliers were exposed as upstream indicators of sustainability. Some analysts felt that the perpetual re-direction of IB analysis efforts needed a common framework. One of the pieces of such a framework is a reliable, parametric connection to the equipment’s support strategies. The problem is that the existing support strategies were seemingly only developed and maintained by career logisticians working in the ILSC (per Figure 3). Support strategy data trends and dependencies between requirements have not been modeled and analyzed like regulations mandate [29, pp. 29, 35]. On the one hand, IB metrics candidates are plentiful in the

logistics world, but logisticians are not applying M&S techniques to understand relationships and identify improvement opportunities. On the other hand, engineering, research, and development (ER&D) organizations well-versed in applying M&S have been mostly unaware of the abundance of logistics indicators that influence the bottom line. Clearly, a demonstration of an applicable framework adjoining the two disciplines is overdue.

1.2.2 U.S. Military R&D Contracting Trends

When DoD researchers have future capabilities objectives and research goals, they often initiate acquisition contracts with industry and academia (i.e. the IB) to create prototype deliverables. The DoD is constantly striving to understand the most recent capabilities of the IB. Meanwhile, the IB is constantly striving to understand the most recent requirements of the government [30]. One problem is that government requirements have to be publicly accessible to ensure fair competition and a diverse bid response from the IB. However, the specifics of government research requirements detail are often not safe to share publicly. Instead, government research requirements may need the confidentiality and protection of a legally binding non-disclosure instrument in order to ensure all parties have a certified clearance and are operating under a formal agreement. This case is inherently not a public-wide scenario. One of the ramifications is constrained competition, because it is a huge investment of time and money for a company to complete the initial stages of a Federal Acquisition Regulation (FAR) process. These initial stages are necessary, however, for a company to get enough tactical requirements to be able to properly estimate and align their resources for the mere

possibility of an award. For many original equipment manufacturers (OEMs), this investment is on the order of \$100K USD per proposal [31, 32]. If the proposal does not result in an award, this manifests as a sunk cost. For smaller businesses with scarce legal resources, the investment is lower, but the burden to propose is thought to be qualitatively equal (or even greater) to that of the OEMs [33]. In addition, incumbent OEMs have advantages over smaller competition, such as: access to and influence over information, due to retired general officer recruitment practices, strategic positioning of lobbyists, and significant congressional district employment leverage. The end result is that OEM proposals are often the only ones that reach the government researcher, because the small competitors are often subliminally handicapped from proposing. In many cases, small competitors are not interested in competing for Federal Acquisition Regulation contracting opportunities.

Even novel business models to improve R&D contracting competition and lead times can get stuck in old paradigms, deficient in parametric links to modern needs and technological developments – even the very same technology they were chartered to advance [34]. As an example, the benchmark DoD Section 845 Other Transaction Agreement (OTA) with the Robotics Technology Consortium (RTC) disallowed manned ground vehicle systems related research initiatives, pronouncing manned ground vehicle systems research mutually exclusive from unmanned ground vehicle systems research [35]. This is despite the fact that even the definition of “robot” and the most successful research effort under the RTC OTA includes manned ground vehicle systems intermingled with unmanned ground vehicle systems [36]. The advent of software

intensive technology influencing manually-operated ground vehicle systems has put the question of “what is a robot?” under constant scrutiny [37, 38]. Commercial vehicles that self-park and leader-follower military vehicles that convoy themselves have enough common technology opportunities and constraints to justify more universal acquisition laws that encourage joint competition and partnerships for mocking up ground vehicle prototype systems.

As an example, an unnamed organization had FY2014 objectives to demonstrate a mobility system with improved performance over a legacy, traditionally-manned, ground vehicle system that was fielded. A multi-phase demonstration was desired within six months and was to solicit state-of-the art innovation from the entire IB in the form of research proposals leading to prototype deliverables. Industry and academia new to defense work were included to ensure warfighters received the best technological overmatch the U.S. had to offer. Under traditional FAR guidelines, prototype efforts could only be initiated if funding was already in place. In addition, the contracting process under the FAR took a minimum of 18 months before a start of work could be expected. Further, the RTC OTA was unable to take on the research, because the scope of work did not expressly identify a “robotics” theme. OTAs are known for offering lean alternatives to getting industry/academia to propose prototype deliverables to the DoD. In this case, an OTA did not exist in the manned ground vehicle domain.

Barrier-to-entry politics within the contracting domain also manifest in the Defense Acquisition University (DAU) Certification Program. As depicted in Figure 11, DAU

demands the Defense Acquisition Workforce to jump through more hoops (i.e. course work) to be certified in contracting than any other discipline.

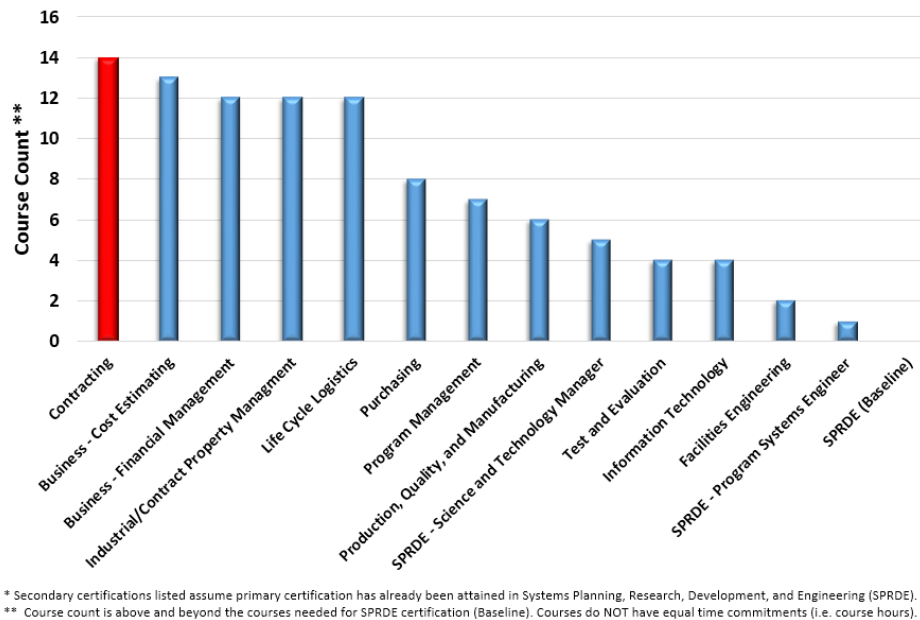


Figure 11. Defense Acquisition University certification programs and their course count [39]

In summary, existing contracting processes are not agile enough to meet the needs of most research initiatives with reasonable lead times. Furthermore, being able to generate alternative sustainment acquisition under the constraints of the FAR is even more out of the question, since most DMSMS cases equate to negative lead times. Even when a company is thriving, the thought of having to deal with the FAR is unwelcome. As a final example, in 2010, a company was contacted by the DLA for a purchase requisition and, although the company historically supplied a repair part to a prominent DoD platform, the company preferred to give away their remaining warehouse (and even showroom) stock, as opposed to doing business again under the FAR.

1.3 Theoretical Sustainment Support Strategies: Many Different Lenses

The methods for analyzing sustainment support strategies are not universally documented outside of the considerations that the SD-22 DMSMS Guidebook provides [6]. Within TACOM, heuristics only exist informally, depending on the experiential knowledge of individuals dispersed throughout multiple directorates. Often, IB analysis consists of detached briefs that hint on a process that never gets formally documented or does not get used by everyday analysts. One benefit to being exposed to multiple IB analyses is an increased awareness of the varying graphical models on which different organizations focus. Using clever graphics to visualize data has always been a way to charm teams into recognizing patterns and trends that would normally be hidden from sight [40]. With practice, more sophisticated graphical analytics can offer an accelerated technical analysis through visual recognition. As an example, Dorian Shainin's ISOPLOT offers the refined capability to appraise the robustness of measurement systems, which is a characteristic that is often misunderstood, leading to premature (or even ill) conclusions [41].

Capitalizing on the perception and cognitive abilities of the human eye-mind system has proven to offer leverage, during analysis, for centuries. One of the more famous examples in history, developed by Pierre Vernier, involves exploiting the capability of the human eye to accurately judge collinearity. Essentially, the Vernier scale allows users to repeatedly pinpoint a measurement on a continuous scale, with attribute-like precision, beyond the competence of resolution available to the unaided eye [42]. Spatial awareness through scientific visualization also delves into graph theory and the study of

the space-time continuum [43]. Huntley proposed that the distance intervals between geometric elements and forms are instinctive to corresponding travel time intervals, due to the number of nerve impulses associated with the muscular effort of the eyeball as an onlooker's eyes traverse along an edge [44]. Choosing to represent systems through graphic models and geodesics helps with concept understanding and inspires thinking under new dimensions. Examples include Figure 4, as illustrated previously, and the use of the cube plot in the portrayal of designed experiments [45]. The name *visual analytics* has been given to this craft which stands for the science of analytical reasoning and decision making from interactive data visualizations [40]. Even the boom of the “app” market, with its subtle incorporation of haptics, demonstrates the power of amassing hidden resources, in that intelligent use of data visualization enables diverse participation. Tracing the geometry of visual analytics back to its awakening of the human eye-mind system is an untapped area of research in the military equipment support strategy domain. Seeking new knowledge in the area of sustainment analysis, using visual analytics, presents new opportunities for researchers to “increase the use of prototyping and experimentation” [10]. Formally, the Army Capabilities Integration Center (ARCIC) defines experimentation as:

an analytical activity, founded upon observation or experience derived from unbiased trials conducted under controlled conditions within a representative environment to discover something unknown, to test a hypothesis, or demonstrate some knowledge within a specific context. Army experimentation is the conduct of experiments involving Soldiers and leaders within live, virtual and constructive environments for exploring concepts, capability requirements and solutions across DOTMLPF domains, in order to learn and mitigate risk for current and future forces. Experimentation exists to gain knowledge, in order to reduce risk to Soldiers and

investments and is uniquely suited for concept development. This is due to the fact that experimentation creates complex, uncertain environments and allows for innovation – creating new knowledge. Overall, experimentation provides an integrating analytical infrastructure for assessment across: 1) warfighting functions and DOTMLPF, 2) academia, industry, government, and 3) joint, interagency, intergovernmental & multinational domains. Experimentation has value, because understanding is essential for decisions – for concepts, requirements and solutions. In addition, experimentation is deemed valuable to the Army, due to the understanding gained by learning, in that knowledge must be developed in a manner suitable to the problem. Constructive analysis is suitable for complicated problems. Experiments uniquely provide complex environments – an essential complement to other learning methods [1].

Deploying this research within the context of a visual modeling paradigm gives strategic planning analysts an enhanced capability [3, p. 90]. Coupled with the fact that a new generation of workforce already thinks and lives a majority of their lives in a virtual world inundated with visual models, conceptual modeling is deemed a rapidly growing discipline [46]. Promoting related science technology, engineering, and mathematics (STEM) offshoots of virtual, experimental strategy visualizations, targeted at today's youth, is expected to be a relevant area of M&S research for years to come.

Figure 12 depicts a paradigm shift in that a more influential problem lies in the whole ground vehicle and robotics enterprise, specifically in the prototype R&D and acquisition areas.

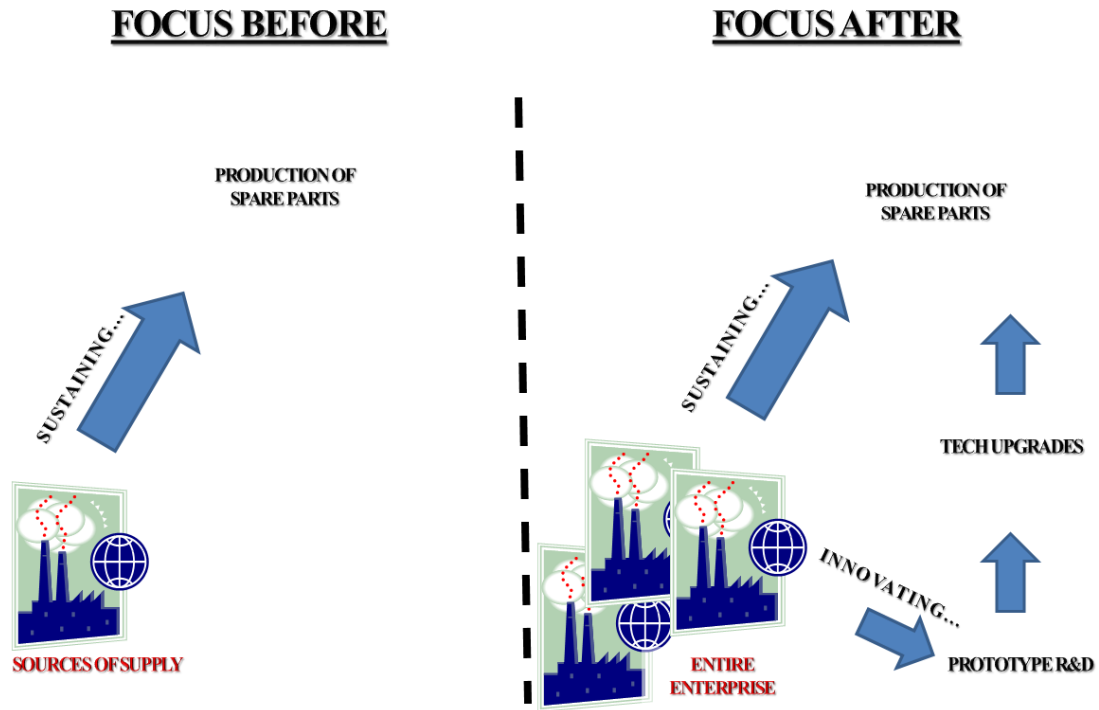


Figure 12. Paradigm shift towards more of an enterprise view

The R&D phase has been constrained by a much larger systems problem for many years, causing not only DMSMS but constricted S&T throughput, due to the challenges of Federal Acquisition Regulations (FAR). In many cases, the same companies that produce spare parts also have innovative prototype solutions to demonstrate the advancement *and* replacement of the parent systems they sustain. It is important that systems engineers “understand the relationship between DMSMS and technology refresh” [21]. Adopting an enterprise view of the IB enables the throughput improvement of prototype R&D to stage more advanced equipment solutions that present themselves as alternatives to aging equipment experiencing sustainment risk.

Innovative systems solutions oftentimes do not manifest as prototype demonstrators or alternatives due to lack of an efficient, ground vehicle systems prototype acquisition mechanism that simultaneously *sustains* the R&D side of the IB. In accordance with SD-22, the Guidebook of Best Practices for Implementing a Robust DMSMS Management Program, DMSMS management and mitigation should be inherently part of the design phases of acquisition [6, p. 90]. Through application of model-based systems engineering (MBSE), varying levels of abstraction can be characterized within the relationship between the logistics world and the R&D world. Similarly to how classic problems involving objects in motion can often be analyzed using Newtonian equations and/or energy equations, the power of offering varying levels of abstraction to problem solving provides new capability to strategists. This refined granularity can decouple “DMSMS risk” from the more generic “equipment readiness risk”, which are terms often synonymous with each other. A successful MBSE application can also create distinctions between “DMSMS” and “obsolescence”, since there is often a debate on whether one is a subset of the other [47, p. 3]. For example, in the 2015 DMSMS Conference, the International Institute of Obsolescence Management (IIOM) proclaimed the word “obsolescence” to be the all-encompassing term and that DMSMS is a term only used in the United States [48, p. 9.15, 49]. However, a few DMSMS subject matter experts (SMEs) at the conference vehemently disagreed and argued that there are many reasons aside from obsolescence as to why manufacturing sources diminish. In another example, when referring to electronic parts, the FY14 National Defense Authorization Act only mentions the word “obsolescence” to refer to the situation when the “part is no longer in production and the original manufacturer of the part and its authorized dealers do not

have sufficient parts in stock” [50]. Since the IEC62402 International Standard for Obsolescence Management applies to much more than just the defense sector, additional viewpoints are constantly being gathered [49]. It should be noted that the mission of the IIOM is to capture these practices and “advance the science and practice of obsolescence management” through obsolescence management research, professional certification, and even a path to fellowship.

To illustrate these distinctions, Figure 13 a, b, and c show a progressive viewpoint on the proposed Venn relationship between readiness risk, obsolescence risk and DMSMS risk. Risk, in general, is the product of numeric values assigned to: 1) the likelihood that an event will take place and 2) the consequence to the system if an event takes place. Readiness risk can be thought of as the anticipated condition immediately preceding a “deadlined” vehicle or system. “Deadlined” is the grave term used to describe military equipment that is operationally unavailable or non-mission capable. Obsolescence risk is the risk of a system becoming obsolete. DMSMS risk is the risk of a system experiencing diminishing manufacturing sources and material shortages. Figure 13a represents the mindset that readiness risk embodies the same concept as obsolescence and DMSMS risk, since the worst-case outcome of all these risks results in deadlined equipment.

Figure 13b proposes that readiness is different than the other two risks and should be visualized as such. Figure 13b depicts that readiness risk is the downstream *effect of* obsolescence and/or DMSMS risk – thus a preparation time element is introduced to the

distinction. This preparation time element may be associated with the differential $t_f - t_i$ previously introduced in Figure 1. On the other hand, a system that has actually become obsolete may not equate to readiness risk at all, if the system is undergoing a long overdue technology upgrade. Similarly, if there are diminishing manufacturing sources in a supersaturated market supplying outdated equipment, there may not be a risk to readiness at all.

Figure 13c is an extension of Figure 13b in that it adopts the convention that obsolescence risk is just a subset of overarching DMSMS risk. In addition, Figure 13c illustrates that a condition formerly denoted under the guise of readiness risk (i.e. “BEFORE”) could be denoted more accurately as DMSMS risk only (i.e. “AFTER”), if applicable. In theory, with technology transfer alternatives staged to a more advanced TRL, situations formerly denoted as readiness risks under the lens of Figure 13a can be decomposed to visually isolate technology transfer mitigation opportunities. This decomposition is first achieved by acknowledging a visual movement of the situation to the DMSMS-only region of Figure 13c.

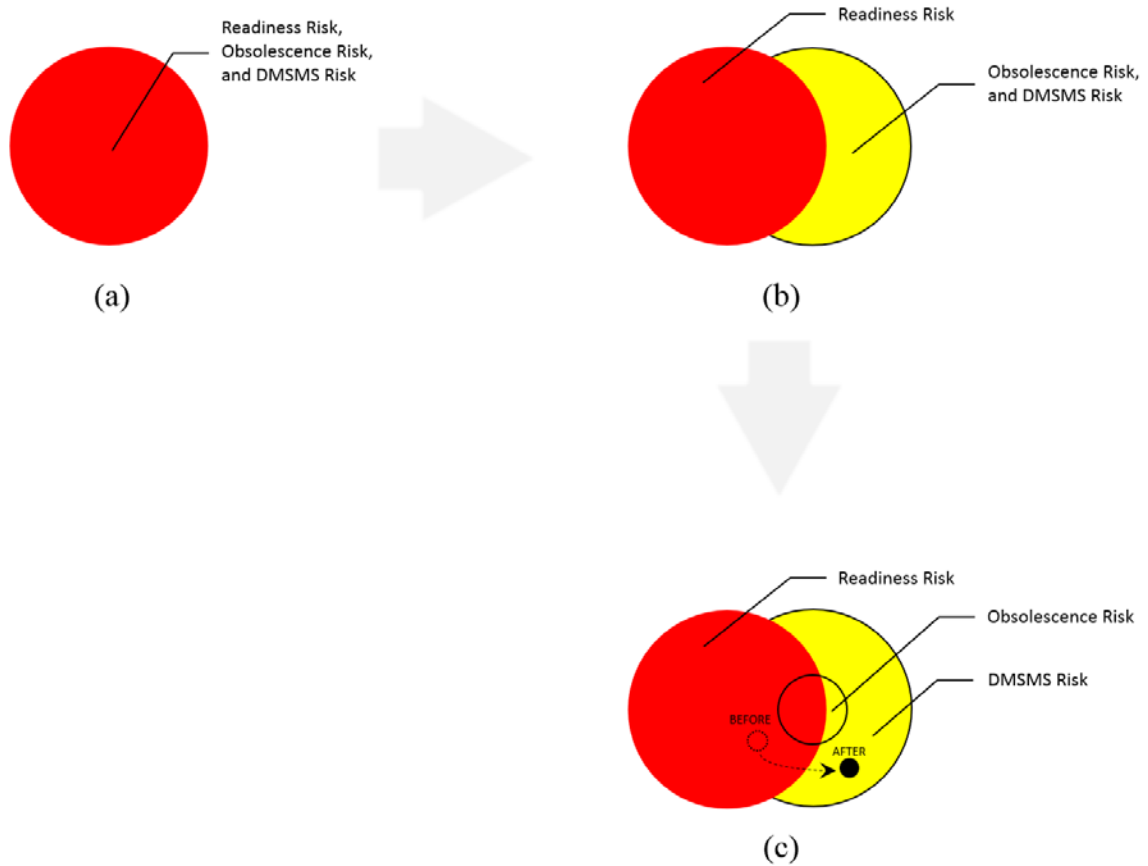


Figure 13. Risk relationship between readiness, obsolescence, and DMSMS

The Defense Standardization Office depicts the relationship between DMSMS and Obsolescence in Figure 14. The DMSMS domain is represented by the box with the solid line, whereas the Obsolescence domain is represented by the box with the dashed line. In this case, the distinctions between the two domains focus on whether or not the items are in production. Items out of production reside to the left of the DMSMS box boundary, whereas items still in production fall to the right of the DMSMS box boundary. Therefore, it is clear that there are many ways with which to characterize sustainment problems. Consequently, sustainment support strategies have different lenses through

which to view risk mitigations related to industrial base health, equipment readiness, and capability enhancement options.

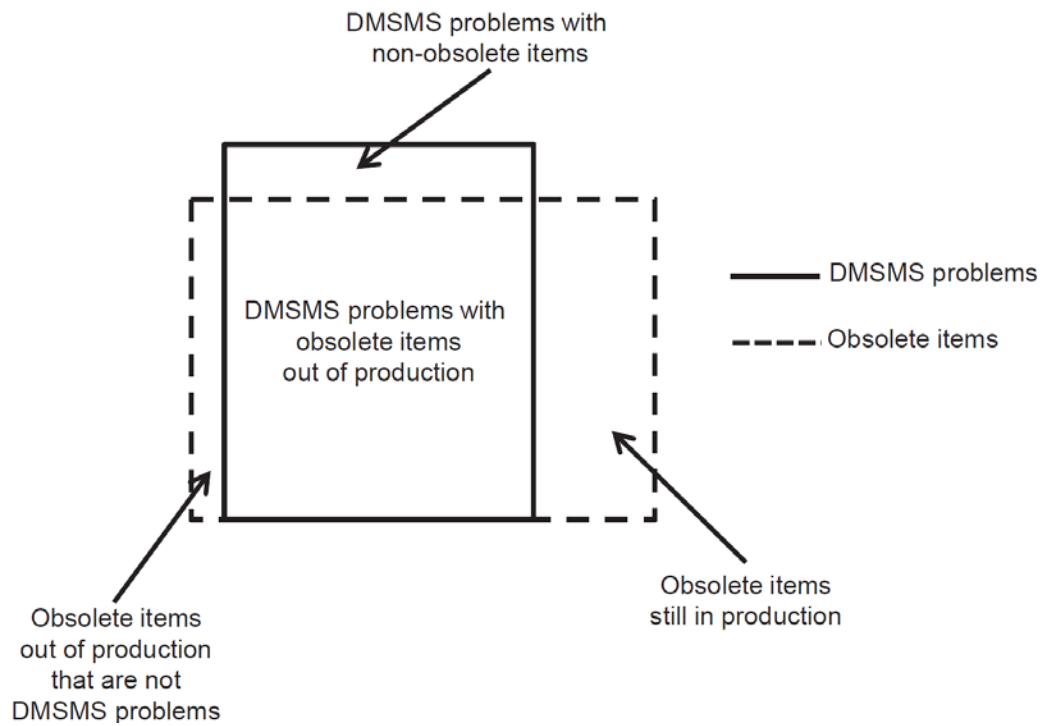


Figure 14. Notional relationship between DMSMS and Obsolescence [47, p. 3]

On a timeline, the DMSMS domain manifests as an interval, such as the interval marked t_{DMSMS} in Figure 15. The t_{DMSMS} interval, or end of life (EOL), represents the time between: 1) the current sustainment state of a piece of equipment and 2) the point in time when the equipment becomes unavailable. Sometimes, equipment is unavailable for a short time through the incumbent supply chain and then becomes available again. This could be due to unexpected lead times caused by manufacturers giving a lower priority to military production or sporadic supply disruptions. Either way, this vertical t_{DMSMS} line represents a universal EOL reference for all National Stock Numbers (NSNs). On the other hand, imagine that the black dot shown in Figure 15 represents a particular NSN's

DMSMS mitigation solution, whose horizontal component reflects the time it takes to execute a technology transfer project, t_{MIT} . Therefore, the term MITSLACK is introduced as the difference between t_{DMSMS} and t_{MIT} , representing how out of synch the problem (i.e. readiness issue) is with the proposed mitigation. The *slack* portion of the term MITSLACK was chosen to mimic scheduling nomenclature commonly used to describe the time difference between a required action and its corresponding due date [51].

The horizontal coordinate of the black dot, in this case, lags behind (i.e. to the right) the t_{DMSMS} line meaning that this particular NSN will encounter a readiness issue before a mitigation can be realized. This is the case of negative MITSLACK. Obviously, positive MITSLACK is preferred over negative MITSLACK, which is analogous to being proactive over reactive when dealing with readiness issues.

In other words,

$$MITSLACK > 0; \text{ for } (t_{DMSMS} - t_{MIT}) > 0 \quad (\text{Eq. 1})$$

$$MITSLACK < 0; \text{ for } (t_{DMSMS} - t_{MIT}) < 0 \quad (\text{Eq. 2})$$

Now that the horizontal frame of reference for the measurement system has been established, let the vertical position of the black dot represent the cost saving potential, S , of the particular mitigation solution. It is likely that mitigation solutions exhibiting more positive MITSLACK have a higher cost saving potential, due to the high cost of reactive

problem solving. In other words, the optimization objective is:

maximize MITSLACK and maximize S

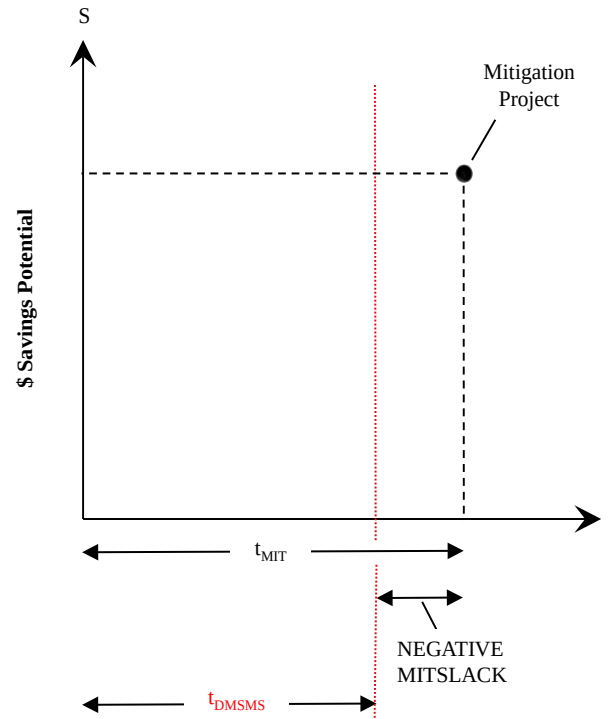


Figure 15. MITSLACK attribute

Proliferating the visual analytic of Figure 15 over an entire platform of NSN mitigation solutions/projects, and against a common t_{DMSMS} line, reveals a MITSLACK distribution, shown notionally in Figure 16. At this point, an objective, 2D visual analytic is available that can depict an entire platform's Sustainment Support Strategy State (SSSS).

Comparing the SSSS between platforms is also visually plausible by leveraging a depth dimension in a 3D version of the model, as is a fourth dimension to animate state changes across time periods. The potential visibility that a fourth dimension offers to the SSSS model could rival the effectiveness of simulating weather pattern movement across

weekly forecasts. Obviously, animation allows data and the knowledge of relationships to reach a broader audience than would be possible if only tabular data is displayed.

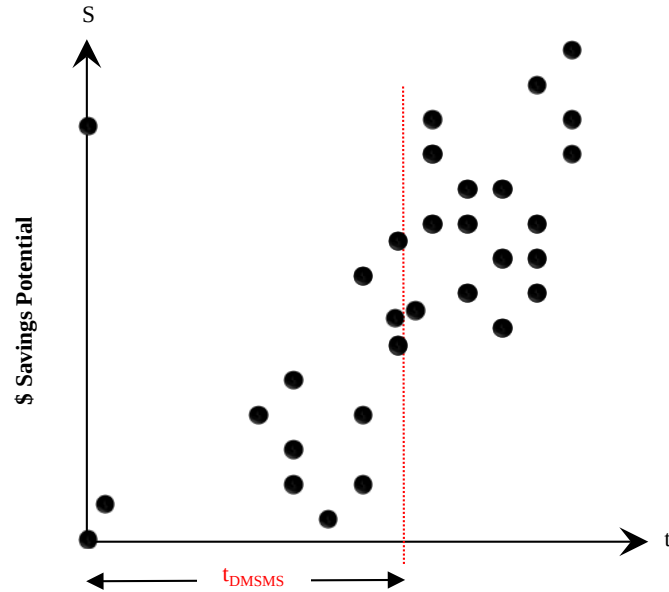


Figure 16. Sustainment Support Strategy State (SSSS) model

1.3.1 System Modeling Theory

Systems engineering practices lend themselves well to situations that are under the scrutiny of, and benefit from, multiple lenses. In systems engineering, the perspective of multiple lenses is formally termed *levels of abstraction*. Model-based systems engineering (MBSE) brings multiple levels of abstraction under one parametric roof, while allowing each level of abstraction to also operate somewhat independently. The specific discipline of managing concepts for metamodeling various levels of abstraction has been formally termed *conceptual modeling* [52]. Conceptual modeling has been

building momentum via professional societies, conferences, standards discussions and will be covered further in Chapter 2.

Fortunately, there has been a movement towards a standards-based method to practicing systems engineering. Figure 17a depicts how even the standards themselves are organized into the various levels of abstraction of M&S. For example, “Modeling and Simulation Standards” is one level of abstraction that can be even further divided into: standards pertaining to “System Modeling” versus standards for “Simulation and Analysis”. SysML was at the center of the System Modeling sub-domain as the official modeling language of systems engineering as “a standardized and robust modeling language is considered a critical enabler for MBSE” [53, p. xi]. In 2008, this breakout was considered to be the accepted convention, or lens, with which to view the systems engineering taxonomy. However, in 2013, Figure 17b was deemed the way to view things, noting that “System Modeling” and “Simulation and Analysis” were no longer distinguished from one another under the overarching label of Modeling and Simulation Standards.

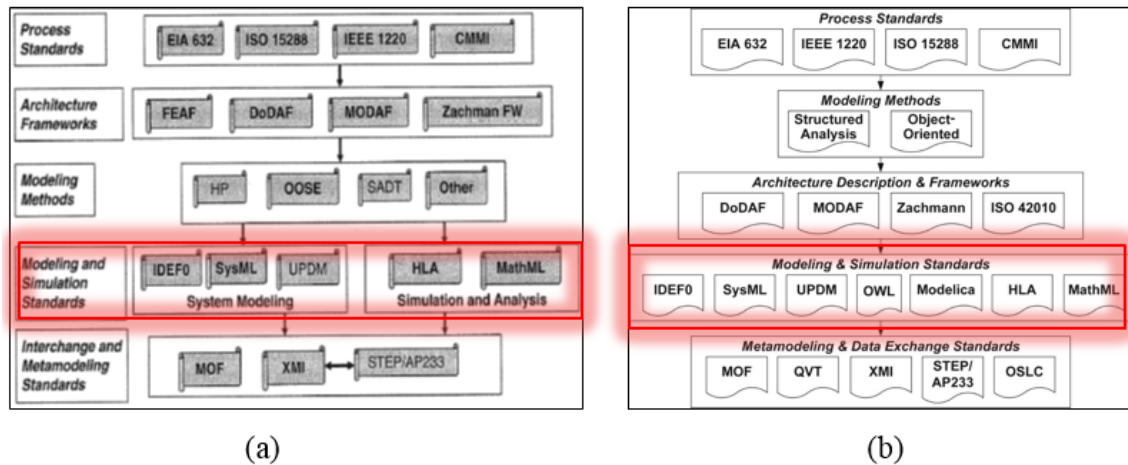


Figure 17. Inventory of systems engineering standards, frameworks, and methods [53, p. 11]; [54]. Copyright © 2015, 2012, 2009 Elsevier Inc. All rights reserved. Used with permission.

The Modeling and Simulation Standards tier of Figure 17a parallels Computer Aided Design (CAD) practices, which exercise the MBSE construct. In the CAD world, a system often starts as an inspiration or an aesthetic strategy. The strategy may be a mixture of philosophies or influential elements, like the artist's renderings of a vehicle concept called "Rebil", shown in Figure 18a. Often, the inspiration has roots or reference elements that are already in some sort of CAD model, like the CAD surfaces of the silver bullet modeled in Figure 18b.

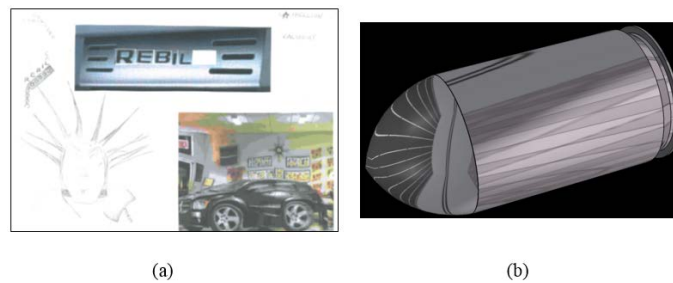


Figure 18. Aesthetic elements of influence. Source: Chrysler 2007

Often, an inspiration is immediately modeled so that multiple departments can access the elements and start collaborating – adding more and more content to the community model as time goes on. In terms of sharing geometry and other product characteristics/requirements, distributed networks of employees all interact with various layers of the same source files. The interior and exterior surfaces of a new commercial vehicle often start out this way. Before long, an entire system model results, as depicted in the CAD vehicle concept called “Silver Bullet” of Figure 19.



Figure 19. CAD system model. Source: Chrysler 2007

Only after a system is modeled can scenarios be simulated, giving way to coordinated analysis between departments, as shown in Figure 20. In the figure, a packaging analysis is being executed between the body and powertrain departments. The intake manifold runners, shown in red, protrude out quite a ways from the cylinder head. Therefore, the components that surround the red intake manifold, must not violate the packaging space requirements communicated in the model by the powertrain engineer.

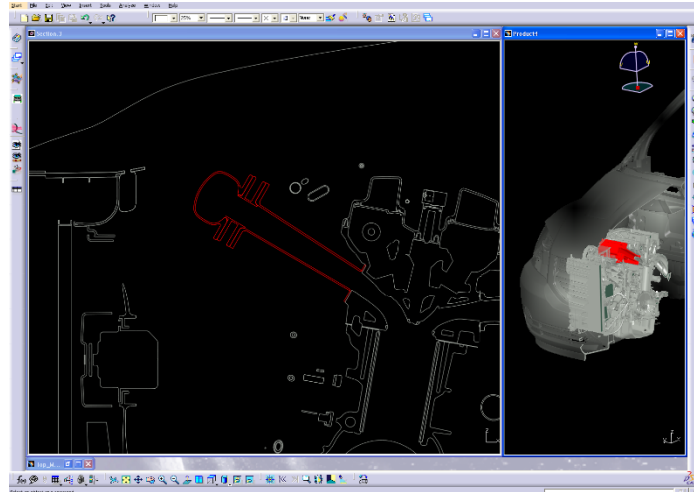


Figure 20. Coordinated analysis – powertrain/body example. Source: Chrysler 2007

In this example, the virtual coordination is parametric in nature, since all have access to the same source files. Similarly, if a powertrain engineer proposes a design decision that violates a constraint set by the body engineer, the CAD system has the capability to automatically flag the community that a conflict is underway. Recall, Figure 17a acknowledged this distinction between: 1) system modeling and 2) simulation and analysis.

Since the system model is parametrically accessible by other analysis software, coordinated simulation of various what-if environments can be executed also. Figure 21 shows how the extreme rebound (left picture) and jounce (right picture) states of the suspension of the aforementioned Silver Bullet vehicle example were simulated (with the body geometry in the foreground) to identify design changes to the strut.

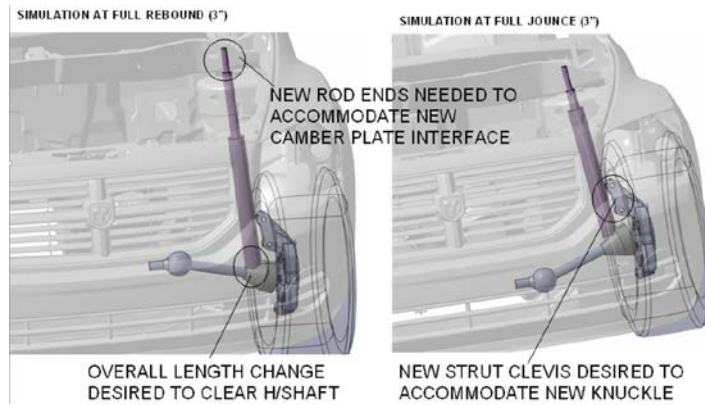


Figure 21. Coordinated simulation – chassis/body example. Source: Chrysler 2007

One of the enabling features of a community-accessible system model is the hierarchical meta data that can be overlaid next to the product geometry. Figure 22 shows a kinematics simulation with the suspension component geometry in different colors and the meta data corresponding to each component along the left hand side.

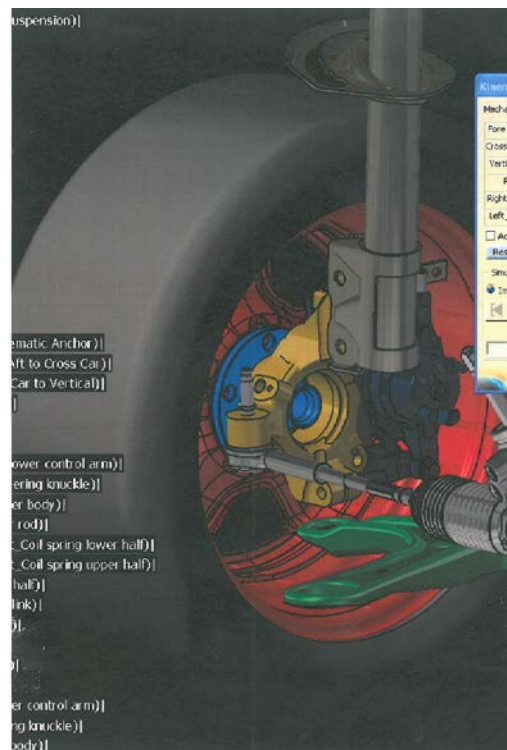


Figure 22. Kinematics simulation with meta data overlay. Source: Chrysler 2007

The hybrid interface of the virtual product on the same screen as the pertinent meta data provides the ability to establish levels of abstraction via a work breakdown structure (WBS). This WBS serves as the grounds for a common dialogue, so that collaborators are all adding content to a product information structure that everyone is familiar with, because they are working in it every day. Thus, the live model is the key enabler to replacing document-based systems that still rely too much on email communications between collaborators.

Unfortunately, most systems engineers are not fluent in their own dialect, causing the structures, systems behaviors, and requirements with which they work to be isolated from the other realms of their command, leaving huge voids in communication channels, and ultimately resulting in unbalanced, unstable designs that are not properly characterized [55]. SysML calls for fluency in object-oriented communication. “One of the key advantages of the object-oriented approach is that it allows you to think at the level of a real-world system, not at the level of a programming language” [56]. Applied to this work, the object-oriented diagramming has highlighted that the priority is not only DLA Form 339 prediction capability, but the involvement of DLA (and other agencies) upstream in the prototype stages of R&D and exposing DLA to the M&S capabilities of engineering. This improved perspective emulates the core principles of systems engineering by inviting cross-agency input to “sustainment support strategy modeling” and the upfront analysis of equipment alternatives, adding further balance to equipment system model design.

Parametrically linking simulation and analysis back to strategic objectives in a system model is a best practice. The Chief of Staff of the U.S. Army orders “we must link tactical actions to strategic objectives”, as can be seen in the red highlighted portion of Figure 23.

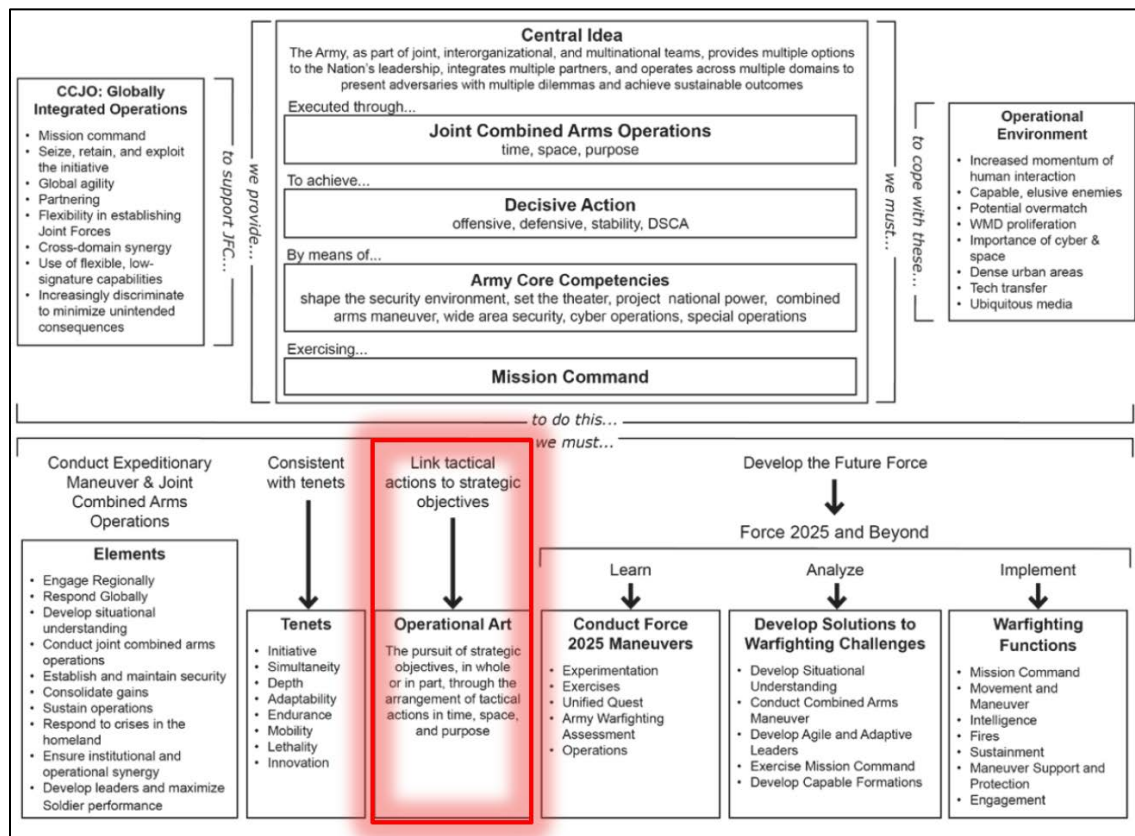


Figure 23. Win in a Complex World [57]

Figure 23 is an excerpt from the U.S. Army Operating Concept that decomposes the central idea of who the U.S. Army is (top of the figure) and cascades down into the active components of what “must” be done (bottom of the figure), in order to maintain that identity.

According to SysML best practice, a system model is to embody the key system aspects of: structure, behavior, and requirements [53]. By applying mock-up MBSE templates of

developmental environments, it is theorized that difficult systems can be modeled and the interfacing they experience with other systems tools can be simulated and improved.

Note how Figure 24 shows the System Modeling Tool at the hub of an orchestrated communication environment. The orchestration is shown with black arrows traveling to and from the various tools that are often used in product development, such as the System Modeling Tool (positioned on the right side of the figure).

In fact, the interfaces that offer the best modeling & simulation tie-in between the logistics and contracting worlds are the trunk lines connecting the System Modeling Tool to the: 1) System of Systems (SOS)/Business Modeling Tool and the 2) Simulation & Analysis Tool (shown on the left side of the figure). For example, SysML offers the ability to use the variables and equations from virtual performance experiments run in a Simulation & Analysis Tool and code them as parametric system model elements and properties that are used in the SOS/Business Modeling Tool. Internal Block Diagrams (symbolized as ibd), like the one shown in Figure 24, are used to describe the structure of conceptual entities and/or levels of abstraction for a system and interfaces between the parts of a block [53, p. 95]. With object oriented diagramming, like Internal Block Diagrams, “their simplicity is their deception” [56] and “a picture is worth a thousand lines of code” [58].

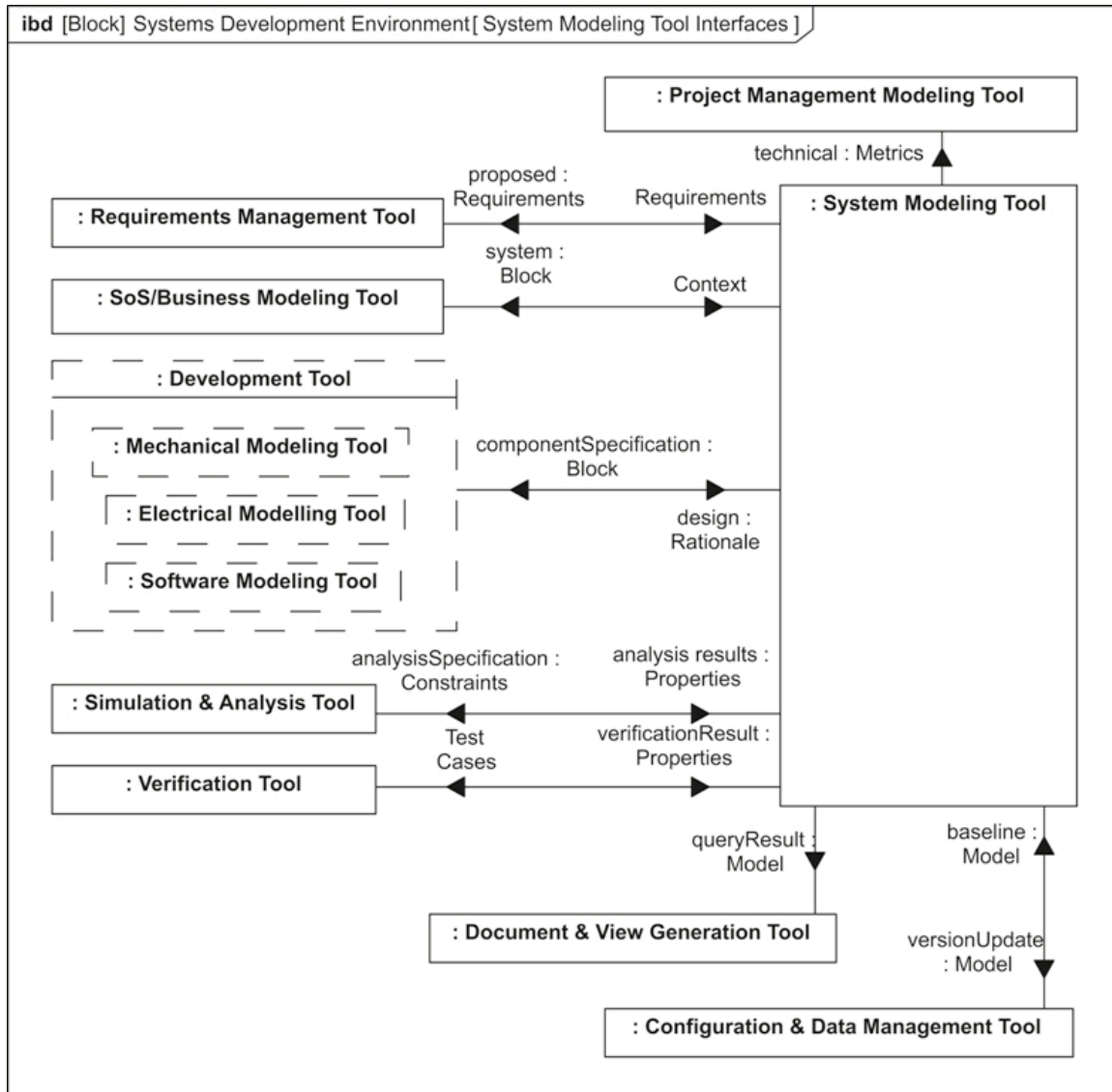


Figure 24. Orchestrated environment captured in an Internal Block Diagram [54]. Copyright © 2015, 2012, 2009 Elsevier Inc. All rights reserved. Used with permission.

1.3.2 Theory Applied to Repair Parts Sustainment Support Strategies

In SysML, the block entity is the object experiencing the states of sustainment risk. The block can represent any real or abstract entity that can be conceptualized as a structural unit with one or more distinguishing features [53]. An equipment sustainment support

strategy is one such block. The split between the current and future Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) elements of a sustainment support strategy can to be acknowledged upfront in the Block Definition Diagram (symbolized as bdd), which represents the structure of users and intended environment, as shown in Figure 25 [3, pp. 14-15]. Note how a diverse range of personnel are represented in the figure, emphasizing the importance of perspective, balance, and impact when dealing with equipment strategy design. In actuality, the design layout of Figure 25 codifies the vision of this research, immediately setting the stage for a proactive M&S-in-the-loop environment that intermingles the logistics (i.e. Current DOTMLPF) and science & technology (Alternative DOTMLPF) communities.

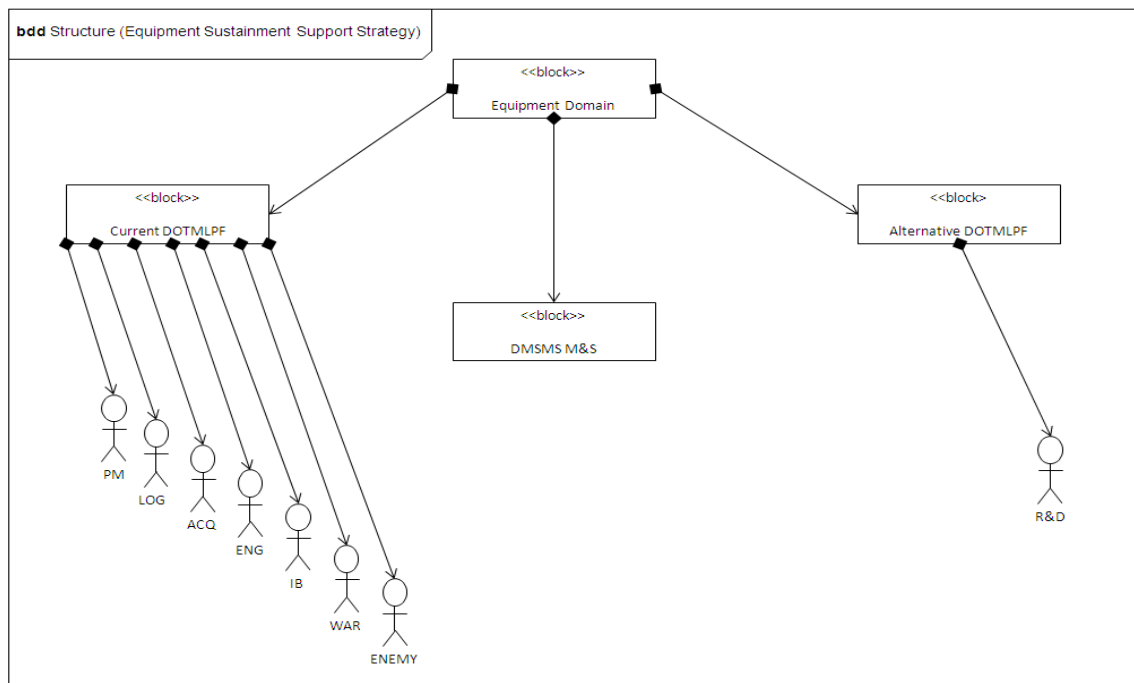


Figure 25. Block Definition Diagram depicting equipment, DOTMLPF, and M&S relationship

Using another lens of SysML, the Requirements Diagram (symbolized as req) of a robust sustainment support strategy, shown in Figure 26, displays the elements of its structural counterpart: the Block Definition Diagram. Note how the figure specifies cross-cutting domains in the support strategy, such as Contracting Profile, Manufacturing, IB Classification, etc.

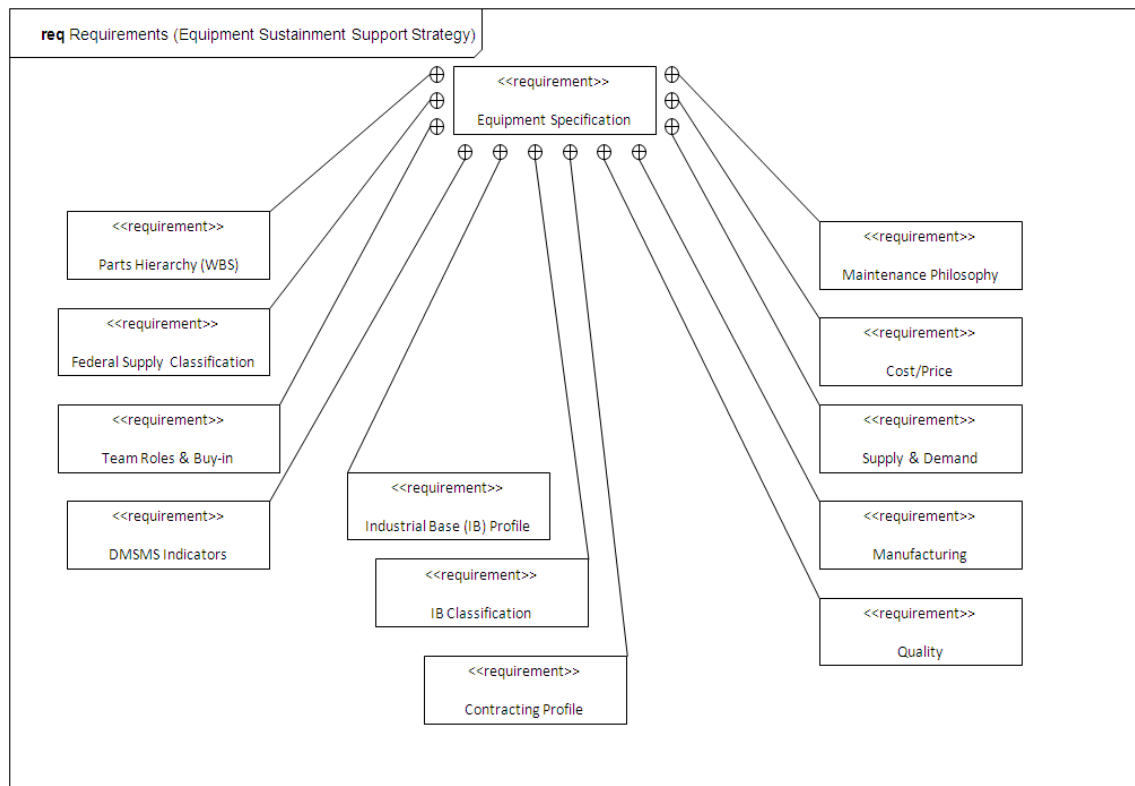


Figure 26. Requirements Diagram decomposing equipment specifications

Another type of behavior diagram to codify the maturity of sustainment support strategies is the State Machine Diagram (symbolized as stm), due to: 1) its abstraction representation flexibility, 2) its ability to describe the state-dependent behavior of a block throughout its life cycle in terms of its states and the transitions between them and 3) the multiple input and dynamic nature of economic-based systems. State modeling of non-

observable support systems is also practiced [59, pp. 97-98]. Incorporating M&S in the parts sustainment realm will help give equal consideration to the logistics and DMSMS ramifications of systems design decisions, protecting the readiness of fielded systems.

1.3.3 Cost Avoidance Modeling

Developing awareness of DMSMS indicators is an important aspect of IB/sustainment risk management. Therefore, a cost model for this research is viewed as the avoidance of: 1) cost and 2) equipment readiness decline associated with a series of DMSMS cases; each having a probability of occurring and are treated as a failure of sustainment support (see Equation 3 below)

$$C \sim \sum_{i=1}^n P_i (D_i + \varphi(t)) \quad (\text{Eq. 3})$$

where C is the total burden to the platform, n is the number of DMSMS cases in a given time frame, P is the probability of a DMSMS case, D is the cost of a DMSMS case, and φ is a penalty function that burdens a platform when the platform resides below equipment readiness thresholds for a given interval.

Although the aforementioned cost model includes factual DMSMS costs, it is important to remember that when dealing with critical equipment and its readiness related to national security (i.e. HMMWVs used by the National Guard), “national priorities can’t [really] be priced” [60]. Similar to other risk management measurement systems, the mitigation quality of sustainment support strategy *risk* may be objectively assessed with

respect to the product of likelihoods, consequences, and detection capabilities of the foreshadowed sustainment support strategy *issue*.

The theoretical investment to proliferate an MBSE solution that encompasses sufficient IB analysis is expected to follow a modified annuity series cash flow diagram, of form:

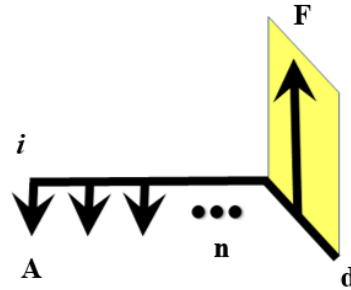


Figure 27. Cash flow diagram depicting productivity economics of DMSMS MBSE research

where F is the benefit, or the avoided cost increment (i.e. markup) per mitigation decision, A is the cost per head (related to the fraction of time each analyst/stakeholder spends on maintaining their parametric area of responsibility within the cost model), n is the time period between mitigation decisions, I is the interest rate of opportunity cost, and d is the depth of human capital/support structure (i.e. how many analysts/stakeholders presently manage equipment risk for the command).

This equates to a breakeven equilibrium of:

$$F = d * A \left[\frac{(1+i)^n - 1}{i} \right] \quad (\text{Eq. 4})$$

In which case the overhead cost of human capital is fixed at $A*d$, Newman simply recommends to maximize the equivalent uniform annual benefits (EUABs) [61]. Note

that the EUABs manifest themselves as an avoided markup, F , in Figure 7. Both, the avoided markup, F , and the depth of analysts, d , are presented in a third dimension to illustrate the cost-to-benefit tie to the variable pool of analysts contributing to the cost model's upkeep. In other words, each analyst will be responsible for maintaining his/her particular attributes of the cost model (for which they already manage equipment risk in some way).

With respect to Equation 3, the cost, D , of a real DMSMS case can be demonstrated in the following example, related to the aforementioned HMMWV case study, where a reactive demand arises for fuel lines that are out of production. The total anticipated, life-cycle demand calls for \$7,552,000 of fuel lines (3200 lines * 8 lines per fuel pump * 2 fuel pump variants per vehicle) at \$147.50 per line. Approximately one-third of the quoted piece price can be attributed to a markup that is the result of a bounded support strategy tied to a single source of supply who owns the full rights to the fuel line technical data. Market constraints like this that are identified through IB M&S (and proactively mitigated) can equate to a cost avoidance, F , of \$2,517,333 (33% of \$7,552,000). Substituting $3 * F$ in for D , in Equation 3, yields:

$$C \sim \sum_{i=1}^n P(3 * \left[d * A \left[\frac{(1+i)^n - 1}{i} \right] \right] + \varphi(t)) \quad (\text{Eq. 5})$$

Therefore, a cost avoidance model is established, that includes allocation of human resources towards IB analysis. This is important because, ultimately, IB issues influence Operational Availability (A_o). Operational Availability is just the complement of

operational unavailability. Decomposing unavailability even further, Equation 6 reveals that the number of days a piece of equipment is Non-Mission Capable for Supply (NMCS) is an ingredient of the numerator in the second term, along with the number of days a piece of equipment is Non-Mission Capable for Maintenance (NMCM) [62].

$$A_o = 1 - \left[\frac{(NMCS+NMCM)}{\text{Possible Days}} \right] \quad (\text{Eq. 6})$$

It is important to note that a portion of NMCS could be attributed to a DMSMS event. Given that a proportion of equipment applications historically become reactive, DMSMS issues, uncovering factors that tend to be associated with higher risk scores will help concentrate analyst resources towards more likely risk candidates. Although the adage of “past performance is no guarantee of future results” always applies to systems subject to economic market forces, if trends can be unearthed that accurately predict outcomes more than 50% of the time, the effort is mathematically worth investigating (i.e. the status quo is 50/50). Proper risk management will reduce the population of DMSMS candidates. Along with theorizing a broader understanding of manned and unmanned equipment sustainment risk, a new facet of M&S is underway within the Department of Defense (DoD).

1.3.4 Theory Applied to Science and Technology (S&T) Acquisition

It is theorized that the best common attribute between sustainment risk assessments and technology readiness opportunities is the Federal Supply Class (FSC). This is due to the

fact that all equipment eventually gets an FSC assigned, becoming the first 4 digits of the National Stock Number (NSN). Unfortunately, much of the R&D community is not aware of FSCs, which is a missed opportunity. By associating concepts and prototype systems to FSCs early on, the S&T and Logistics communities (both organic and inorganic) could have a common ground with which to pair up needs with upcoming capabilities. Once the two communities become aware of each other's trade space, innovative and diverse collaborations can begin to seed. For example, under a tactical DMSMS resolution scenario (where a needed repair part will soon leave the viable market), questions arise like:

1. When does the current contract end?
2. How much time is needed to qualify a new source?
3. When could new manufacturing methods be introduced?

Sharing a strategic timing awareness between the S&T and Logistics communities will reveal that many of these lead times can be coordinated to complement each other. When processes are aligned to operate more in a parallel fashion, as opposed to in series, lead time reductions result. Therefore, the throughput of S&T projects needs to be maximized to generate more parallel paths of additional risk mitigations in the form of technology pull opportunities. Once modeled, the prototype acquisition bottlenecks can be identified and broken, freeing the bottleneck to manifest elsewhere with weaker effects. Once more S&T projects start to accumulate, the effect of their mitigation capacity can be realized. As depicted in the 'no recent demand state' of Figure 28, both state machine sub-states dispatch some form of alternative behavior. This research theorizes that one of the most

critical alternate behaviors is: actively participating as a stakeholder in the readiness of new technology, whether the risk is inactive or eminent (i.e. positive slack).

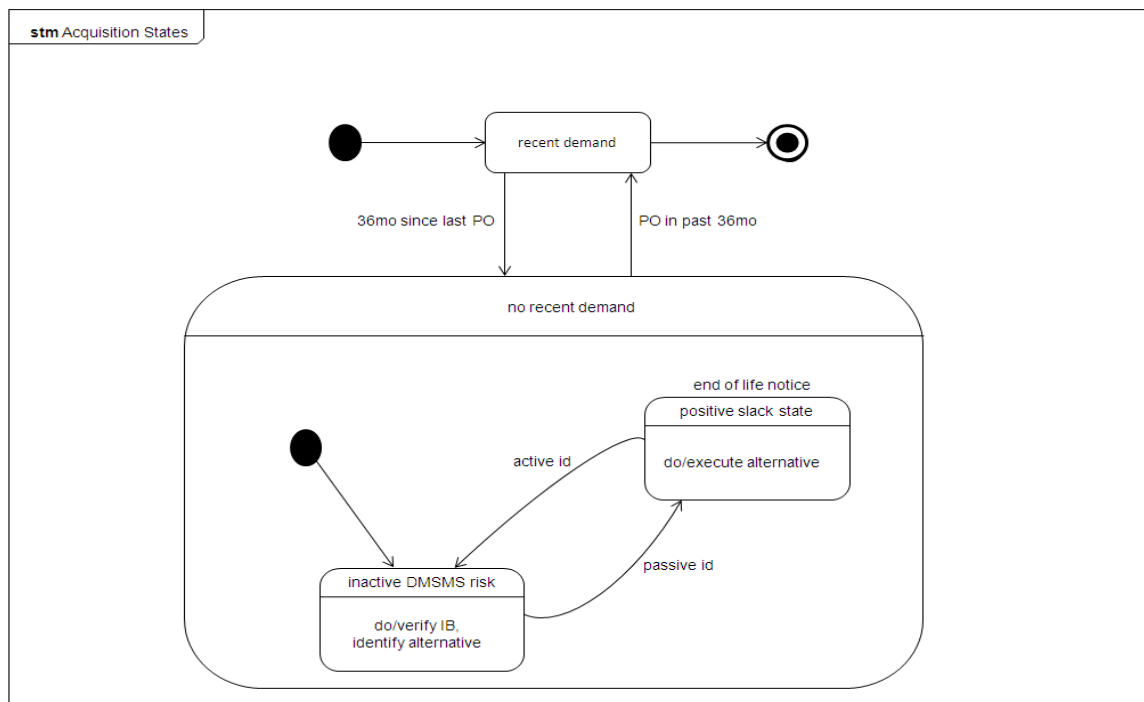


Figure 28. State Machine Diagram depicting equipment demand frequency trigger of 36 months

A better sense of ownership among systems and their sustainment support strategies will help drive stakeholder input to a parametric model. Demonstrating a user interface that allows cross-domain analysts to travel from a macro-level analysis space towards a low-level solution space is considered to be of high-value to organizations like the Department of Defense [63, p. 126, 1, 58] and is thought to be the heart of object-oriented M&S development. Therefore, creating a model that relates strategic S&T lead times with tactical logistics and readiness lead times is expected to be value-added research that is deeply rooted in classic systems engineering principles.

1.4 Research Plan

The plan of this research is as follows:

1. Mine logistics and industrial base data spanning across multiple databases, while simultaneously developing conceptual models that depict sustainment support strategy relationships
2. Use models to identify data trends via experimentation
3. Determine whether correlation exists between sustainment support strategy risk and real Diminishing Manufacturing Sources and Material Shortages (DMSMS) issues
4. Analyze experimental results and come up with a DMSMS risk mitigation implementation plan focused on technology transition opportunities and industrial base (IB) participation
5. Exercise new knowledge by demonstrating actual increases in risk mitigation throughput and agility

1.4.1 Scope

In Scope

1. M&S results of data mining experimentation pertaining to High Mobility Multi-Purpose Wheeled Vehicles repair parts and industrial base sustainment support strategies
2. Empirical application of model-based systems engineering (MBSE) that is capable of designing the interface between, parametric architectures and management control system frameworks
3. Design, analysis, and demonstration of an innovative, systems engineering solution that enables cross-domain, technical collaboration, advancing the logistics engineering discipline upstream into the prototype R&D and contracting fields

Out of Scope

1. M&S results of entire command portfolios
2. Basic research
3. Holistic, executable software

1.4.2 Contribution

This research has contributed to the systems engineering body of knowledge through:

1. Development of working models that depict interdependencies between conceptual frameworks and revenue-generating applications, such as the Sustainment Engineering Risk Assessment (SERA) and the Defense Mobility Enterprise (DME).
2. Advancing the state-of the-art in logistics engineering, by linking acquisition modeling and simulation (M&S) to sustainment risk mitigation.
3. Establishing best practice, by applying previously published methods to new bodies of data to include the use of SysML and Kepner Trego diagrams in sustainment support strategy specification and Principal Components Analysis (PCA) of SERA data.

1.5 Organization

The organization of the dissertation is as follows. Chapter 1 introduces the business of sustaining military equipment, along with some sustainment system attributes and modeling opportunities that exist. Chapter 2 reviews literature in six domains: visualization, systems engineering, conceptual modeling, supply chain management and military sustainment, lean six sigma, and benchmark sustainment analysis initiatives underway at TACOM. Chapter 3 explains the development of the Sustainment Engineering Risk Assessment (SERA). Chapter 4 discusses the application of the SERA to three major vehicle platforms and compares the results to actual DMSMS issues those

platforms experienced. Chapter 5 discusses how model-based systems engineering principles were applied to the formation and workloading of the Defense Mobility Enterprise (DME) and how the DME metrics serve as inputs to the solution implementation phase of DMSMS management. Chapter 6 concludes the work and offers continuous improvement recommendations.

2. LITERATURE REVIEW

2.1 Visualization

Järvinen, Puolamäki, Siltanen, & Ylikerälä reported the findings of a joint visual analytics project, noting that the topic of information visualization has been an active research area since 1990 [40]. The authors illustrated the visual analytics concept via demonstration tools developed in the project. The authors also outlined roadmaps for industrial and consumer applications. The building blocks of visual analytics were also presented: 1) information visualization, 2) data mining, 3) analytical reasoning, and 4) integrating data sources. Some of the aspects of human perception analyzed in the study included the Gestalt laws of pattern perception. Visual grammars, like Systems Modeling Language (SysML), are considered to be applications of Gestalt laws. Specialized software (available in the market) was found to reside in the following domains: 1) office tools, 2) business intelligence tools, 3) statistical and mathematical tools, 4) visualization-related libraries and software packages, 5) algorithmic tools, 6) visual data mining tools, 7) web tools and packages, and 8) scientific visualization tools for modeling complicated physical phenomena. Mobile, collaborative devices deploying haptic interfaces exemplify one of the long term prospects that the authors envisioned on the horizon.

Monczka, Handfield, Giunipero, and Patterson presented a study that was conducted in 2008 that considered visibility to be the number one capability that allows an organization to assess its supply chain risk management [64]. The secondary and tertiary capabilities included early warning systems and supply chain analytics, so that risk events

can be better understood. The research of this dissertation demonstrates the use of early warning systems and industrial base analytics within a working model of the DoD R&D, acquisition, and sustainment support domains.

Christensen proposed that adding a third dimension to the traditional performance versus time visual analytic helps see disruptive innovation through a new lens [65]. Adding “non-consuming occasions” to the axis system presents an additional view of the IB that allows the product model to start assessing untapped IB opportunities. Operating within an interface that offers fluidity between the measured phenomena (observed during experimentation) and the hypotheses (proposed during requirements generation) points to a Model-Based Systems Engineering (MBSE) atmosphere. Ascending the pyramid is analogous to zooming out, or entering into the analysis phase established by Kimmel [58]. Unlike the research of this dissertation, Christensen does not provide an MBSE framework that actually enables the IB to respond to the future needs of the DoD.

Leydesdorff & Meyer propose the use of multiple axes, in their triple helix model, that considers additional perspectives, which enables the specification of relevant categories for observation in terms of expectations [66]. Leydesdorff & Meyer explain how a diffusion dynamics parameter, pulled by an economic system’s thirst for profit, is responsible for distributing systems into other domains, sometimes to their own demise. This tri-lateral relationship between industry, academia, and government is a useful insight to explore further in an MBSE atmosphere targeting the analysis of ground vehicle and robotics sustainment support strategies. An example is given that shows once

an innovation travels a certain distance along its trajectory, is dissolves into a new stage of challenges and opportunities. Leydesdorff & Meyer's model, however, does not establish the overarching framework for how to actually leverage (or mitigate) forces like the diffusion dynamics parameter. The research of this dissertation, however, deploys an actual parametric framework for leveraging and mitigating forces like the diffusion dynamics parameter. The leverage comes from the DoD-wide audience, where collaboration, technology read-across, and economies of scale reward the positive side of diffusion.

Wang & Dunston agree with Ellis, Gibbs, & Rein in that groupware entails computer-based systems that support groups of people engaged in a common task and interacting in a shared environment [67, 68]. Wang & Dunston also found that frustration levels and conceptual performance were significantly improved (up to 41.4%), during experiments deploying a range of mixed realities, competing against a range of augmented reality and augmented virtuality [69]. Wang & Dunston explain some of the issues associated with multi-user, face-to-face, and augmented reality systems, including social distractions (non-task-related topics) and model disorientation amongst distributed users, following the model navigation of another distributed user.

Ries, Lance, and Sajda describe brain-computer interaction technologies that enable large datasets to be accurately interrogated by analysts in a short amount of time [70]. Ries, Lance and Sajda recognized the speed and precision of the human visual system to pick up minute distinctions in various stimuli and establish situational awareness.

Experiments were conducted to identify when an observer detects a sought after pattern or target. Also computer aided tools helped with target detection, using measured neural signal data, such as electroencephalography. Although the authors recognize the power of human-in-the-loop visual analytics, no real application (nor framework) is presented.

Samson & Peterson present an application of a Design Structure Matrix that enables the modeling, visualization, and analyses of any system [71]. The authors stated that the greatest leverage in organizational architecting lies between relationships. In fact, an organization's inability to integrate team structures can lead to information overload. The resulting Design Structure Matrix for organizations offers single-picture visibility on the communication frequency amongst teams. After decomposing products, processes, or organizations, the relationship or pattern of interactions between decomposed elements ends up defining the architecture. Samson & Peterson only present the concept of enabling models, visualization, and analyses, without application to a real-world community.

Woody & Hoff offer an analogous middleware solution to managing independently developed applications that provide situational awareness data to warfighters [72]. What is deemed as an Application Framework, an overarching infrastructure orchestrates coexisting applications like: 1) command and control (C2), 2) sensor control, 3) presentation, and 4) communication that can be selectively deployed based on mission parameters and objectives. Woody & Hoff exemplify how software can breakdown

communication barriers and offer community-wide situational awareness, especially when under a master framework.

2.2 Systems Engineering

Mehta & Cooper state that design is essentially a process of generating knowledge about how to build platform-based design systems and results in structured libraries of design projects and risk assessments categorized by typical ground vehicle systems taxonomies [73]. Their research brought to light the important systems engineering (and Lean Six Sigma) principles of: process and risk assessment are the lifeblood of design and management and how aligning resources under multiple levels of abstraction (i.e. systems configuration hierarchy) brings forth flexibility. Consequently, the more parametrically linked the pieces of the process are to one another, the more efficient (and enjoyable) the experience is. Unfortunately, Mehta & Cooper's research does not include a working model of their claim. Mehta & Cooper's research does, however, pave the way for the development and application of a process-centric design of parametric information libraries.

Estefan defines methodology as the overall application of: 1) the “what” of processes, 2) the “how” of methods, and 3) the corresponding tools and meta models that aid in process and method execution and development [74]. Estefan surveyed different levels of MBSE analysis abstraction, as well as the connotations of model-driven system design, including state analysis. Estefan also depicts an onion-shaped model that uses layers of systems engineering activities to aid in cognition and solution exploration. Unfortunately, Estefan

presents no relation to a working business process that he refers to as the “evolving system”. Although Estefan keeps state estimation separate from state control, opportunity exists to parametrically link the two domains.

Pilemalm, Hallberg, Sparf, and Niclason report on their experiences of model-based development, using case studies from the Swedish Armed Forces [75]. In summary, the authors state that a solid combination of scientific research and practical experience is needed to carry out the inherent complexity of a model-based development approach. The top identified challenges in the model-based development and implementation processes were found to be common organizational and system development related problems like: change management, team participation, and execution of requirements engineering. The authors state that there is a need to study aspects of model-based development and implementation from the perspectives of organizations, practitioners, and system stakeholders. The authors also state that the application of models to the development of capabilities constitutes pioneering work. Finally, Pilemalm, Hallberg, Sparf, and Niclason’s research emphasizes that non-technical experts should be able to participate in strategic decisions, where a full, system stakeholder perspective is often missing. There is a need to study of aspects of model-based development and the implementation of commercial-off-the-shelf tools from the research, acquisition and logistics perspectives of the DoD. The visualization of systems architecture data is accomplished through models which manifest as “documents, spreadsheets, dashboards, or other graphical representations and serve as a template for organizing and displaying data in a more easily understood format” [76].

Mendonza & Fitch propose mapping all systems engineering knowledge to a database of object classes and subclasses (within appropriate hierarchies), while leveraging the evolution of attributes and relationships, as opposed to relying on view-based artifacts. View-based artifacts, such as the Department of Defense Architectural Framework (DoDAF), typically fall victim to clerical degradation and unnecessary variance [77]. Distinguishing Object-Based Systems Engineering (OBSE) from that of Model-Based Systems Engineering (MBSE), the authors agree that only OBSE truly captures the essential elements (e.g. objects, attributes, relationships) of systems engineering, fully noting that information architecture may vary for different domains. Mendonza & Fitch promote the proactive analysis of custom diagrams and tables. The authors also asserted that a shared information model fosters collaboration. Finally, Mendonza & Fitch confessed that the roadblocks to OBSE realization include: 1) process inertia, 2) tool limitations, 3) cultural boundaries, and 4) the interaction between tight budgets and fear of scope creep.

Mendonza & Fitch state that effective decision management is much more than a mere analysis of alternatives (AoA) and is comprised of three elements: 1) decision patterns through which subject matter experts influence designs with their unique knowledge, 2) a decision management methods engine, and 3) a decision-centric information model [78]. The authors' research explains that a tool-driven systems engineering outreach strategy works best when it is built around a specific tool that already has gained traction among engineers. Also, cross-pollinating systems engineering tools to other groups can

be accelerated if systems engineering champions from other industries have already infiltrated the target domain. Cognitively, object classes and their relationships have ties to human thinking and cause & effect patterns that should be acknowledged.

Mendonza presented the Tank Automotive Research Development and Engineering Center Advanced Systems Engineering Capability which is an integrated systems engineering knowledge creation and capture framework built on: a decision-centric method, high quality data visualizations, data traceability, real-time collaboration, and knowledge pattern leverage [79]. Mendonza acknowledged that the five models from which systems engineering knowledge is created and captured include: 1) systems engineering vee models, 2) M&S, 3) architecture models (SysML), 4) lifecycle models (e.g. sustainability), and 5) roadmap models. Also, Mendonza presented a traceability solution to upstream decisions from which requirements are derived. It is suspected that Mendonza's Advanced Systems Engineering Capability (ASEC) will be the target framework with which to integrate the IB and R&D acquisition modeling applications of this dissertation. After all, within the ASEC, the decision model for a system provides the integration point for all other system models.

Friedenthal offered that commercial-off-the-shelf capability already exists to visualize the structure, behavior, and requirements of multiple systems, while managing mission resource allocation amongst an enterprise of organizations [55]. Taylor complements this teaching with his findings: the more that models are used for multiple applications in an object database, the more the applications lose their identities, due to integration of data

[56]. Making M&S capabilities more user friendly across an organization also helps to alleviate collaboration problems. Some organizations, have capitalized on offering lite versions of sophisticated software programs, in order to encourage diverse usage. For example, Chrysler Corporation benefitted greatly in the 1990s, by deploying a visualization interface that was more user friendly than the Computer Aided Design (CAD) software from which it stemmed. By significantly lowering the learning curve for most of the basic design decision activities, such as viewing, comparing, and dimensionally analyzing product environments, Chrysler was able to get more engineers and managers involved in the product development process [80]. Similarly in the DoD, the Army Corps of Engineers at the Engineering Research and Development Center (ERDC) and Quantum Signal LLC developed the Autonomous Navigation Virtual Environment Laboratory (ANVEL), which is a lower fidelity version of the Virtual Autonomous Navigation Environment (VANE), which is a physics-based M&S tool [81]. Friedenthal demonstrates that shared models enable the simulation of various company operations. By populating some of the primary SysML diagrams with structured links to models from other domains, systems engineers can start to pave the way towards a more parametric society. Considering that energy and resource distribution follow definite paths which can be analyzed by means of geometric construction, sustainment and acquisition process modeling can inspire more what-if analysis capability through the interactive deployment of visual analytics [82, 56]. Used in conjunction with other commercial-off-the-shelf tools encouraged by the Doctorate of Engineering in Manufacturing Systems curriculum, such as Rockwell Arena, Minitab, and Matlab, M&S scenarios can be economically tested in a benign, proactive environment orchestrated by

SysML, which is recommended by the International Council on Systems Engineering (INCOSE).

Kleinjen and others characterize strategic analysis in terms of an observer's ability to zoom in and out from the current view. A model that has the capability to toggle back and forth between high level perspectives and low level perspectives is said to be an asset to a strategic analyst [83, 58, 84, 28]. Kimmel explains how the macro phase, itself, is to be thought of as the analysis phase [58]. For example, the macro view of a supply chain is its parent IB. From this analogy, it can be concluded that SysML diagrams pertaining to IB analysis dive more into the strategic planning discipline than does the supply chain management discipline. Kimmel also establishes that the most detailed micro view is the code of the modeling language itself. Unfortunately, the authors did not consciously exploit the strategic lens of an IB model, which would help to understand the problem space of a sustainment support strategy.

Bell and Booch cautioned the sole reliance on the modeling language code [85, 86]. The authors demonstrate how a sole reliance on the modeling language code ignores the strategic side of what should be a value-added modeling approach. Unfortunately, Bell and Booch did not present an actual solution demonstrating a healthy mix of the two: coding and strategic support strategy modeling. Reviewing class diagrams and adding operations and attributes is advised. Operations, behaviors, and methods all refer to the same thing, although Unified Modeling Language (UML) generalists use the word "operation", but when coding, the word "method" is most popular [58].

2.3 Conceptual Modeling

The DoD has stood up a Defense Modeling & Simulation Coordination Office and is drafting a handbook on conceptual modeling for use by all DoD agencies [87]. The office formerly acknowledges that conceptual modeling for models and simulation systems has been identified as a key factor by academia and industry toward ensuring the longevity, understanding, usability, repeatability, interoperability, and reusability of M&S products. Van der Zee, Tolk, Pidd, Kotiadis, and Tako conclude expert panel discussions on what conceptual modeling is and its future as a standalone discipline within the M&S community [52]. The authors reveal the many connotations of the words conceptual model, framework, and conceptual engineering. The authors also stress the importance of abstraction and discipline diversity as an M&S foundation.

Diallo, Tolk, Graff, and Barraco presented the distinctions between the words: model, simulation, valid model, and simulator to exemplify the characteristics of interoperability in terms of Model Theory [88]. The authors explain the benefits of storing their Coalition Battle Management Service documents in their native XML format, as opposed to providing a relational database management system. Zhou, Zhang, and Chen present considerations for facilitating the transition between model conceptualization and model implementation [89]. The authors decompose a modeling framework and map modeling tasks in a way that exposes the man-machine interaction, during the course of conceptual simulation modeling. Sok defends that conceptual modeling is a form of validation, even for inherently subjective systems deemed as non-observable systems [59]. Sok demonstrates that conceptual modeling can be used to establish user trust through

documentation of subject matter expert values (referred to as “faces”) and validation of digital threads of information stemming from requirements (referred to as “traces”).

2.4 Supply Chain Management/Military Sustainment

Appelqvist, Lehtonen, & Kokkonen gathered bibliometrics on 15 technical journals between 1997 and 2001 to classify various supply chain modeling papers in a framework, in order to match the modeling approach with the decision-making situation [90]. The classifications in the decision-making framework included: 1) continuous improvement, 2) re-engineering, 3) Design for Logistics (DFL), and 4) breakthrough, depending on whether the supply chain, and product being supplied, was new or existing [90]. Using a benchmark case study of a Patria Ltd (a Finnish defense company) aerospace structure development project, the authors observed that the 3D characteristic of simulation offered the most convincing aspect of analysis. Furthermore, simulation models that interact within an overarching information technology infrastructure and follow the product life cycle from concept to full-scale production are considered as obligatory. The authors found that most research (i.e. 80 out of 83 papers) was conducted within the classifications involving existing product (i.e. continuous improvement and re-engineering), as opposed to classifications involving new product (Design for Logistics and breakthrough). Also, models were used more for one-time analysis, as opposed to continuous decision support.

Terzi & Cavalieri surveyed more than 80 pieces of literature, coined under the mantra of supply chain management, dealing in simulation and the industrial collaborative

environment [91]. The authors confirmed that simulation's main property, what-if analysis, plays an important role in analyzing complexity problems associated with logistics networks. Among other quantitative methods such as advanced planning and scheduling systems, supply chain operations reference modeling, linear programming, and genetic algorithms, simulation knowledge is one of the most important competencies for many different processes, including business, marketing, and manufacturing.

Kleijnen surveyed literature pertaining to four different types of supply chain management simulation and discussed their methodological issues, while emphasizing the role of statistical methods for the design of experiments [84]. The four types of supply chain management simulation covered: 1) spreadsheet simulation (i.e. corporate modeling), 2) system dynamics, 3) discrete-event simulation, and 4) business games.

Kleijnen defined simulation as an experimental method where analysts experiment with various factors and model structures. Kleijnen emphasized that simulation is important, because it supports the quantification of benefits resulting from supply chain management and, thereby, guides decisions through multiple zoom levels (i.e. strategic and operational).

Tolone presented that small reductions in inventory, facilitated by Virtual Situation Room technology (i.e. data sharing technology) incorporating feature rich protocols, could result in billions of dollars of savings, since approximately \$1 trillion USD is tied up in inventory, globally [92]. In a related effort, the Department of Commerce, the National Institute of Standards and Technology, and the Advanced Technology Program joined forces to create the industry-sponsored Consortium for Intelligent Integrated

Manufacturing Planning and Execution as an initiative for advancing data sharing amongst organizations [93]. Contested issues still relevant today, like lean contracting and technical data package definition were covered. Respecting the need for situational knowledge, a series of portals were proposed, including: 1) enterprise information portals, 2) enterprise collaborative portals, 3) enterprise expertise portals, and 4) enterprise knowledge portals. These portals showcase entities termed as “zones”. The zones are labeled: infospheres, teamrooms, commonpoints, virtual offices, and media spaces are comparable to the Facebook chats, Skype, SharePoint, and Google Docs tools popular in 2016. This dissertation aims to test the observations of Tolone in the DoD community, by leveraging milSuite. Basically, milSuite is a DoD version of tools, such as Facebook and YouTube, but is only accessible by DoD employees with certified common access cards (CACs).

Jain and Leong proposed a simulation model using Rockwell Arena software to determine the readiness of a supply chain providing equipment to a defense contractor [94]. By depicting a virtual operation, the paper describes the reduction of perceived risk of sourcing from small and medium enterprises. A questionnaire also accompanied the study, but received little response. The survey was an attempt to gather opinions on M&S and value stream mapping. The importance of an M&S solution exhibiting a good graphical user interface was underscored, along with the capability to interface with popular tools, like Microsoft Excel. The lessons learned from the study included: 1) committing enough resources to gather data in a timely fashion, 2) using the right level of model abstraction, 3) focusing on only the critical data, 4) establishing the key output metrics up front, 5) building internal cross-checks to ensure the model is behaving

logically, 6) validating the model with subject matter expert reviews, and 7) utilizing visualization techniques for improved understanding.

Marpe concluded that mega-companies, such as Wal-Mart, that are successful in logistics orchestration on a grand scale, have expressed that DMSMS M&S is not worth the effort [95]. Other popular beliefs exist in the alternative medicine and faith-based communities that actually encourage a reactive mindset, over a proactive one [96, 97, 98, 99]. Even Henry Ford states, “I believe God is managing affairs and that He doesn’t need any advice from me. With God in charge, I believe everything will work out for the best in the end. So what is there to worry about” [100]. Opponents to IB and sustainment M&S argue it is more effective to establish agile, “fire-fighting” capabilities as they arise, as opposed to being burdened with the non-value added waste of constantly expounding real resources towards the proactive mitigation of alpha error that never manifests as a problem.

Kang and McDonald used Microsoft Excel spreadsheets and Arena models to generate lifecycle cost and operational availability responses, after varying spare parts reliabilities, inventory levels, operational tempo, and repair turnaround times [101]. Kang and McDonald demonstrated a practical execution of commercial-off-the-shelf analysis tools in the sustainment support domain. The authors’ analysis assumes that a healthy IB is a given, which this dissertation does not take for granted. The most cost-influential metric was found to be operational tempo and its dependence on repair part availability proved to be trivial.

Ortland, Bissonnette, and Miller applied data mining and analysis to proactively assess the wear of military ground vehicle components [102]. The study involved the trending and graphic display of equipment demand information over extended periods of time. With the ability to assess entire platforms for part data trends, the authors uncovered strategic trends that were not visible when looked at in piecemeal. Ortland, Bissonnette, and Miller did not include any IB health metrics, DMSMS indicators, nor any tie-in to the acquisition community.

King and Driessnack analyzed the F-22 IB competition as it applies to the Theory of Transaction Cost Economics [103]. The authors showed that the perceived lack of competition at the prime supplier level, resulted in more sub-tier competition, synergetic alliances, specialized work, and lower overall costs. King and Driessnack did not offer any actual policy nor a conceptual enterprise model for increasing competition through barrier removal, but they did express its importance [103, p. 59].

Linshan & Yanji present the factors that influence how and why certain Chinese geographic regions develop faster than others, for specific resource-rich industries, such as labor, capital, and technology [104]. The authors showed how IB analysis can reveal patterns and how policy can influence economic growth in certain domains. Their analysis exemplifies the work that the Army Industrial Base Process encourages [29].

Leontief describes economic phenomena in terms of qualitative consumables and quantitative ratios in context of three technical coefficients: 1) cost coefficients, 2)

productivity coefficients, and 3) coefficients of distribution [105]. Leontief devised a visual analytic, called the “circular flow”, which models the period of production as a constant vector that permits the measurement of many potential production paths, relative to any element in the system. Leontief demonstrates that establishing a visual analytic is an important piece of economic analysis.

Blakely portrays strategy as manufacturing problem mitigation in that appropriate IB strategy enables industrial capability to meet DoD needs, whereas an inappropriate IB strategy oftentimes stifles technology development [2]. Blakely details how the DoD can inadvertently encourage industry to reduce or eliminate capacities that the DoD might actually acquire in the future. In addition, Blakely recaps how differing demands in the notional strategies of the DoD had significant impacts on industry. The author states that the most important element of IB strategy is a common DoD/industry view of the future requirements for industrial capabilities. Because of the lack of a coherent and adequately funded sustainment strategy, incumbent acquisition policies do not consider IB consequences and a “huge procurement challenge” results. Blakely advises that “it will be critical to sustain defense industrial base manufacturing technologies, design and development capabilities and the information-based analytical tools needed to support defense industrial and technology planning”. Finally, Blakely recommends that the DoD “optimally manage workflow through more effective contracting strategies and better use of Defense Production Act authorities with the goal of maintaining the health of needed defense-unique suppliers and allowing for greater civil-military integration of commercial suppliers” – with a particular focus on the mechanics of transactions.

Although Blakely recommends institutionalizing defense IB planning considerations into strategic thinking processes, the author does not provide a framework for execution.

Petersen relates the lack of a proactive IB strategy, especially with respect to technology transfer, to a National Security threat [106]. Petersen also describes an example of how contracting mechanism reform quickly advanced the development of Poland's IB.

Petersen vouches for the importance of organically-developed sustainment strategy, because "delegation of policymaking can undermine economic and national security interests and, as such, their focus and responsibilities may or may not align with the economic and national security interests of the U.S.". Petersen discusses "offset policy" which entails governments demanding that exporters invest resources in certain countries. Although Petersen explains how strategic offsets may "exacerbate the decline in defense IB" and "multiply the chances that leading edge weapons and the technology for producing them may go to countries that represent a threat to U.S. national security interests", the author does not provide a strategic solution to replace the offsets.

Gansler asserts that "human contact is the primary instrument of technology transfer and innovation" and that scientists and engineers rarely communicate. Gansler also confirms that the procurement system experiences absurd variation and competing objectives, while at the same time produces contracts that restructure the IB each time [107].

Gansler also reveals that "civilian-military integration may not have been feasible in the past, when defense technology was more advanced than commercial technology and more capable of operating in severe environments – but in many cases, this is no longer

true”. The author highlights the discrepancy in how the DoD spends only about 1% of their R&D budget on process improvements, whereas the leading Japanese commercial companies spend between 30-60% of their R&D budgets on process improvements. Gansler also points out that “streamlining defense is fully within the current authority” and a deliberate vision and developed strategy are to be followed. The author recommends forming partnerships, leveraging government-industry-university consortia, and even commends the National Center for Manufacturing Sciences (NCMS) for their track record of satisfying future military needs through collaboration – a reference that will be revisited later in Chapter 5 [107, p. 57]. Gansler does not provide the actual vision or strategy to streamline civilian-military integration.

Hensel reveals how innovative IB strategies help “balance conflicting economic, political, and military procurement objectives”, as illustrated by one of the largest defense contracts in U.S. history [5]. Hensel provides the historical significance that taxonomies play in strategy development. The author re-affirms that “current U.S. procurement law prevents IB concerns from being considered in the awarding of a military procurement contract”. In addition, the author acknowledges that “contractors may focus on locating production in states that have powerful members of the House of Representatives and the Senate, rather than the states that have the lowest cost or that are otherwise more appropriate for production”. Most importantly, Hensel brings to light that “the importance of having a transparent and well-documented government procurement process is reduced if Congress can ultimately block the funding for the winning proposal”.

2.5 Lean Six Sigma & TRIZ

TRIZ (theoria resheneyva isobretatelskehuh zadach) is Russian for theory of inventive problem solving. Blackburn, Mazzuchi, & Sarkani held that the Quality by Design approach, when coupled with TRIZ principles, addressed more physical and technical contradictions with inventive solution, thus thwarting the psychological inertia associated with engineers stepping outside their background to observe useful patterns [108]. The authors deemed that aligning the 39 abstracted engineering parameters with the 40 already successful inventive principles eliminated system contradictions better than the idea generation heuristics derived by trial and error alone. The authors' research re-emphasized that observing and applying patterns reuses the expertise of experienced designers and is considered to be a low investment with high potential returns. Therefore, TRIZ is considered to be a heuristic approach to innovation with applicability to manufacturing systems and supply chains.

Fey instructed that the act of zooming in and out amongst different levels of analysis helps remind TRIZ practitioners that their problems, and thus their solutions, are probably not unique to their industry [109]. Problem spaces can manifest themselves differently under varying zoom levels, such as a curve resembling a segment, when under high magnification. Visual models often lead to mathematical models which lead back to geometry. TRIZ breakthroughs and mathematic representations dwelling outside of some familiar domain have been represented as geodesics and applied to topics like supply chain streamlining. These depictions are not unlike the paradigm shift S-curve of Christensen [65] and the Kano Model reviewed by Chowdhury [110]. TRIZ leverages

cognitive splits, similar to Lean Six Sigma [111] and Kepner-Tregoe [112] practices, including primary and auxiliary functions, as well as requirement conflicts and distinctions.

Tian, Zhong, Xiao, Du, and Yang studied the integration of axiomatic design and TRIZ for the conceptual design of heating and drying equipment in a bitumen reproduction device [113]. The authors presented that there are four domains of axiomatic design: 1) the customer domain, 2) the function domain, 3) the physical domain, and 4) the process domain. Also, Tian, Zhong, Xiao, Du, and Yang presented an integrated model comprised of six steps, with an accompanying flowchart, including: 1) requirements transformation, using Quality Function Deployment, 2) construction of functional requirements and design parameters (using axiomatic design), 3) design matrix assessment (in terms of coupling), 4) coupling resolution (using TRIZ), 5) design matrix reassessment, and 6) detailed design. The authors did not offer any specific tactics for how to implement axiomatic design or TRIZ in an organization, however.

Wang & Chen successfully applied Lean Six Sigma and TRIZ methodologies to a banking operation [114]. Customer satisfaction and the operational availability of a banking service were analyzed by: 1) acknowledging the social relationships (and deficiencies) between organizations, 2) mapping a detailed process, and 3) monitoring process capability indices. Cheng & Chang applied Lean Six Sigma methodologies to storage rack design [115]. The authors showed how process cycle efficiency was raised 27%, by value stream mapping the process to a discrimination of seconds. Cheng &

Chang did not apply any of their productivity improvements to an office environment, however.

Furterer & Elshennawy successfully applied Lean Six Sigma (LSS) and Total Quality Management (TQM) methodologies to a financial management operation run by a local government [116]. The authors demonstrated that LSS and TQM methodologies can produce double-digit percentage improvements to government productivity. Furterer & Elshennawy did not apply LSS and TQM methodologies to federal government office operations such as sustainment, R&D, and acquisition disciplines, however.

Drohometerecki, Gouvea da Costa, Pinheiro de Lima, and Andrea da Rosa Garbuio distinguished between Lean Manufacturing, Six Sigma, and LSS methodologies across multiple competitive priorities (e.g. speed, quality, innovation) under multiple decision areas (e.g. capacity, vertical integration, organization). Survey feedback on these distinctions was collected and analyzed across large manufacturing companies in southern Brazil [117]. The authors presented that LSS covers the widest range of competitive priorities and creates organizational flexibility. Reliability was found to be the most common objective/benefactor, which supports the idea that reliability trumps even the quality domain [118]. Van den Bos, Kemper, and de Waal analyzed 62 LSS improvement projects within a Dutch construction company, in an attempt to identify patterns for improving throughput [119]. Through their study, the authors illustrate how process improvements increase efficiency and, on a grand scale, can support sustained national objectives.

Atmaca & Girenes discuss techniques used by various authors who published LSS improvements across multiple sectors, such as aircraft, service, insurance, and pharmaceutical. The techniques include: value flow map, experimental design, and Pareto analysis. The authors also present the results of implementing LSS methodologies in a Turkish dishwasher body manufacturing operation [120]. Atmaca & Girenes show that the proper execution of LSS analysis can bring benefits to any organization. The authors state that LSS is rarely practiced in the service and public sectors.

2.6 Analysis Initiatives Involving Sustainment

There have been nine major analysis initiatives, involving some level of sustainment abstraction, within the Tank Automotive Lifecycle Command (TACOM) between 2009 and 2013, each with their own underlying approach:

1. AT Kearney (ATK) Vehicle Manufacturing Network Analysis,
2. Sector-by-Sector-Tier-by-Tier (S2T2),
3. Integrated Systems Engineering Framework (ISEF), formerly known as the Advanced Systems Engineering Capability (ASEC),
4. Industrial Base Baseline Assessments (IBBA),
5. Industrial Capability Assessments (ICAs),
6. Capability Portfolio Analysis Tool (CPAT),
7. Industrial Base Analysis Tool (IBAT),
8. Sandia Corporation's System of Systems Analysis Toolset (SoSAT), and
9. Sustainment Engineering Risk Assessment (SERA).

A brief explanation of each initiative, within the confines of publicly releasable (i.e. Distribution Statement A) granularity [121], follows:

1) ATK (ATK) Vehicle Manufacturing Network Analysis

The ATK Vehicle Manufacturing Network Analysis, conducted in 2012 and 2013, was sanctioned by Program Executive Office (PEO) for Ground Combat Systems (GCS) to study the IB and develop a network strategy which included the supply base [122]. The study consisted of multiple manufacturing site visits and platform briefings pertaining to most of the PEO GCS portfolio, including prime contractors and organic depots. The war production volume declines around 2012 were taken into account and a sensitivity analysis was conducted. General recommendations were made on how the PEO GCS portfolio should be allocated in the areas of production, modernization, and sustainment.

2) Sector-by-Sector-Tier-by-Tier (S2T2)

The S2T2 initiative, conducted in 2012 by the Department of Commerce (DoC) and DoD, involved a national security supply chain assessment concluding on the notion that many companies show signs of military contract dependency [123]. The backbone of the assessment was a survey that was sent out to a sample of over 5000 tiered suppliers of military equipment/services gathering proprietary company data in areas including: finance & investment, R&D, capability, capacity, and employment. A framework was established for assessing industrial capabilities that weighed various hierarchies of equipment and services in terms of “criticality” and companies in terms of “fragility”. Criticality takes into consideration aspects like: defense uniqueness, certain future demand, and highly-skilled labor, whereas fragility looks at whether a supplier’s finances

were weak, sub-tier suppliers were vulnerable, or production was at a minimum sustainment rate (MSR). Two-dimensional plots of criticality (on the y-axis) versus fragility on the x-axis) were generated for different hierarchies, including red, yellow, and green overlay zones depicting a level of severity. In total, the survey results were highly sensitive and access was restricted to only one computer in the Detroit Arsenal (in conjunction with a limited need-to-know).

3) Integrated Systems Engineering Framework (ISEF)

ISEF is an integrated systems engineering knowledge creation and capture framework built on: a decision-centric method, high quality data visualizations, data traceability, real-time collaboration, and knowledge pattern leverage. ISEF consists of three parts: 1) problem space (inputs), 2) innovation/analysis space, and 3) solutions space (outputs). ISEF has been approved at the DoD level and provides an opportunity as an integration point for all other system models [79].

4) The Industrial Base Baseline Assessment (IBBA)

The IBBA is a 500+ page report designed to provide senior U.S. Army leadership with a “Common Operating Picture” of the risks and issues which impact the IB’s ability to sustain warfighter readiness. An IBBA is executed in an annual cycle with quarterly updates supported through the Army Materiel Command’s (AMC) Quarterly IB Review Process. The specific information contained in each cycle of IBBA is considered business sensitive and proprietary. Strategically, the IBBA Program is a key component in the U.S. Army’s strategic initiative to reshape the IB, commercial and organic, to

sustain the current operational environment, while transforming to support future operations.

5) The Industrial Capability Assessments (ICA)

The ICAs are investigative reports on selected suppliers that include a questionnaire response, utilization of the Fragility and Criticality (i.e. S2T2) measurement system, and often include site visits. The assessment concludes with a narrative explaining the state of the supplier in relation to the state of the business. The ICAs, themselves, are not releasable to the public.

6) The Capability Portfolio Analysis Tool (CPAT)

The CPAT is designed to identify the optimum courses of action for portfolio investment at the PEO level [124]. The CPAT determines a single number (using 49 attributes) to grade a PEO GCS fleet of vehicles across several mission roles, in terms of cost, schedule, and performance. Some degree of sustainability analysis, in terms of demand gaps, is included in the Industrial Base Impacts output and the details are not releasable to the public.

7) The Industrial Base Analysis Tool (IBAT)

The IBAT, created by Booz Allen Hamilton (BAH), focuses on the PEO GCS platforms' repair parts structure over a planning period of around 30 years. By leveraging information from related IB studies circulating within the IB community, along with

CPAT outputs, the IBAT aims to offer supply chain strategies, PEO lifecycle requirements, and identify IB risk. The details are not releasable to the public.

8) Sandia Corporation's System of Systems Analysis Toolset (SoSAT)

SoSAT was originally created to support the Future Combat Systems (FCS) team in orchestrating multiple distributed systems embedded in networks at multiple levels and in multiple domains. The basic, parametric entities of SoSAT are programmable and include: 1) primary elements, 2) personnel, and 3) consumables. Through use of State Model Objects (SMOs), SoSAT demonstrates encapsulation, during stochastic simulation runs, which allow the user to step through discrete time intervals. Unfortunately, as of March 2015, only a beta version (i.e. v3.0.0.31) of the software under a 2011 copyright was made available to government analysts looking to explore and use the tool. Also, training and support is no longer available.

As seen in Figure 29, the SoSAT interface includes a tree structure along the left pane and an operation state graph (as a function of time) on the main window.

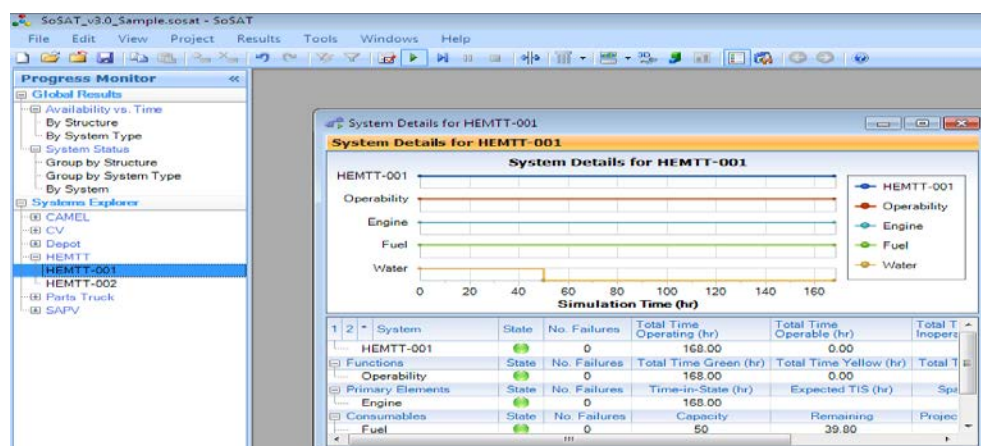


Figure 29. System of Systems Analysis Toolset (SoSAT) interface

The operation states are categorized as green, yellow, and red with association to a multitude of systems or abstractions. Note how in the figure that four different abstraction levels are being monitored:

1. System: Heavy Equipment Medium Tactical Truck (HEMTT) 001
2. Functions: Operability
3. Primary Elements: Engine
4. Consumables: Fuel and Water

In conclusion, the structure, behavior, and requirements of the entire sustainment IB, as a system, is a multi-dimensional entity. Acknowledging the influence of information technology (IT), missions involving IB data access and strategic decision making can be rich in visual analytics, where various agencies can “explore the behavior of many objects across a use case” [58]. This kind of lateral thinking facilitates situational awareness (SA) and enables pattern recognition [125]. Once patterns are exposed, innovation can follow. TRIZ innovation is often thought to be an adaptation of ancient physics and existing geometry, in order to resolve the secondary problems, or contradictions, unveiled during systems analysis [108, 126, 109]. In other words, trend recognition is oftentimes considered to be the seed of the fruit of innovation. Analysis often evolves, following the S-curve of technology improvement as analysts begin with alphanumeric lists, migrate towards 2D visual analytics, and pinnacle as a distributed workforce using 3D collaborative models [109, 97]. This mind-set, coupled with the decision to use the momentum of established commercial-off-the-shelf tools upholds the most recent DoD Research & Engineering Strategy [127, 128].

3. SUSTAINMENT ENGINEERING RISK ASSESSMENT (SERA)

In order to “improve our leaders’ ability to understand and mitigate technical risk” [10], a diverse collection of relational information needs to be accessible. The SERA was developed to address this need. In a Microsoft Access environment, the SERA stores configuration management (CM), supply/demand, logistics, and contracting data in a multi-level abstraction model, much like those defined in section 1.3. The SERA consists of multiple views of relational tables of part and supplier characteristics pertaining to an entire vehicle platform of equipment [129]. Similar to many smart phone “apps”, the SERA takes existing information from various sources and presents it to analysts working in different disciplines in an easy-to-read, easy-to-analyze interface. This chapter is dedicated to describing the SERA and its construction. Although a few examples will be illustrated, under permission via operational security (OPSEC), the aggregate information of the SERA has not been deemed releasable to the public [121].

3.1 Motivation for using the SERA

Most often, analysts will start a study given only a part number, or a National Item Identification Number (NIIN). From there, analysts will data mine additional characteristics, slowly adding pieces of contextual information, eventually describing the situation of sustainment capabilities and limitations. Contextual information may include: which vehicle models the part is used on, current supply chain, past contracts, and demand history. These are frequently queried from multiple databases, each requiring their own logins and exhibiting their own user interface nuances. By

comparison, SERA displays commonly queried characteristics in a single interface, as shown in Figure 30. The SERA database shortens the learning curve for novice users who would not normally be able to quickly mine data from unfamiliar sources. This shortened learning curve effect is similar to how analysts from other organizations have benefitted in the past from lite versions of more sophisticated software [80, 81]. Note how Figure 30 allows a novice user to quickly generate the list of suppliers or part numbers with a single button input from the Lists section (top-center of figure).

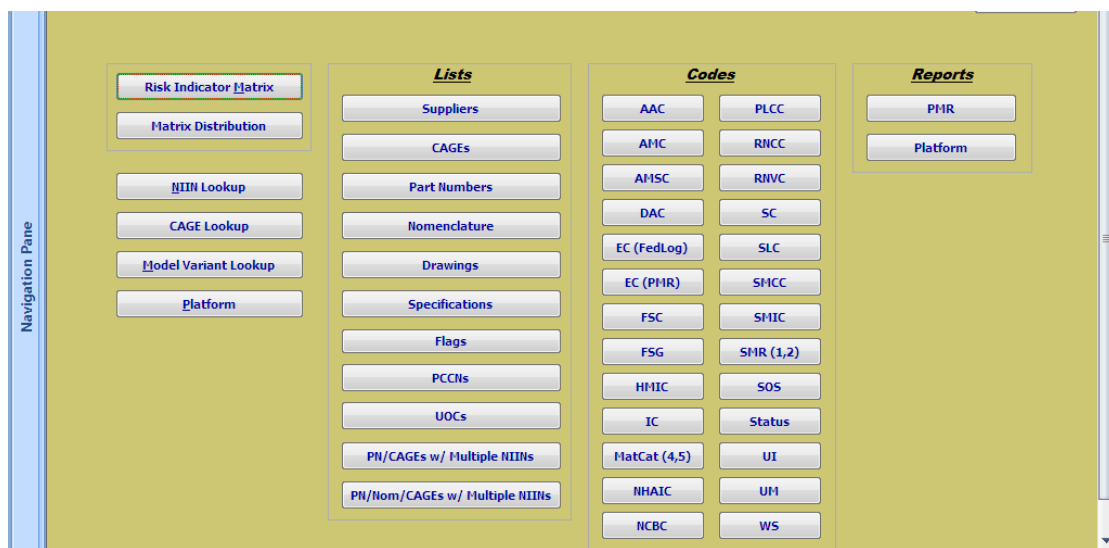


Figure 30. Sustainment Engineering Risk Assessment home screen

Figure 31 shows the result of selecting the ‘Suppliers’ button from SERA home screen. By default, a list of all the suppliers for the platform (LTV in this case) is displayed in rank order by which suppliers have the most Commercial and Government Entity (CAGE) codes. CAGE codes are a unique identifier for each facility of a company or agency. Large companies may have several CAGE codes to identify factories, warehouses, or headquarters. Hierarchical data elements, displayed as blue hyperlinks in the SERA, offer the user additional information. One convenient feature of Microsoft

Access implementation is that the contextual window (used for sorting and Boolean logic filtering) for any screen can be quickly accessed, via a right click of the mouse.

Therefore, any list generated by the SERA can be quickly sorted and/or filtered for further analysis.

Average NIIN rank	Average NIIN Weight	Name	Govt	Std	CAGES	Active CAGES	Company names	Addresses	Part numbers	Nins	Counts		
											Sole source NIINs	Sole source pct	Standard NIINs
6693.5	2.32	<Unknown>	☐	☐	85	85	1	0	1	120	0	0.0%	87
5678.3	3.40	EATON	☐	☐	54	45	24	50	308	197	1	0.5%	129
5728.7	3.34	PARKER	☐	☐	52	47	11	47	399	195	1	0.5%	132
5984.8	3.03	UNITED TECHNOLOGIES	☐	☐	46	34	32	36	249	184	0	0.0%	158
5103.3	3.91	GM	☐	☐	43	28	23	37	2584	1598	47	2.9%	398
6150.6	2.85	GE	☐	☐	38	23	10	28	142	111	0	0.0%	104
5768.3	3.20	LOCKHEED	☐	☐	31	27	6	31	234	405	0	0.0%	226
3296.7	6.18	BAE	☐	☐	30	26	22	29	2070	857	476	55.5%	156
6023.9	2.97	HONEYWELL	☐	☐	28	24	14	24	202	132	1	0.8%	107
4941.8	3.95	CHRYSLER	☐	☐	23	16	16	17	187	345	1	0.3%	86
6922.9	2.13	RAYTHEON	☐	☐	23	19	9	21	339	182	2	1.1%	172
6553.2	2.40	THALES	☐	☐	23	20	22	23	83	46	0	0.0%	43
6337.0	2.69	GENERAL DYNAMICS	☐	☐	22	21	19	20	243	219	2	0.9%	124
6198.0	2.83	NAVY	☒	☒	20	18	18	14	486	257	0	0.0%	215
6954.6	2.06	NORTHROP GRUMMAN	☐	☐	20	19	9	17	264	194	0	0.0%	181
7203.7	1.84	ALCOA	☐	☐	19	18	9	14	115	79	0	0.0%	62
5631.5	3.52	DANA	☐	☐	19	12	11	12	335	232	3	1.3%	79
6602.9	2.42	ITT	☐	☐	19	14	15	17	79	62	0	0.0%	41
5236.3	3.81	ARMY	☒	☒	18	14	15	13	7299	4746	0	0.0%	435
5898.9	3.13	Finmeccanica SpA	☐	☐	18	18	14	16	121	88	0	0.0%	71
Count:		6820	Overall:		8424	6554	7719	7157	53503	91340	1464	0.3%	31018

Figure 31. Supplier list interface of the Sustainment Engineering Risk Assessment

3.2 Risk Management

Although there are many variations in the terms that are used, most risk management includes steps that fall under the planning, preparing, and executing phases, like the ones shown in Figure 32 and Appendix B. In the planning phase, risks or hazards are identified and assessed through brainstorming sessions with cross-functional teams. This basic premise also applies to other systems engineering analyses like Failure Mode Effects Analysis (FMEA) and may leverage additional Lean Six Sigma tools and

techniques like Ishikawa diagrams and Fault Tree Analysis (FTA) [48, 130]. Risk mitigations or controls are developed and decided upon in the Prepare phase. Finally, the risk mitigations are actually performed and evaluated in the Execute phase. Variations of this risk management construct may include similar steps labeled as: risk identification, risk analysis, risk mitigation planning, risk mitigation plan implementation, and risk tracking [131].

Step 1 – Identify Hazards Step 2 – Assess Hazards	Plan
Step 3 – Develop Controls/ Make Risk Decision	Prepare
Step 4 – Implement Controls Step 5 – Supervise & Evaluate	Execute

Figure 32. Composite Risk Management aligned with command and control (C2) [132]

Assigning values of likelihood and consequence is one of the fundamental planning steps to any risk management scheme, following the identification of risks, as shown in Figure 33 [48].



Figure 33. Typical steps in a risk assessment

For example, an identified risk such as an electronics control board assembly becoming unavailable, due to its supplier going out of business, may be assigned a likelihood score of 3 and a consequence score of 4 [7]. These scores are typically within a scale of 1-5. The scores would then be the coordinates of a point in the yellow zone of Figure 34, where likelihood is vertically oriented and consequence is horizontally oriented. The yellow zone depicts a medium level risk, whereas green is considered low and red is high. Entire lists of identified risks may be assessed and plotted on the same grid, or risks may be categorized and plotted on domain-specific grids that make up an overarching family.

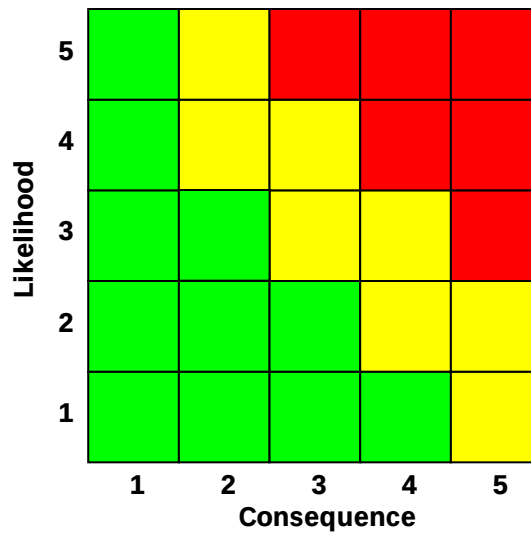


Figure 34. Typical risk assessment measurement system

Further detail may be assigned to the risk scores, noting that variation in the terms used is commonplace, as shown in Table 1. In this case, likelihood is referred to as probability and consequence as severity. Also, lower scores can translate to more severe and/or more probable situations, instead of the other way around. Overall labels as to how large the risk is, based on where the scores reside within the grid, may include: extremely high, high, moderate risk, and low risk. Risk mitigations come in a few categories, such as: risk avoidance, risk control, risk transfer, and risk assumption. Risk assumption is also known as: risk monitoring or risk acceptance [133].

Table 1. Composite Risk Assessment Matrix [132]

RISK ASSESSMENT MATRIX						
		Probability				
SEVERITY		Frequent (A)	Likely (B)	Occasional (C)	Seldom (D)	Unlikely (E)
Catastrophic	I	E	E	H	H	M
Critical	II	E	H	H	M	L
Marginal	III	H	M	M	L	L
Negligible	IV	M	L	L	L	L
E - Extremely High H - High M - Moderate Risk L - Low Risk						

Risk, in the context of the SERA, relates to DMSMS risk. The risk identification and assessment capability of the SERA differs drastically from the aforementioned risk management measurement systems. In terms of risk identification, only one risk is considered: the risk or the inability to acquire a piece of equipment, due to DMSMS. This risk is considered for each piece of equipment, whether the equipment is just an o-ring, or an entire engine. In terms of risk assessment, the SERA does not endorse assigning likelihood and consequence scores, because the likelihood that there would be an inability to acquire a piece of equipment is not well understood and the consequence would be catastrophic. If a vehicle is denied its needed equipment, it is considered unavailable or deadlined. Equipment readiness, which is based on the availability of sustainment support, is considered to be the highest priority for military systems. Therefore, using the typical risk management measurement system would result in all equipment being labeled as extremely high risk. This would not provide any sense of

prioritization and would not leverage available trends and data patterns. Therefore, the SERA assesses risk, not from a likelihood and consequence point of view, but from a stackup of risk indicators point of view.

A risk score is associated with each NIIN in a SERA's equipment list. The score is calculated by adding individual sub-scores located in adjacent columns. Sub-scores correspond to various risk indicators that will be discussed later. Figure 35 shows the result of selecting the 'Risk Indicator Matrix' button from the SERA home screen. A list of all the NIINs for the platform (LTV in this case) is displayed, in rank order, by which NIINs have the highest calculated risk score, or sustainment risk. The data columns to the right of the Nomenclature column are the risk indicators. Not all risk indicators are displayed in Figure 35, for readability purposes. The risk indicators are simply indicators of sustainment risk. The risk indicators, themselves, will be explained later in Chapter 3, but it is important to note that they display three different states of sub-scores for each NIIN: 1) hi, 2) lo, or 3) data not available. The hi state displays a positive risk sub-score highlighted in yellow, whereas the lo state displays an unhighlighted zero as its risk sub-score. The tertiary state is reserved for the case where risk indicator data is unavailable. When data is unavailable, the SERA displays an empty cell where the risk sub-score would normally reside. The risk indicators can be thought of as 'flags', where a flag becomes tripped into a hi state when certain conditions are met, thus displaying a risk sub-score. If those same conditions are not met, the lo state (i.e. a zero risk sub-score) is displayed. Each NIIN, or row, exhibits one of the three states for each flag. For each NIIN, all risk sub-scores are simply added up to give a "Total weight", or risk score. The

total weight works much like a tolerance stack, where the more flags that are tripped, the higher the probability of an issue.

	Rank	Norm RPI	Total weight	NIIN	Nomenclature	No CAGE code	Single source	D&B high risk	D&B medium risk	D&B UNK risk	OCON US only CAGE	AAC with dem-and	Rand
▶	1	0.39	20.5	01-563-8620	WHEEL,PNEUMATIC TIRE	0.0	4.0				0.0	0.0	
	2	0.38	19.5	01-491-2158	CONTROL,REMOTE SWITCHING	5.0	0.0				0.0	3.0	3.0
	3	0.37	19.0	01-541-6816	WHEEL,PNEUMATIC TIRE	0.0	4.0				0.0	3.0	
	4	0.35	18.0	01-470-1931	CONTROL,REMOTE SWITCHING	0.0	4.0				0.0	3.0	3.0
	5	0.35	18.0	01-491-2152	CONTROL,REMOTE SWITCHING	0.0	4.0	4.0			0.0	3.0	
	6	0.34	17.5	01-558-2138	WHEEL,PNEUMATIC TIRE	0.0	4.0				0.0	0.0	
	7	0.34	17.5	01-197-5502	COMPRESSOR,RECIPROCATING	0.0	0.0	4.0			0.0	3.0	3.0
	8	0.34	17.5	01-157-0856	GASKET SET	0.0	0.0	0.0			0.0	3.0	3.0
	9	0.33	17.0	01-203-5746	HUB BODY ASSEMBLY,FOUR WHEEL DR	0.0	4.0				0.0	0.0	3.0
	10	0.32	16.5	01-434-0822	TRANSFER TRANSMISSION ASSEMBLY	0.0	0.0				0.0	0.0	3.0

Figure 35. NIIN list interface of the Sustainment Engineering Risk Assessment

Visually, as favorable sustainment support strategy conditions for a NIIN dwindle, more flags are tripped. A stackup of warning signs, symbolized by yellow flags, equate to a NIIN exhibiting more and more indicators of sustainment risk, as seen in Figure 36. This research explores whether there is a correlation between the stackup of warning signs on NIINs that have already experienced a DMSMS issue, illustrated as Figure 36 is scanned from left to right.

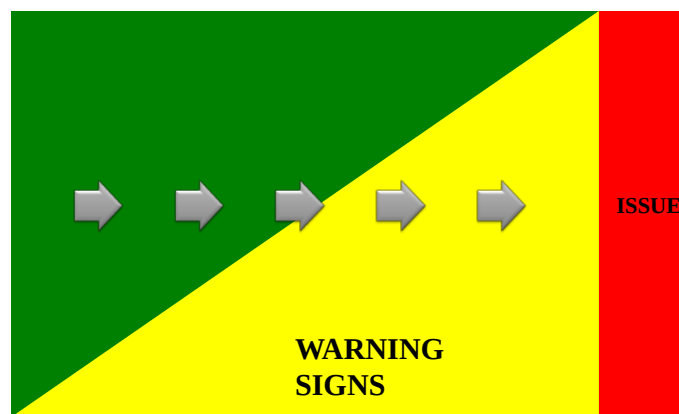


Figure 36. Depicting a stackup of warning signs that foreshadow DMSMS

The risk sub-score, or weight, of each flag was determined by consensus, after conducting multiple cross-functional workshops that included analysts from the Automation Alley Defense Office and U.S. Army TACOM logisticians and IB engineers. A scale ranging from 1.0 to 5.0, in growing increments of 0.5, was chosen to represent the various flag weights, as displayed in Figure 37. Further study of the scale range is warranted, as is often the case with psychometric measurement systems [134, p. 3, 135, 136]. Note that if a NIIN has a particular flag tripped, the number of trips is tallied across the list of NIINs, so a distribution can be analyzed. For example, the flag titled ‘No valid commercial CAGE Code’, with a flag weight of 5.0, was tripped by 211 NIINs in the list of all NIINs for the LTV platform assessed in Figure 37.

Flags (Active)		
<i>NIIN count</i>	<i>Weight</i>	<i>Flag</i>
211	5.0	No valid commercial CAGE Code
171	4.0	D&B High Risk
55	4.0	Persistent Back Order 8-Month
1467	4.0	Single Valid Supplier
2155	3.5	Technical Data Unavailable
167	3.0	D&B Medium Risk
186	3.0	Discontinued AAC with Demand in past 2 years
1095	3.0	No Demand in past 3 years
891	3.0	Readiness Driver
498	3.0	Top 10% CWT
2373	2.5	Technical Data with Limited Availability
159	2.0	Hazardous Materials
0	2.0	Part Complexity
840	2.0	Top 10% Closed Maintenance Work Order
3582	1.5	Single or No Weapon System
445	1.5	Top 10% Open Maintenance Work Order in past 12M for NMC Items
20	1.0	D&B Unscored Risk
0	1.0	OCONUS Only CAGE Code
3247	1.0	Open Maintenance Work Order in past 12M for NMC Items
291	1.0	Shelf Life Sensitivity
0	1.0	Source Controlled
Totals: 17,853		
Total weight: 52.0		
Count: 21		

Figure 37. Sustainment Engineering Risk Assessment flags and their weights

Most flags are simply defined to emulate established Defense Logistics Information System (DLIS) codes that are assigned to NIINs by Defense Logistics Agency (DLA) analysts and serve as data filters. A few of the flags, however, were developed based on heuristics, and involve special combinations of business logic. For example, a NIIN that is considered to be complex, in terms of its design and manufacturing requirements, has been observed as exhibiting:

- a price greater than or equal to \$500,

- an assembly structure comprised of children parts,
- a repairable support strategy (i.e. not considered consumable equipment), and
- an outlier of manufacturing lead time

Some of these characteristics, and others, were included in the business logic for an experimental flag titled ‘Part Complexity’ where a flag weight of 2.0 was assigned. No NIINs tripped the Part Complexity flag, so the NIIN count for the Part Complexity flag displays a zero in Figure 37.

Displaying the tripped flags in context with some of the other data associated with a NIIN is another view that the SERA offers. Figure 38 shows the NIIN Detail dashboard that results after zooming into NIIN 01-491-2158. Note that NIIN 01-491-2158 is the second NIIN hyperlink (blue) listed in the list of NIINs shown in Figure 35. The flags that are tripped for this NIIN are highlighted in yellow on the dashboard also and are amongst a multitude of other characteristics associated with 01-491-2158, including Maintenance Work Order history, Next Higher Assembly count, and annual demand. With this particular NIIN, there appears to be a lack of supply chain visibility. Note how the Suppliers section of the dashboard (bottom center of Figure 38) only displays the word “Army” under the Group heading and the corresponding contract history is empty. As is often the case with mass data mining investigations, “no data found” can result. Therefore, generic placeholders (like “Army”) are sometimes seen, even though the Army is NOT the true manufacturer of 01-491-2158. This results in the No CAGE code flag being tripped, as indicated by the 5.0 highlighted in yellow on the left side of the

dashboard. Further study is warranted on the recommended action items that should follow: 1) a lack of data versus 2) inaccurate data highlighted in a SERA. However, one common trait between these two different conditions is that they both result in a lack of situational awareness, which is a DMSMS risk indicator in and of itself. One benefit of the NIIN Detail dashboard of Figure 38 is that characteristics from seven different data sources are brought together on one screen to paint a strategic picture for the analyst, without the analyst having to muddle through dozens of system access requests (SARs), passwords, and training.

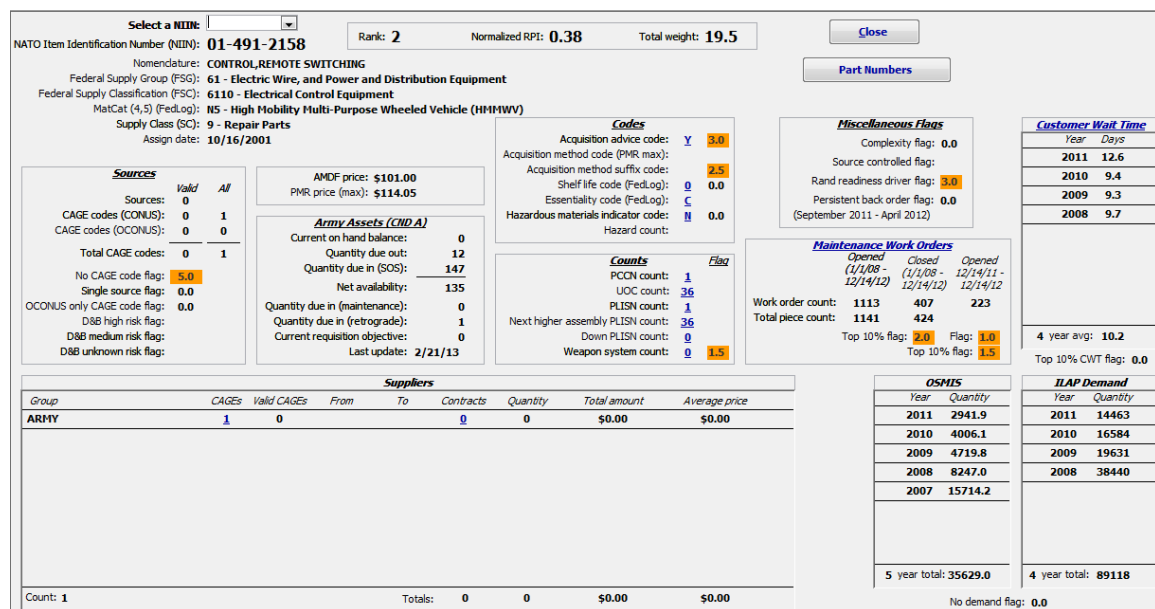


Figure 38. NIIN detail dashboard of SERA

The SERA can help to conduct a “what if” to isolate which equipment: 1) is shared by multiple platforms, 2) is sourced to a single supplier, 3) is limited on data rights sharing, and 4) exhibits low demands. The current state of proactive supply chain management, or IB planning, at TARDEC is undefined. Implementing risk mitigations for equipment

and suppliers exhibiting indicators of sustainment risk in the SERA is anticipated, but not yet realized.

The total weights of all NIINs in Figure 35 are normalized against all possible weights, to create the Risk Priority Indicator (i.e. Norm RPI). If all flags were tripped for a NIIN, the total weight would equate to 52, which is simply the sum of the second column of Figure 37. This serves as the denominator for the normalization calculation. Consequently, the Norm RPI manifests as a number between 0 and 1 in the second column of Figure 35 and the Norm RPIs can be depicted in a histogram, as seen in Figure 39. The tally of NIINs that trip fewer flags are shown on the left side of Figure 39, whereas the tally of NIINs that trip more flags are shown on the right. The prioritization theory is that the NIINs that trip the most flags should be assigned risk mitigation plans first. Conveniently, when in a rank-ordered list format like that of Figure 35, the NIINs that are in the most need of risk mitigation plans are said to “bubble to the top” of the screen.

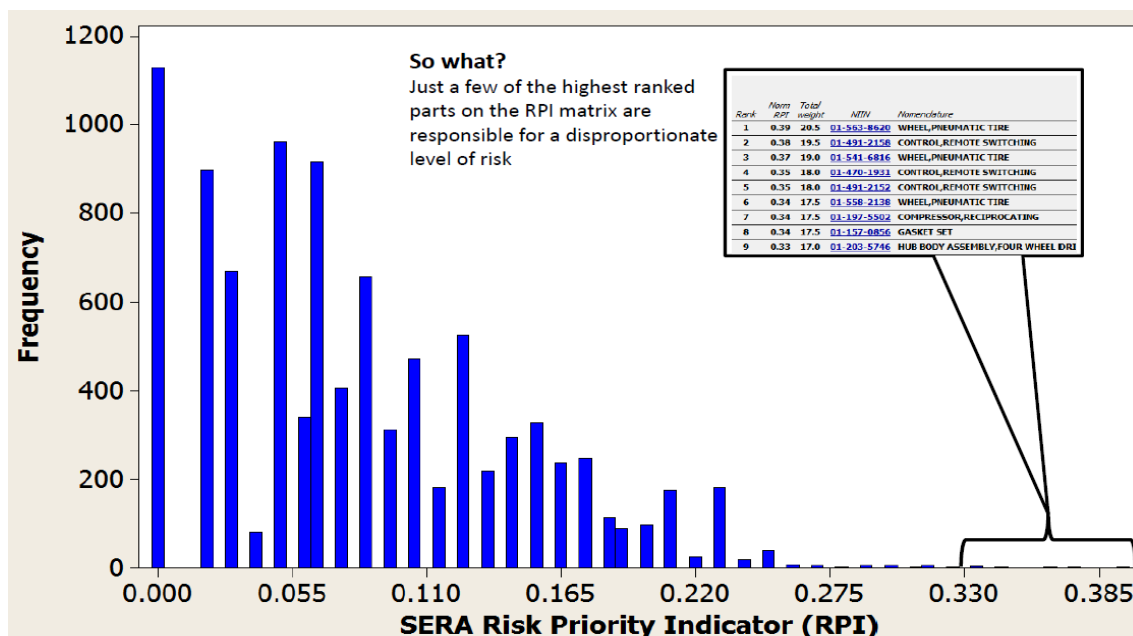


Figure 39. LTV SERA histogram of RPI

3.3 SERA Construction

A vehicle consists of thousands of individual components that are identified by a unique National Stock Number (NSN). The NSN is simply the NIIN, preceded by the four-digit Federal Supply Class (FSC). The first step in constructing a SERA is to compile a complete, up-to-date list of NSNs.

3.3.1 Provisioning Master Record (PMR)

A secret exists among the logistics realm that is unknown in other realms, including engineering and even program management: the entire Work Breakdown Structure (WBS), as well as most of its IB is found within an artifact called a Provisioning Master

Record (PMR). A PMR contains detailed information pertaining to the equipment which makes up a system that has been selected for provisioning [137]. Not all equipment recorded in the PMR will be procured and supported through the sustainment phase, however. Items that are not coded for procurement are also contained in the PMR, in order to support associated functions such as the generation of Repair Parts and Special Tools Lists (RPSTLs) and equipment technical manuals (TMs). The RPSTL is thought to be a key piece of TMs. Within the Logistics Modernization Program (LMP), the indentured Bill of Materials (BOM) portion of the PMR is better known as the Provisioning Bill of Materials (PBOM) and is depicted in Figure 40. Note how equipment that makes up the parent assembly is denoted in a tree structure leading to the component name, quantity, unit of measure (UoM) and description.

PBOM structure	Component	Qty	UoM	Descript'n
--- AAAA	015678852	1	EA	TANK,FABRIC,COLLAPS
-- AABB	MPC-FFDV-4-B:1EMJ6	2	EA	BALL VALVE ASSY4IN
-- AABD	BV-FT-BZ-4:1EMJ6	1	EA	BALL VALVE, 4 IN
-- AADA	008400797	1	EA	COUPLING HALF,QUICK
-- AADF	006406156	1	EA	CAP,QUICK DISCONNEC
--- AADG	008994509	1	EA	GASKET
-- AADK	006499118	1	EA	COUPLING HALF,QUICK
--- AADL	008994509	1	EA	GASKET
-- AADP	006406188	1	EA	PLUG,QUICK DISCONNE
-- AAEE	3610T32-10INCH:39428	2	EA	CHAIN,WELDLESS
--- AAEF	015150537	7	EA	HOLDER,KEY
-- AAFB	MPC-FFDH-4-C:1EMJ6	2	EA	HOSE ASSY 4INX12FT
-- AAFM	015956709	1.000	FT	HOSE ASSEMBLY,NONME

Figure 40. Example PBOM

The PMR lists many other attributes for each item of the RPSTL, such as part number, supplier, price, manufacturing lead time, and so on. The PMR usually conforms to MIL-STD-1388-2B or MIL-STD-1552A and is arranged in an 80-column, 12-row, IBM punch card format [138, p. 136, 139, p. 30]. The PMR is updated based on the

availability of platform support, and some of the information it contains may no longer be valid. The SERA cross-references the data in the PMR with a list compiled from the other data sources. Most PMRs at TACOM are provided as a Logistics Support Analysis Record (LSAR) text file, which can be exported to Microsoft Access tables. Once exported, PMR information can be refreshed within the SERA, on a periodic basis, by the DMSMS team at the Automation Alley Defense Office, under guidance from the TARDEC Industrial Base Engineering Team (IBET).

The key attributes extracted from the PMR that are used to cross check attributes mined from other data sources include:

- National Stock Number (NSN): Contains FSC and NIIN as previously described
- Usable on Code (UOC): Identifies the model/configuration relationship of each Logistics Control Number (LCN) comprising a system and controls this relationship for Logistics Support Analysis Record (LSAR) report generation
- Provisioning Contract Control Number (PCCN): Identifies specific weapon system/item/subsystem
- Provisioning Line Item Sequence Number (PLISN): Identifies specific assembly/subassembly/component
- Source Maintenance Recoverability (SMR): Indicates procured, stocked, manufactured, or assembled categories for each NIIN.

It is surprising to know that even the awareness of technical manuals (TMs) is lacking among many researchers and engineers, thus, proving further that logistics engineering through model-based technology provides value. Regardless, PMRs contain the heart-

and-soul of data mining tokens, which permit analysts to explore other disciplines. Instead of dealing with just samples of repair parts for a particular vehicle, the PMR is, by definition, the population of repair parts for a particular vehicle. This is the key to the sustainment support strategy for a piece of equipment: the RPSTL is the very thing that needs to be sustained, in order to achieve readiness. The RPSTL is also the thing that: 1) contains every tangible culprit to Operation & Maintenance (O&M) costs (i.e. the most influential driver of lifecycle cost), 2) contains every candidate for technology upgrade, and 3) many engineers do not know exists. Given that the RPSTL is, indeed, the entire population of sustainment support equipment, using population statistics, as opposed to sample statistics, to analyze DMSMS trends and patterns is more fitting.

The relative proportion of PMR data relative to the other mined data sources in a SERA are shown in Figure 41.

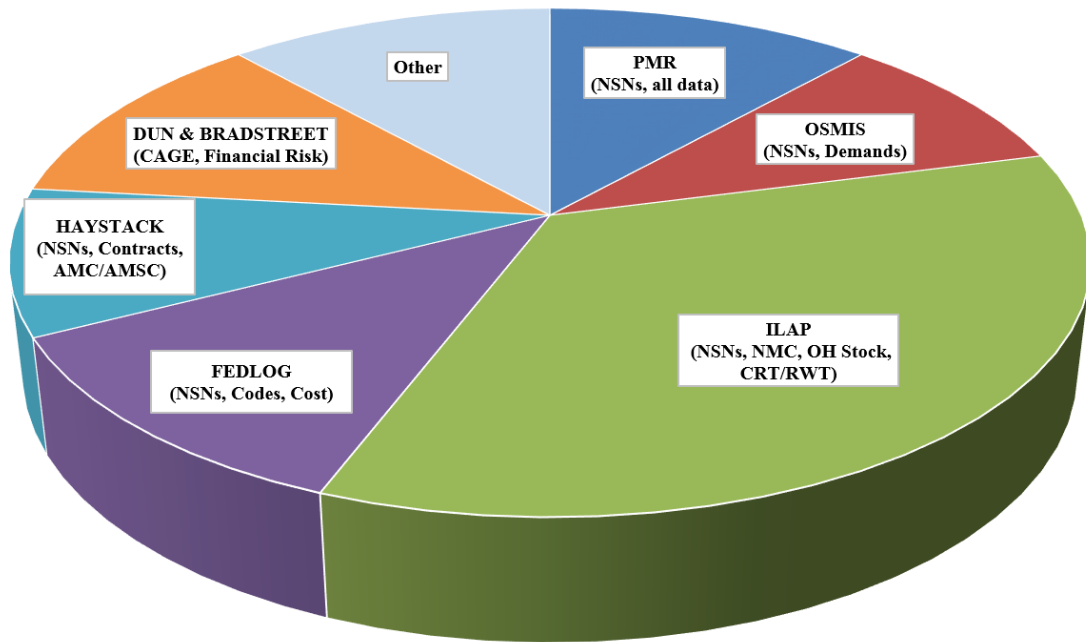


Figure 41. Data sources of a SERA

3.3.2 Integrated Logistics Analysis Program (ILAP)

ILAP is the source for the largest proportion of data in a SERA, as shown by the green region of Figure 41. ILAP is an Army-wide database that integrates logistics and financial information, providing detailed demand and cost history by component and allowing a wide range of search criteria. ILAP is a Logistics Information Warehouse (LIW) application available online with menu-driven options as well as dynamic query capability. ILAP reports all demands for a given part. Some of the main facets of ILAP used in the SERA include:

- ILAP Equipment Downtime Analyzer (EDA) Report: Maintenance records, by vehicle, including reference to the NIINs used in repair and related to Non Mission Capable-Supply (NMCS).

- ILAP-SARSS (Standard Army Retail Supply System): information about backorder status and warehouse stock. ILAP also gives visibility into the Standard Army Maintenance System – Enhanced (SAMS-E). SAMS-E maintenance records are real-time sources showing parts ordered.
- ILAP-RAND: A data field used to indicate, for each NIIN, whether it is currently designated as a “Rand Readiness Driver.” RAND (Research And Development) Corporation pulls data from maintenance work order files and checks for common parts that are keeping vehicles down the longest, applying a propriety algorithm to identify parts considered most critical for readiness. This list is updated every 6-9 months and used for managing the Authorized Stockage List (ASL).

3.3.3 Operating and Support Management Information System (OSMIS)

OSMIS tracks the overhaul and modification of major end items (e.g. tanks) and the rebuilding of secondary items (e.g. engines and transmissions). For each OSMIS-tracked system or secondary item undergoing a maintenance action, information is kept on the number of systems overhauled, labor hours expended, materials cost, and overhead cost. All information is captured at the OSMIS system Weapon Identification Code (WIC) level and common parts are allocated among WICs. Items that appear in OSMIS are only those having a procurement history. The part must have been ordered by a Department of Defense Activity Access Code (DODAAC) or maintenance unit that actually has the target system assigned. Also, certain parts costing less than \$10 are not tracked by

vehicle in OSMIS, because they are often ordered in bulk and quantities are assigned to vehicle families based on their density.

OSMIS is updated annually and contains records of items with an order/demand history.

Therefore, OSMIS may not have the latest supporting information for each NIIN.

However, OSMIS can serve as a NIIN cross-reference for the items related to each vehicle system. The OSMIS database is principally used by the Army for budgeting purposes, allocating funds based on mathematical computation of costs associated with each fleet in service. As a budgetary tool, OSMIS is compiled for specific fiscal years. Contrast this with ILAP, which provides a more immediate record of current demands, as well as parts tracking history. OSMIS provides demand and cost information for total vehicles as well as for the individual replacement components. In addition, OSMIS provides data on average annual fleet density, average annual mileage, and Op tempo (i.e. operating hours). OSMIS calculates a variety of additional metrics, such as average cost per system and average cost per mile. Demand and cost information reported in OSMIS is model and vehicle variant-specific. This is done by means of a statistical estimate. For part orders placed by a given unit, OSMIS accounts for all vehicles in that unit that could use the ordered parts. The total orders are then proportioned among those vehicles, providing an estimate of usage by vehicle variant.

3.3.4 Federal Logistics Data Information Center (FEDLOG)

The Federal Logistics Data Information Center (FEDLOG) data is compiled from the Federal Logistics Information System (FLIS) records provided by the Defense Logistics

Agency (DLA). FLIS is updated daily, whereas FEDLOG is updated monthly. FLIS includes detail on part numbers, item names and numbers, shipping codes, freight data, classifications, and characteristics data. It is important to note that DLA took over contracting responsibility for approximately 80% of the NIINs from TACOM Contracting, so a small portion of items may not have complete records in FLIS/FEDLOG.

3.3.5 Haystack Gold TM

Another data source used is Haystack Gold TM provided by HIS, Inc. HIS is an independent, industry-leading source for business and technical data. HIS Haystack pulls data directly from FLIS and provides a comprehensive procurement and technical data listing for each NIIN. Haystack also compiles data from several other databases, such as: the Procurement History Database, the Vendor/Cage (H4/H8) Database, the Government Solicitations Database, the Manufacturers Drawings Database, the Material Safety Data Sheet (MSDS) Database, the National Forging Tooling Database, the Army Master Data File (AMDF), and several others. Haystack allows the user to perform batch searches of 20,000 NIINs or more. The user may also search for a given set of CAGE codes, or other parameters.

3.3.6 Dun & Bradstreet (D&B)

Dun & Bradstreet (D&B) provides a financial prescreen score for companies with a Data Universal Numbering System (DUNS) number. The prescreen score is based on a

company's credit rating bill payment history. The DUNS number is a non-indicative, nine-digit number assigned to each business location in the D&B database having a unique, separate, and distinct operation. A company may have one or many DUNS numbers, but at least one active DUNS number is required to do business with the U.S. Government. Table 2 breaks down each data source of Figure 41, including: 1) the frequency with which the respective data source is populated from the field (i.e. refresh frequency), 2) the frequency with which the data is published to TACOM (i.e. refresh availability), and 3) the recommended publishing frequency of the SERA back to the community (i.e. planned refresh). For example, D&B data associated with a particular supplier of equipment in a PMR is updated daily by D&B. This is evident in the sixth row and second column of Table 2. With the appropriate D&B subscription, this data is available for extraction on an as-needed basis (i.e. real-time per source), as evident in the sixth row and third column of Table 2. However, the D&B data is not planned to be integrated into a SERA except on a quarterly basis, or as needed. The pie chart of Figure 41 depicts that D&B data comprises about 10% of all data assembled in a SERA.

Table 2. Refresh frequencies of SERA data

DATA SOURCE	REFRESH FREQUENCY	REFRESH AVAILABILITY	PLANNED REFRESH
FLIS	DAILY	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED
FEDLOG	MONTHLY	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED
HAYSTACK	DAILY	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED
ILAP	DAILY	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED
D&B	DAILY	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED
OSMIS	EVERY APRIL	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED
PMR	ANNUALLY	REAL-TIME PER SOURCE	QUARTERLY OR AS NEEDED

3.3.7 Other Codes and Characteristics

- Acquisition Advice code (AAC): denotes how, where, and under what restrictions an item will be acquired. It identifies obsolete or canceled parts, and indicates

when no replacement NIIN exists. When a replacement NIIN does exist, it is added to the SERA for full screening.

- Source Maintenance Recoverability (SMR): codes designate the part strategies for supply, maintenance and disposition. SMR codes communicate maintenance and supply instructions to the various logistic support levels and usage commands and are assigned to each support item based on the logistic support planned for the end item and its components.
- Commercial and Government Entity (CAGE) code: identifies the companies that provide the parts. CAGE Codes are assigned to companies that either fabricate items of production and/or have design control of items procured by the U.S. Government. CAGE codes may also identify certain military specifications or standards and certain numbering systems developed by government agencies, panels, or committees. CAGE codes identify catalog data in the federal catalog system and also identify contractors for data exchange.
- Reference Number Category Codes and Reference Number Variation Codes (RNCC/RNVC): identify the specific part number relationship variations relative to their respective CAGE codes. In general, many codes can be combined with different combinations of risk factors to indicate an increase or decreased risk.
- Acquisition Method Codes and Acquisition Method Suffix Codes (AMC/AMSC): indicate the availability of Technical Data Packages (TDPs) and reflect the planned procurement decision of the primary inventory control activity (PICA). Certain codes indicate suitability for competitive acquisition and unlimited government rights to the complete technical data. However, an AMSC code of

“P” indicates that the U.S. Government does not own the rights to the TDP.

Therefore, the part may have increased sustainment risk, depending on additional circumstances.

- Document Availability Code (DAC): may also indicate whether technical data can be accessed, increasing or decreasing risk. DAC codes establish the type and availability of technical documentation. Numeric codes indicate the type and availability of documents at the time of reference number and item identification submission, whereas alpha codes indicate the same document is available and will be furnished by an activity identified by the Reference Number Action Activity Code (RNAAC), through cross service agreement.
- Hazardous Material Indicator Code (HMIC) and the Hazardous Characteristics Code (HCC): indicate the presence of hazardous material, which could involve coatings, processes, or materials that are being phased out of manufacturing, because of Restriction of Hazardous Substances (RoHS) and other regulations. This serves as a notification to a procuring activity to acquire a Material Safety Data Sheet (MSDS) when a hazardous item is procured and to inform users when more detailed information on an item is available in the Hazardous Material Information System (HMIS). For example, parts with cadmium coating can be identified by using these codes (and part characteristics) and considered for alternate coatings, before the source is discontinued. The HCC is a two-digit, alphanumeric code that ensures incompatible hazards are not stored next to one another. The HCC visibility in the Federal Logistics Information System (FLIS) only pertains to the latest CAGE/part number formulation.

- Shelf Life Code (SLC): indicates the total period of time beginning with the date of manufacture, date of cure (for elastomeric and rubber products only), date of assembly, or date of pack (subsistence only), and ending with the date when an item must be used (expiration date) or subjected to inspection, test, restoration, or disposal action. After inspection and test, an item may remain in the combined wholesale and retail storage systems and still be suitable for issue (or use by the end user). Shelf life is not to be confused with service life.

SERA attributes not deemed as flags do not influence the calculation of the Risk Priority Indicator (RPI) for each NIIN. These secondary factors, however, can indicate whether NIINs pass through various filters, during a what-if analysis. These secondary factors may help mitigate the level of risk associated with a NIIN and can also be used to distinguish medium risk NIINs from low risk NIINs. The data for these indicators is readily available in the SERA database.

3.3.8 Risk Indicators (i.e. flags)

SERA risk indicators, or flags, fall into four major sustainability risk categories:

1. Financial Risk – Dun & Bradstreet risk, market risk, cost,
2. Supply Risk – wait time, part inventory, outside the continental U.S. (OCONUS) sources of supply (i.e. foreign),
3. Industrial Base Risk – including technical data package (TDP) availability, number of companies in a sector, and

4. Environmental and Litigation Risk – including hazardous materials

For example, NIINs with only one supplier, or with only overseas suppliers, would have more risk indication than NIINs with several suppliers available in the continental U.S. Elaborating on Figure 37, Table 3 shows the 21 SERA flag definitions and their associated weight. The weight assigned to each flag was determined based on a rubric. The rubric developed over a series of meetings between TARDEC’s Industrial Base Engineering Team and Automation Alley’s Defense Office in 2011. Team members discussed and compared flags against each other, while examining randomly chosen NIINs, in terms of how much the presence of each flag portrayed an indicator of sustainment risk. Using scales of zero to ten, later compressed to a zero to five range for simplicity, team members cast votes that scored flag weights for various NIIN scenarios. Once initial weight assignments were agreed upon, a few subject matter experts from TACOM’s Readiness Directorate were consulted to get concurrence. The extended team agreed that the assigned weights made sense with the understanding that further research was warranted. Meanwhile, the SERA could be used as a demonstrator keeping in mind that any vehicle platforms were free to customize their own flag weights.

Table 3. SERA flag definitions

Weight	Flag Description	Flag Definition
5.0	No valid commercial CAGE Code	Count of valid cage codes equals zero (0). Validity is based on CAGE being non-government and not a standard; having an ‘active’ or null status code; and RNVC for the Cage/Reference number not being equal to 9.
4.0	D&B High Risk	One or more valid CAGEs are “High Risk” and there are not at least two valid “Low Risk” CAGEs.

Weight	Flag Description	Flag Definition
4.0	Persistent Back Order 8-Month	Appears on ILAP back order list for eight consecutive months beginning September 2011 through April 2012.
4.0	Single Valid Supplier	Count of valid cage suppliers equals one (1). Validity is based on supplier being non-government and not a standard; having an 'active' or null status code; and RNVC for the Cage/Reference number not being equal to 9.
3.5	Technical Data Unavailable	AMSC = A, D, H, M, Q or R.
3.0	D&B Medium Risk	One or more valid CAGEs are "Medium Risk" and there are not at least two valid "Low Risk" CAGEs.
3.0	Discontinued AAC with Demand in past 2 years	AAC = N, T, V, X, or Y, but demand existed in 2010 or 2011 according to OSMIS and/or ILAP.
3.0	No Demand in past 3 years	NIIN assigned date is prior to 1/1/2009 or unknown, and no demand exists in OSMIS or ILAP records in 2009 or later.
3.0	Readiness Driver	Identified by Rand as most associated with deadlined vehicles and recommended for stockage (according to ILAP).
3.0	Top 10% CWT	Top 10% of average number of days between DocNo date and DocNo closed date for orders in 2011 (according to ILAP).
2.5	Technical Data with Limited Availability	AMSC = C, K, L, N, S, T, U, V, Y, Z or null.
2.0	Hazardous Materials	HMIC code = Y or Haystack's technical characteristics file indicates item may contain cadmium or asbestos.
2.0	Part Complexity	Fourth position of SMR code contains a character other than Z, Essentiality Code (from PMR) = 1 or A and price (from PMR) is greater than or equal to \$500.
2.0	Top 10% Closed Maintenance Work Order	NIIN is in the top ten percent of number of closed work orders.

Weight	Flag Description	Flag Definition
1.5	Single or No Weapon System	Count of WPN_SYS_ID + WPN SYS SVC combinations in FEDLOG equals one or zero.
1.5	Top 10% Open Maintenance Work Order in past 12M for NMC Items	Count of work orders is in the top 10% for a period of one year prior to the latest DocNo date.
1.0	D&B Unsourced Risk	One or more valid CAGEs are unsourced by D&B and there are not at least two valid “Low Risk” CAGEs.
1.0	OCONUS Only CAGE Code	All active CAGE codes are OCONUS.
1.0	Open Maintenance Work Order in past 12M for NMC Items	Work orders exist within a period of one year prior to the latest DocNo date.
1.0	Shelf Life Sensitivity	At least one related PCCN/PLISN denotes a Shelf Life Code other than zero.
1.0	Source Controlled	AMSC = B, RNCC = 1 and AAC = A or B.

3.3.9 SERA Assembly

As previously mentioned, the SERA combines NIIN and supplier characteristics from a number of sources. Each NIIN record contains a source identifier and timestamp. Then, the SERA is reviewed and filtered to remove cancelled NIINs, duplicate NIINs, duplicate CAGE codes, etc. When data mining on a grand scale, data errors in the form of duplicates, typos, and voids are inevitable, which is why a filtering process is needed.

The first step is to extract the data from the PMR. This includes NIINs, PCCNs, SMRs, UOCs, PLISNs, and FSCs. Next, OSMIS data is extracted, based on the platform or variant. This provides the population of NIIN's associated with the specific vehicle. Then, FEDLOG data is extracted, by vehicle/weapon system, and also by Material Category (MATCAT). MATCAT's fourth and fifth digits indicate the specific platform. FEDLOG also provides a list of NIINs associated with the specific vehicle. Finally, ILAP data is extracted based on NIINs associated with the top level vehicle. NIINs are assigned to specific vehicles, such as Dump Truck, Tractor Truck, Tank Truck, etc. Searches on these NIINs provide a list of all the lower-level NIINs associated with that specific vehicle. Once gathered, these NIIN lists may be combined and run through various integrity checks to provide the final NIIN list. The integrity checks include ensuring duplicate and canceled NIINs have been removed, as well as verifying the accuracy of replacement NIINs. Once the list of NIINs is finalized, attributes related to each NIIN are pulled from the various data sources. This includes raw data relating to demand quantities, warehouse quantities, company information, maintenance information, and procurement information. Data codes from a number of disparate sources indicate various conditions influencing procurement. Therefore, many codes are gathered and accessible in a SERA.

3.4 Deploying the SERA: Field Research combined with Training

Part of the experimental design of this dissertation was to conduct actual field research, while educating analysts in the logistics domain on model-based design and participation. While developing the SERA, additional data fields and bottlenecks were explored in

exchange for training. The insights gained throughout the process were deemed well worth the effort and the relationships that resulted solidified the systems engineering philosophy of uniting different disciplines [140]. SERAs were loaded on over 30 individual computer desktops (and multiple servers) throughout the DoD, to solicit user feedback and test the effectiveness of diverse model-based collaboration and analysis. Organizations such as Natick Soldier Research, Development, and Engineering Center (NSRDEC), Defense Logistics Agency (DLA), Aviation and Missile Research, Development, and Engineering Center (AMRDEC), Communications and Electronics Research, Development, and Engineering Center (CERDEC), MARCORSYSCOM Marine Corps Systems Command, as well as various organic depots, forts, and arsenals, all had feedback to offer that helped screen variables (i.e. factors and levels) in preparation for experimentation. After the pilot of deploying the SERA, advancements to the SERA were made in a number of areas, including the development of a web application, which expanded the reach of the pilot even further within the DoD. Figure 42 shows the main interface of the web application, illustrating the expanded memory capacity of the web-based SERA over its 4GB-limited predecessor. Diagrams, videos, and supplemental doctrine and training references became part of the SERA user experience, once the web-based SERA came online.

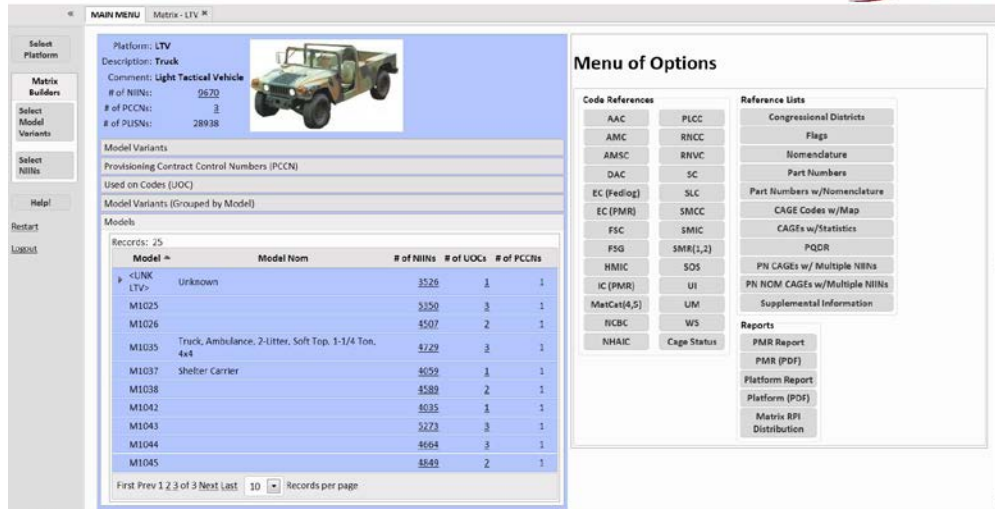


Figure 42. SERA home screen for web application

The streaming video capability ended up being the most impactful feature of the SERA, replacing the constraints of face-to-face training sessions and the monotony of ineffective PowerPoint communications. The SERA videos were condensed to 2-3 minute lessons that launched automatically within Windows Media Player, demonstrating the success of a commercial-off-the-shelf (COTS) solution, as shown in Figure 43.

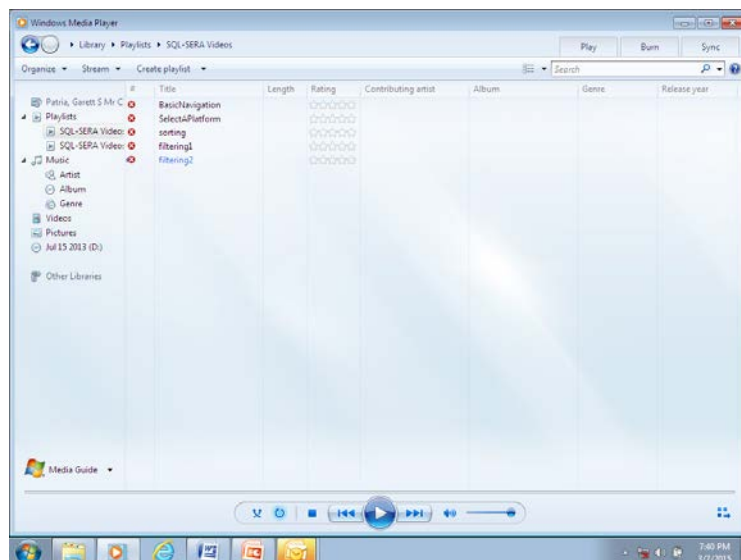


Figure 43. SERA video tutorial interface

In fact, because of the video capability success, the primary mission of the SERA is under debate between those who feel its greatest strength is still just risk assessment, versus those who feel its greatest strength is remotely instilling the entire logistics engineering philosophy.

Specific platforms were targeted for this experimental research in order to efficiently capture a diverse balance of DoD ground vehicle architectures including:

1. Manned vehicles versus Unmanned vehicles: manned vehicles are simply vehicles primarily operated by a human. These are, obviously, the overwhelming majority of vehicles in the world (at least as of 2016). Unmanned vehicles are robotically controlled to some degree (otherwise known as “robots”), including vehicles that are operated by a human through a teach pendant or operator control unit (OCU) of some sort [37].
2. Tactical vehicles versus Combat vehicles: tactical vehicles are vehicles that often relate to a commercial vehicle, whereas combat vehicles are focused on target engagement and do not usually have a commercial vehicle counterpart [3, pp. 10, 23, 141, p. 2]. Combat vehicles usually have an armament greater in caliber than an M2 (.50 caliber machine gun).
3. Wheeled Vehicles versus Tracked Vehicles: wheeled vehicles are those vehicles that use wheels to advance across terrain, similar to commercial automotive vehicles. Tracked vehicles, however, rely on a track or linked band that interfaces with the terrain, similar to commercial bulldozers.

Figures 44-51 depict common examples of the different combinations of aforementioned vehicle architectures:



Figure 44. Unmanned, tactical, wheeled vehicle



Figure 45. Unmanned, tactical, tracked vehicle



Figure 46. Unmanned, combat, wheeled vehicle



Figure 47. Unmanned, combat, tracked vehicle



Figure 48. Manned, tactical, wheeled vehicle



Figure 49. Manned, tactical, tracked vehicle



Figure 50. Manned, combat, wheeled vehicle



Figure 51. Manned, combat, tracked vehicle

The platforms studied in detail were: Light Tactical Vehicles (LTV), Abrams, Bradley, and M160. Abrams and Bradley were selected together to capture any within-domain trend variation associated with manned combat tracked vehicles. It is important to note that each domain has its own hierarchy of sub-platforms and/or vehicle variants that proliferate into the equipment Work Breakdown Structure (WBS). Exploring the WBS through the SERA is easy in that all that is required is that the analyst select the UoCs (used on codes) button from the SERA home screen, as seen in Figure 52 for the LTV (i.e. HMMWV) platform. This results in the SERA displaying a list of the many vehicle variants that make up the LTV platform, as can be seen in the pop up window in the lower right hand corner of Figure 52. Note how the first vehicle variant displayed in the pop up window is the expanded utility truck 01-413-3739 which has 3260 NIINs associated with it and 379 NIINS are unique to that variant alone.



Figure 52. LTV WBS view of the SERA

The WBS, as viewed in a SERA via the UoCs button and corresponding cascade of windows, resembles an indentured bill of materials (BOM) and provides sustainment analysts with key information when trying to familiarize with equipment and

corresponding support strategies. Sometimes, when a piece of equipment is unavailable, the most economical and expedient solution is to acquire the next higher assembly (NHA) in the WBS. Other times, there is no NHA in between the equipment in question and the vehicle variant itself. For example, a steering gear usually does not have a parent sub-assembly. Instead, the steering gear assembles directly to the vehicle chassis or engine cradle. Either way, following the parent-child relationships of the WBS eventually links analysts back to the vehicle variant level of abstraction. Without a SERA, these relationships are difficult to visualize after data mining. It should be noted that some of the results of this dissertation have been purposely decoupled from the corresponding platform, in order to create anonymity, for the purposes of sharing this information under public distribution [121].

4. RESULTS OF SERA APPLICATION

4.1 Support Strategy Awareness

After much field experimentation between 2011 and 2016, it was determined that sustainment support strategies need a standardized format so that the strategy can be analyzed consistently. This is analogous to design drawing standards in that once a common way to communicate the important elements of a design are learned, a regimen of analysis and refinement becomes more feasible. During SERA application coaching sessions conducted across dozens of DoD organizations, it was clear that analysts did not have a way with which to view relationships and communicate concerns between equipment, supply chain, and DMSMS risk. Just as a standardized format of design features is shared by teams working in multiple locations across a live CAD network, the SERA, along with the logistics engineering philosophy that accompanies it, has given the distributed workforce a standardized tool for sustainment support strategy awareness, analysis, and communication.

The process for applying the SERA tool is: 1) describe the support strategy, 2) ensure that the support strategy characteristics are accurate through community input, and 3) ensure that the various integrated product teams (IPTs) are aware of alternative strategies and reference them in their daily activities. This process is shown in Figure 53.



Figure 53. Process for establishing a standard sustainment support strategy communication protocol

The corresponding Lean Six Sigma (LSS) Communication Plan for distributing SERA results in context of an overarching sustainment support strategy is shown in Table 4. The LSS Communication Plan is simply an abstraction of the responsible, accountable, consulted, and informed (RACI) chart recommended by DMSMS experts [47, p. 41]. The major players of a Support Strategy IPT are identified in the Audience column of Table 4 as: the Product Support Manager (PSM), representatives from the Program Executive Office (PEO), the DLA Weapon System Support Manager (WSSM), Engineering and/or R&D, Logistics or Product Support Integration Directorate (PSID), and Cost and Systems Analysis. Aside from interactions in regularly scheduled IPT meetings, personal communications have been maintained with each member organization of the Audience for the Purposes listed. Note that the main purpose of PSM and PEO interaction is to establish consensus on how the Program Manager (PM) is impacted. Establishing ownership of support strategy communications, via the appropriate Engineering Support Activity (ESA) point of contact (POC), was found to be critical. Informal communication protocol often overlooks the sense of ownership, resulting in consistent communication and baseline awareness not being treated as true deliverables.

Table 4. Lean Six Sigma Communication Plan

<u>Audience</u>	<u>Media</u>	<u>Purpose</u>	<u>Owner</u>	<u>Frequency</u>
PSM	Personal/IPT	PM Impact	ESA POC	As needed
PEO	Personal/IPT	PM Impact	ESA POC	As needed
WSSM	Personal/IPT	Supply/Demand	ESA POC	As needed
ENG	Personal/IPT	Change Outlook, Performance	ESA POC	As needed
LOG/PSID	Personal/IPT	Equip. History, Supply/Demand	ESA POC	As needed
CASA	Personal/IPT	Equip. Economics	ESA POC	As needed
IPT	Meetings / E-mail/ IBIT DB	Biz Case, Strategy Decisions/ Chgs	ESA POC	Workshops w/ weekly IBIT

The primary forum for support strategy communications is the Industrial Base Integration Team (IBIT) and the corresponding database of IBIT activities referred to as Industrial Base Action Requests (IBARs). To ensure the widest dissemination possible, with the smallest degree of accessibility hassle, the TACOM Lifecycle Management Command (LCMC) Intranet Portal has served as the gateway to the IBIT/IBARs. As shown in Figure 54, under the Guidance header of the TACOM LCMC Intranet Portal, the IBIT has been placed under the Logistics submenu. Again, until model-based software is able to integrate engineering and logistics user interfaces, an interim solution buried in menu-intensive environments is inescapable.

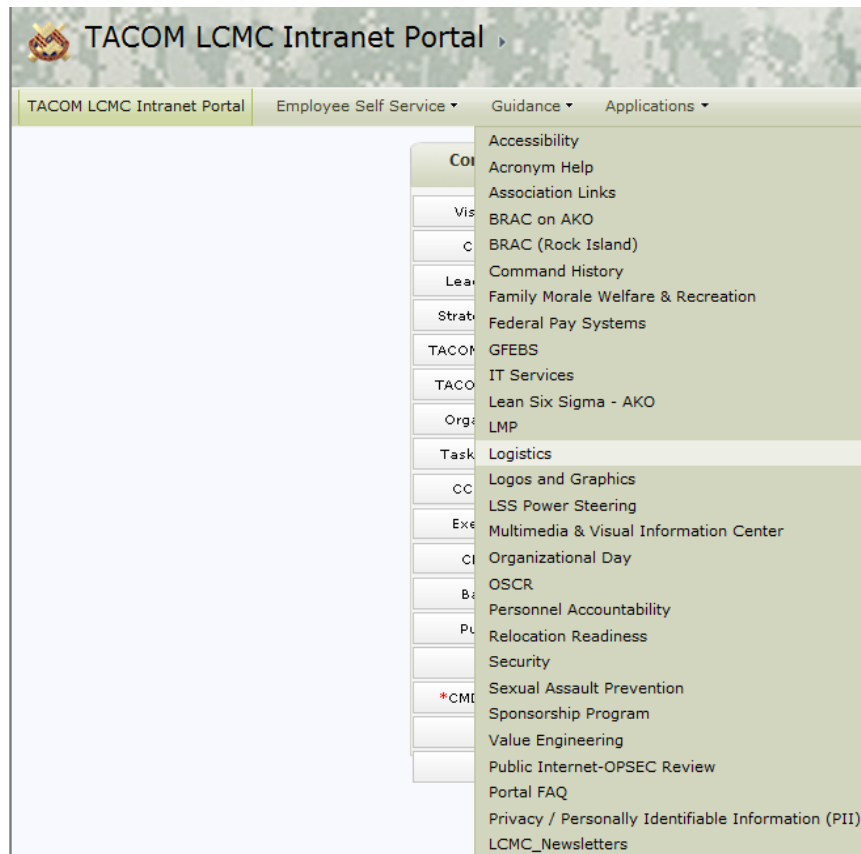


Figure 54. Integrating the sustainment support strategy interface within the TACOM-wide intranet portal

An example IBAR, relating to SERA-aided analysis performed on LTV in 2013, is shown in Figure 55. Although categorical, meta data fields can be populated for each IBAR, the comments field is the one most currently used. As can be seen in the figure, the comments field houses meeting minutes and target objectives that were established while the IBAR system was being piloted for support strategy communications across the IPT.

IBAR2 - Identify LTV NIINs that show potential for...

View

Version History

Alert Me

Manage Permissions

Workflows

Edit Item

Delete Item

Manage

Actions

LIN	
Other Reference	
AWCF Requested	No
AWCF - Funding Requested (\$)	
AWCF - Obsolescence Cause	
AWCF - Issue Impact	
AWCF - Effort Description	
AWCF - Secondary NSN	
Comments	11/07/2013, Garrett Patria - Final report on DLA LTV VE initiative containing recommended SERA/VE processes, awaiting TARDEC management approval. ETA COB 07 Nov 2013. 10/24/2013, Garrett Patria - Recommended process for facilitating SERA IPT meetings, including VE identification format for LTV DLA parts, to be published by Garrett 31 Oct 2013. 08/27/2013, Garrett Patria - attached document (VE1 for LTV.xlsx) from Lou Jaquish showing NIINs from July's status report that have VE activity history already on record. 08/14/2013, Garrett Patria - Amanda Osborne/Tom Wagner introduced to PD LTV LOG (John Ziegler/Kevin Ramey) and ENG (Clifton Ellis/Brian Kachadurian) on 13 Aug. Also, the VE mission of this IBAR was confirmed by DLA VE (Lou Jaquish) and the DLA WSM for LTV (Duane Gross) was briefed on the mission goals and given a SERA walk through over telecom. LTV SERA IPT being slated for 26 Aug at 1000. 07/31/2013, Garrett Patria - Path forward is to assign NIINs for vetting based on Pareto chart and NIIN list from attached progress report titled "VE Identification Strategy for LTV.doc". This path forward is approved by the lead, Frank Wojcik as of 7/31/2013. Also, per Tony Mitek on 7/30/2013, the progress reports do not need to go through OPSEC prior to TARDEC/TACOM distribution at the end of each month.
Submitted Status	Submitted
Resolved?	No

Figure 55. Meta data associated with LTV sustainment support strategy analysis

Many visual analytics were trialed to see which ones best proliferated the logistics engineering perspective and were most intuitive to users being coached on how to apply the SERA. What follows are the visual analytics used in reports to LTV and DLA management showcasing the SERA. The first visual analytic leverages the format of a Kepner Tregoe Problem Definition Diagram. In logistics engineering, “support strategies should be re-evaluated every three to five years” [83, p. 27]. Similar to reassessing the requirements and constraints of a product design through functional analysis, a support

strategy can be effectively characterized in the same manner [83, p. 60]. For example, a Kepner Tregoe Problem Definition Diagram highlights the current conditions, or problem symptoms, and characterizes them in terms of what was observed, followed by where, when, and the extent of the observation, as shown in Figure 56 [112]. These observations are recorded in as much detail as possible in an area of the diagram labeled IS, representing “what the problem is”. Mutually exclusive to what is recorded in the IS section, the possible conditions that did not manifest are recorded in the IS NOT section, presenting “what the problem is not”. The key to the root cause of problems has a tendency to lie in the distinctions between the IS and the IS NOT. Therefore, recording IS NOT observations that are as similar as possible to their opposing IS observations is crucial, so that the threshold of distinctions between the IS and the IS NOT can be as focused as possible. Documenting a support strategy in this same manner can bring light to why one piece of equipment exhibits a particular support strategy, but a seemingly equivalent piece of equipment does not.

Interestingly, many of the attributes recommended for appropriate capturing of a support strategy are already fields in the Military Handbook 115B Data Call Form for a reverse engineering case [142, p. 60], depicted as a thumbnail on the left side of Figure 56. Attributes like parent model variant and source, maintenance, recovery (SMR) code can embody the exact level of abstraction on which a support strategy depends. Therefore, vetting the core reason behind an existing support strategy is considered critical, before it is analyzed for alternatives. Some Lean Six Sigma (LSS) Master Black Belts claim that a properly constructed Kepner Tregoe Problem Definition Diagram is as effective as a

blueprint in an engineering situation, where a newcomer that is fluent in problem diagramming can quickly become familiar with the basic premise of a design just by reading a standardized format [143].

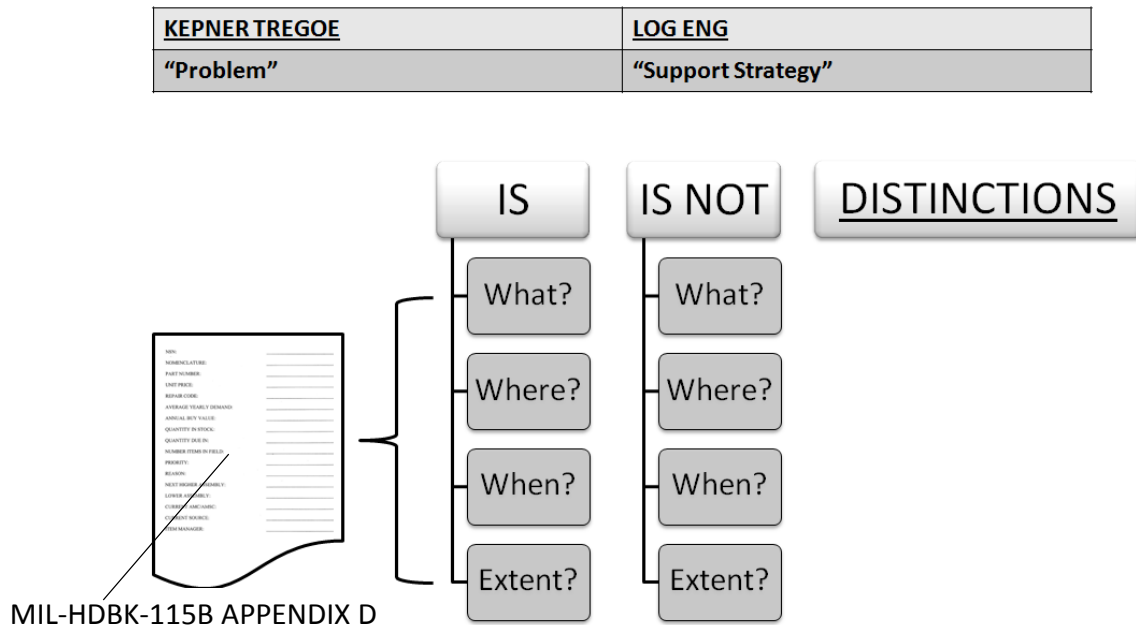


Figure 56. Sustainment support strategy characterized as a Kepner Tregoe Problem Definition Diagram

Incorporating rich, object orientation within a Kepner Tregoe structure paves the way for association with CAD models and technical manuals, which are already a mainstay in the daily activities of engineers and logisticians. Figure 57 shows the power of using objects to represent the attributes in a problem definition diagram. In this case, the choice to use a side view thumbnail allows the user to quickly pick up geometric cues between the wall heights of the trailers – a significant distinction driving this particular support strategy difference. In addition, the displayed meta data communicates that the IS refers to both $\frac{3}{4}$ ton and $1\frac{1}{4}$ ton trailers, whereas the IS NOT refers to only $1\frac{1}{2}$ ton trailers.

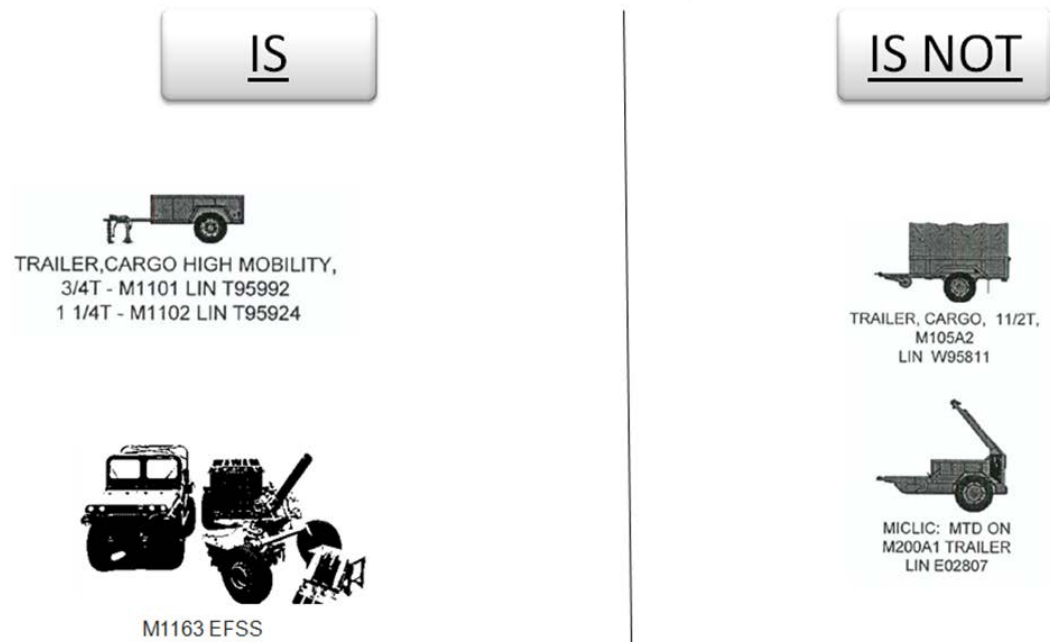


Figure 57. Object orientation depicting scope of sustainment support strategy

In a true, model-based infrastructure, the distinctions of various support strategies would possibly be displayed through contextual windows. The vision portrayed in this research is for the applications of the future to automatically suggest alternate choices and background information, similar to spell check on a PC or a smart phone. Various equipment support strategy characteristics translate into ramifications in many other realms, such as supply chain analysis, maintenance depot utilization, acquisition agility, and lifecycle economics. The unseen opportunities and constraints these support strategy characteristics create should be the baseline for the daily activities of analysts and decision makers.

A visual analytic depicting the domain path of the top 50 LTV NIINs, as determined by historical contract value, is shown in Figure 58. In this example, the proportion of the IS

and the IS NOT was illustrated in pie charts along the right hand side of the tree diagram. Management appreciated the context of what was NOT part of the study almost as much as the study itself. This proves the educational obligation that a model bears in describing a support strategy, while ensuring the proper context is communicated in preparation for strategic decision making by leadership.

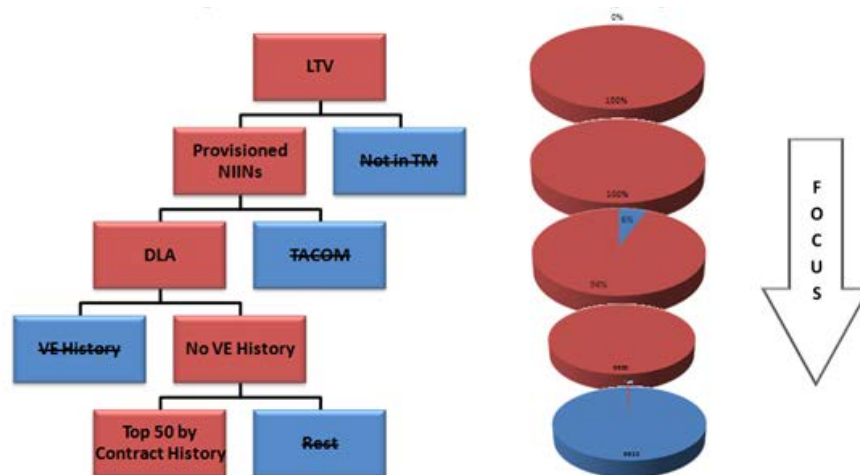


Figure 58. Target NIINs depicted in context of a definition tree

The SERA was used to analyze the acquisition pattern of a particular tire, as shown in Figure 59. A bubble chart was used, with the contract price of the tire on the y-axis, the contract end date on the x-axis, and the contract quantity represented by the bubble diameter. Low Rate Initial Production (LRIP) quantities stand out immediately in the earlier contract dates to the left of the figure and the largest contract of 461,754 tires shows as the largest bubble in the center. The takeaway from this figure, however, was deemed to be the price instability since 2009, relative to the current Army Master Data File (AMDF) price of \$432.39.

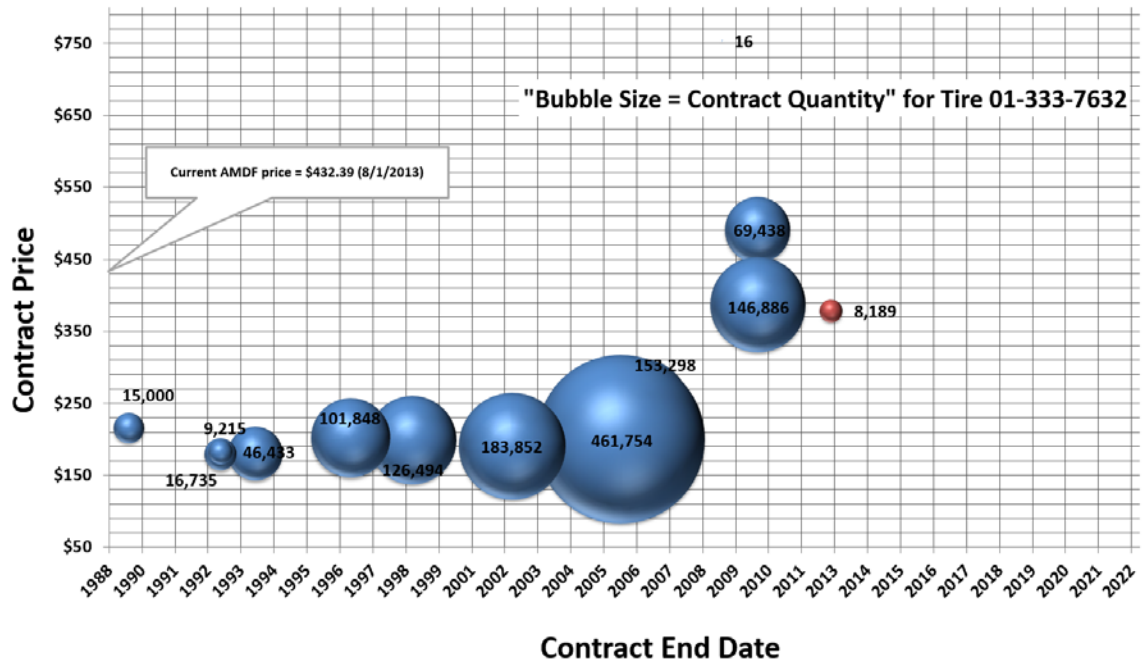


Figure 59. Model of contract price vs. end date vs. quantity for LTV tire

In another study, the ease with which SERA filters can be applied demonstrated the quick isolation of NIINs which: 1) were single sourced, 2) the government did not own any technical data, 3) were TACOM managed, and 4) had maintenance orders in ILAP within the past year, resulting in the top three NIINs shown in Figure 60. Of the three NIINs, the generator was targeted for functional analysis based on its relatively high AMDF price relative to surrogate generators assessed in the M915 (i.e. a line haul truck) SERA.



Figure 61. Buying power history for the family of LTV generators

Finally, to illustrate the awareness that the SERA application provides through visual analytics, Figures 62 and 63 show the bubble charts for a single control arm and a family of control arms, respectively. In Figure 62, a small prototype buy occurred in 1984, followed by the main production buy in 1987. However, it is not until additional control arm NIIN buys are added that a greater perspective is unveiled, as shown in Figure 63. The takeaway is that the contracting patterns of surrogate NIINs expose opportunities and limitations of various support strategies. In Figure 63, the red bubble represents the sibling control arm that resides on the other side of the vehicle, almost doubling the control arm buy volume per vehicle. Also, the other bubble colors represent similar buys for other control arm variants competing for the same resources, such as contracting officers, steel, procurement funding, and certified manufacturers.

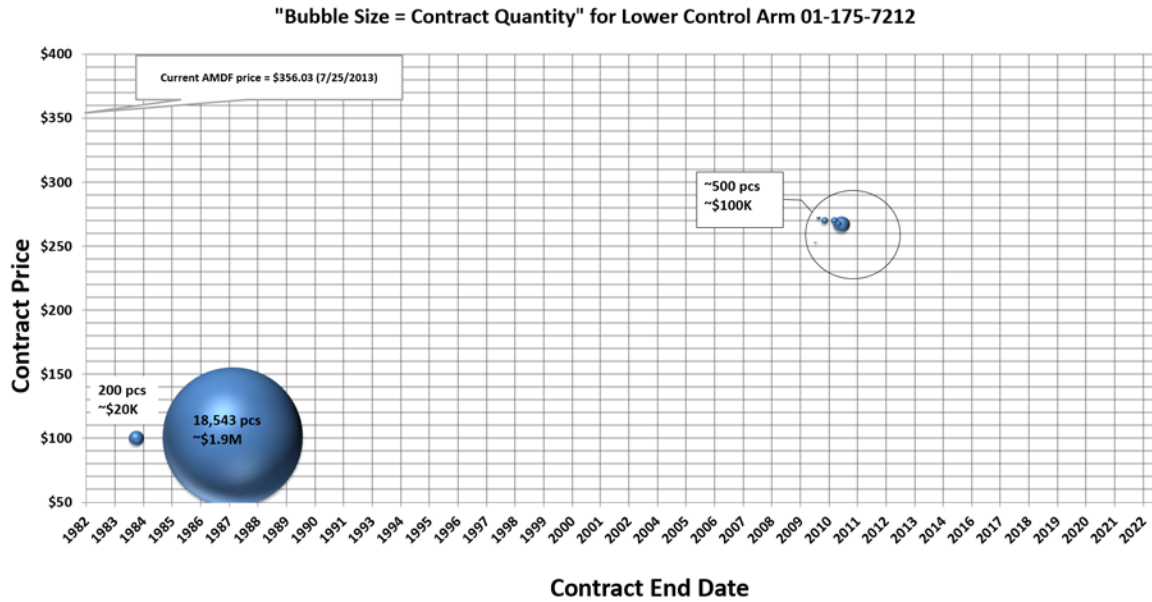


Figure 62. Economies of scale and contracting patterns of LTV lower control arm

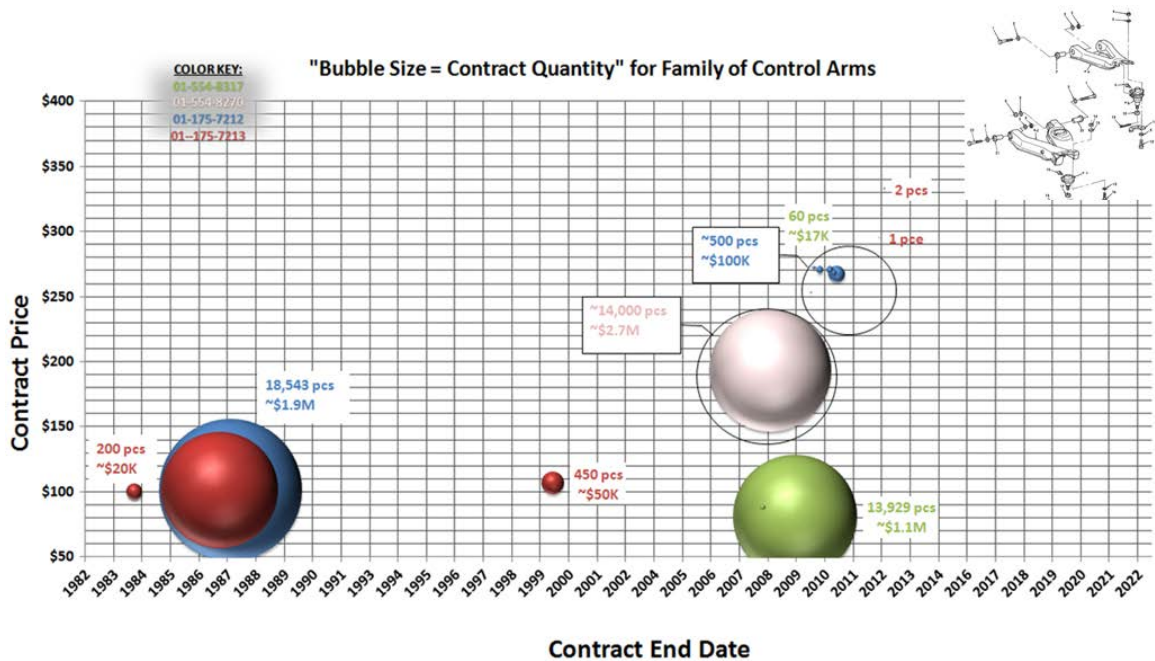


Figure 63. Contract analysis of families of control arms

4.2 Analysis of SERA and DMSMS Indicators

Using a SERA to identify the equipment support strategies that have the most influence over operations and support (O&S) costs is as easy as querying the NIINs that are tied to the largest total contract dollar amounts over time [140]. Multiple NIINs that have similar nomenclature can then be bundled to consolidate model variations within the same basic piece of equipment. Figure 64 shows the top LTV repair parts contracts by value, where all contract totals, for equipment such as tires, were bundled together.

Tires, batteries, and generators (i.e. alternators) are known to be top O&S cost drivers for ground vehicles. Figure 64 confirms this pattern for LTV, showing that tires, batteries, and generators are among the top ten when filtering the SERA to rank order equipment by cumulative contract value. In this case, the LTV repair part with the highest contract value is the TIRE, PNEUMATIC, VEHICULAR.

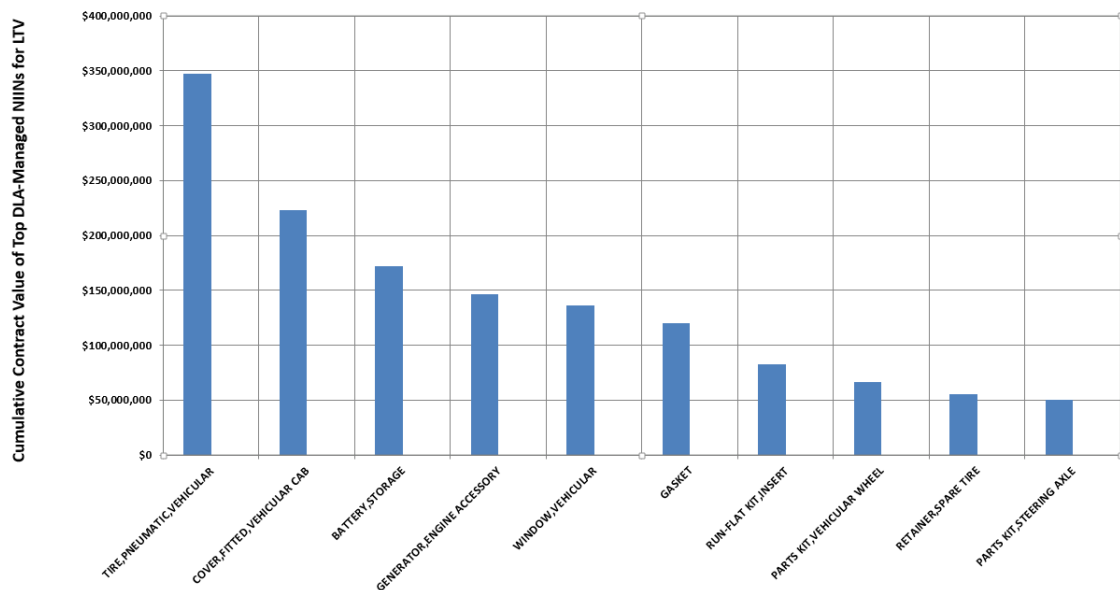


Figure 64. LTV repair parts contracts by value

Understanding where the majority of the money is spent is always a good place to start a sustainment support strategy analysis, since this equipment has the most potential for lifecycle cost savings. Therefore, having the capability to quickly sort an entire platform of equipment by lifecycle cost is a strength of the SERA. Targeting equipment for improvement initiatives in this manner also justifies the alignment of research resources and continuous improvement initiatives.

Another important lens through which to view a sustainment support strategy is NIIN application across fleet density. Fleet density refers to how many of each vehicle variant exist in the world [144, p. 26]. Knowing the fleet density in conjunction with knowing which vehicle variants a particular NIIN is used on gives analysts an understanding of how a NIIN impacts the field. Visual analytics such as Figure 65 give analysts the ability to identify logistics coding patterns that may exist within families of vehicle variants within the WBS. For example, the aforementioned tire is being used on the majority of the LTV vehicle variants, including 100% of the legacy variants (blue) and some of the extended capability variants (red). When determining a particular NIIN's DMSMS impact on the existing fleet, focusing only on the bars highlighted in Figure 65 makes the fleet impact more of a standard when communicating to management.

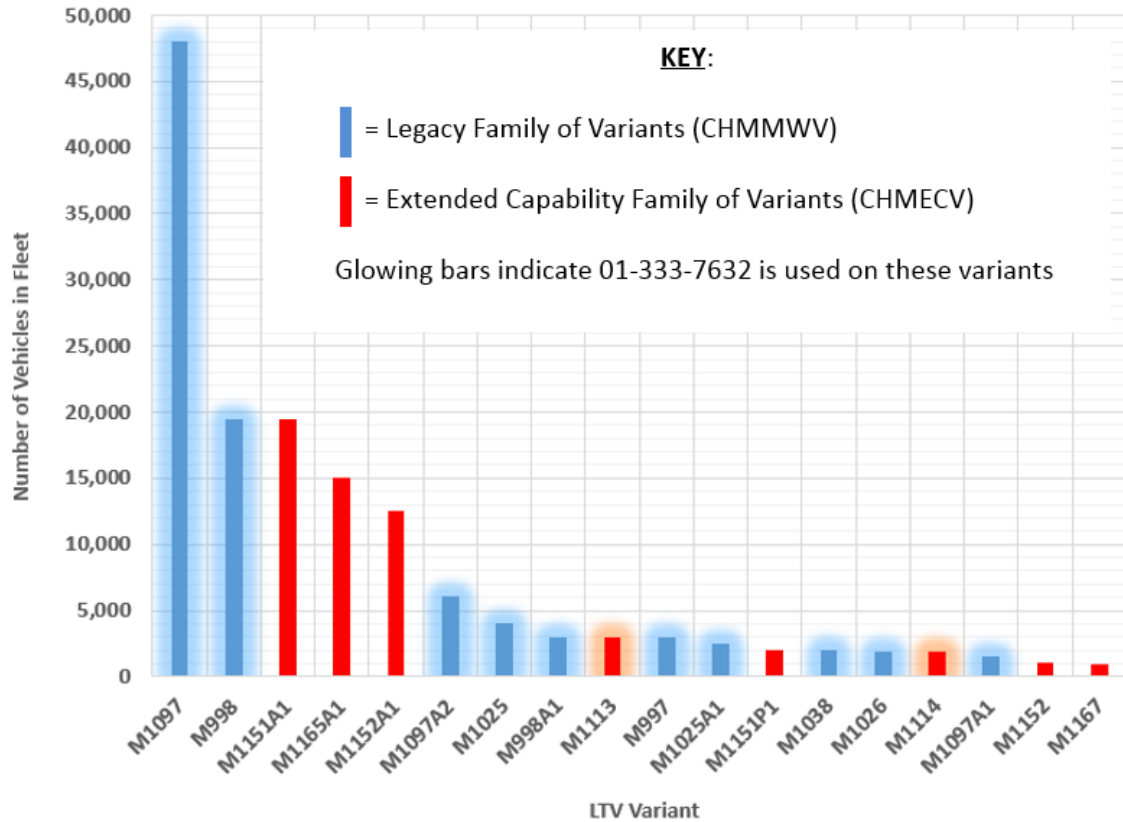


Figure 65. NIIN application across LTV fleet density

4.2.1 Screening for Patterns

There are two hierarchical taxonomies integrated into the NSN that are also useful when identifying the most influential equipment: 1) the Federal Supply Group (FSG) and 2) the Federal Supply Class (FSC). The FSG consists of the first two digits of the FSC, where the FSC is the first four digits of the NSN. Figure 66 rank-orders the number of LTV SERA NIINs in each FSG. The LTV SERA NIINs occupy 45 FSGs total. Note how approximately 80% of the list of LTV SERA NIINs can be binned into just the first four FSGs: 1) Hardware and Abrasives, 2) Vehicular Equipment Components, 3) Pipe, Tubing, Hose, and Fittings, and 4) Electrical and Electronic Equipment Components.

The benefit to exposing this trend is that resources can be allocated in relation to where most of the equipment resides. This type of prioritization can also be done on a CAGE basis, as shown by the list of CAGEs that are shown along the right side of the figure.

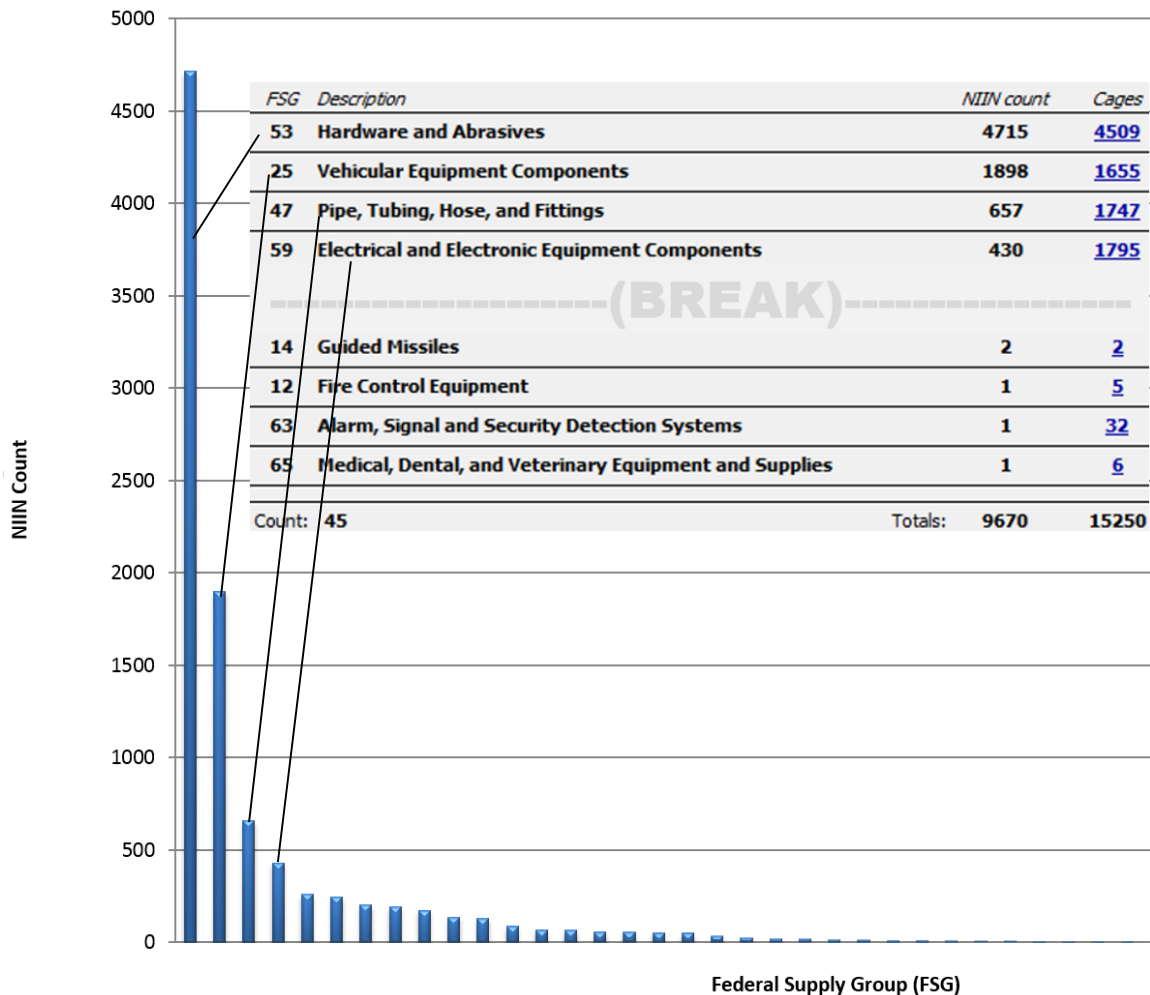


Figure 66. LTV NIIN breakout by FSG

Figure 67 rank-orders the number of LTV SERA NIINs in each FSC. Contrast this tally with the 45 FSGs of Figure 66. FSCs are more specific than FSGs, so there is a little more visibility into the various, standard taxonomies that exist. In this case, 23 FSCs

represent 80% of the LTV SERA NIINs. In total, the LTV SERA NIINs occupy 154 FSCs.

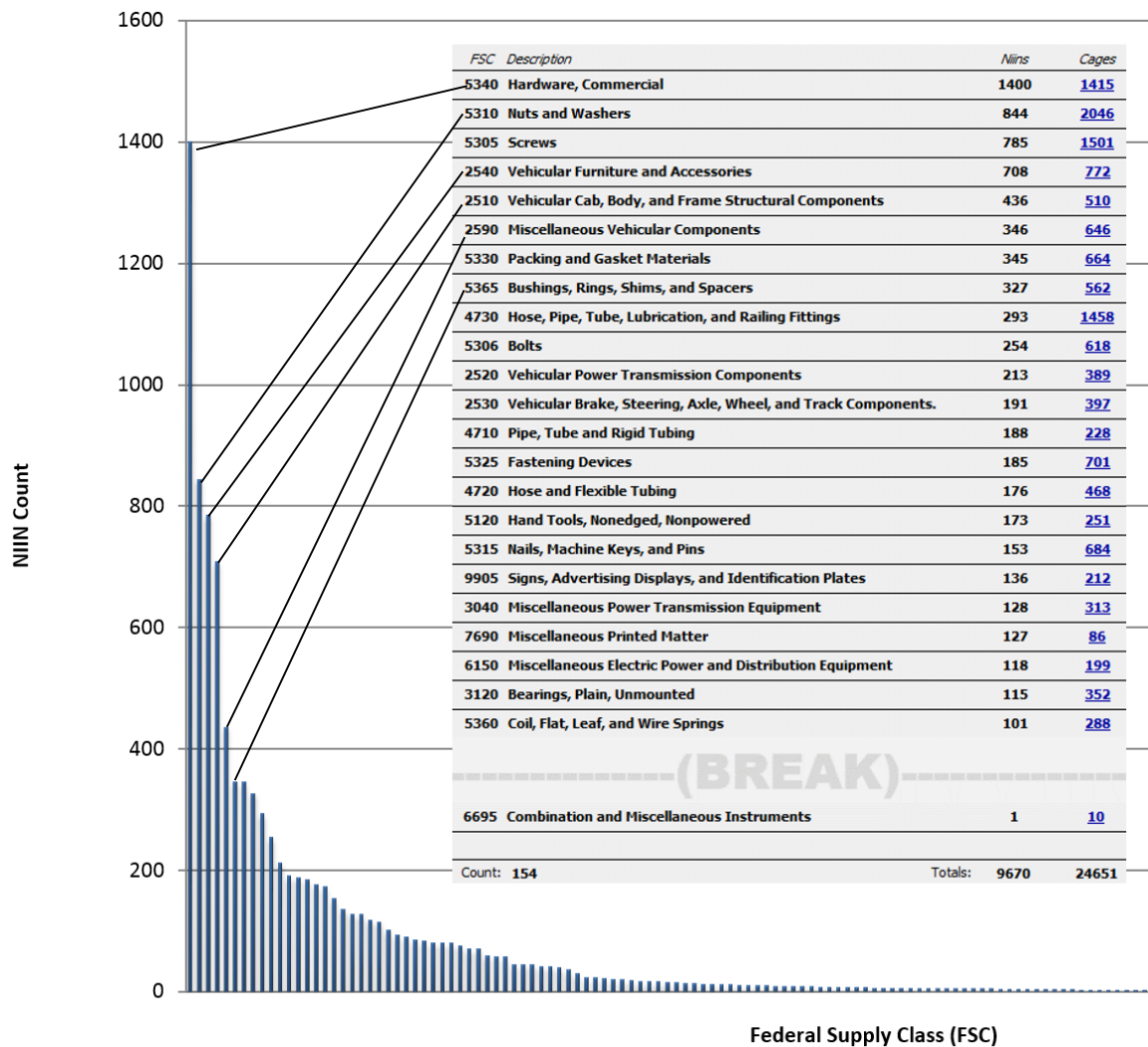


Figure 67. LTV NIIN breakout by FSC

Concentrating proactive, DMSMS analysis towards these first few FSGs/FSCs could prove to be a more efficient strategy with respect to allocating sustainment risk mitigation resources. This resource allocation strategy can also apply to technology development,

which would contribute to the advancement of the logistics engineering mantra upstream into the R&D domain.

As mentioned in Figure 67, FSC prioritization can also be done on a CAGE basis. In the example of Figure 68, a single equipment taxonomy (electrical wiring) is spread over a few different FSCs. For example, FSC 5995 houses 23 NIINs and 75 CAGEs, whereas FSC 6150 houses 118 NIINs and 199 CAGEs. From an IB perspective, it is convenient to be able to quickly identify how many CAGEs currently provide equipment NIINs under a particular FSC. Figure 69 is a visual analytic that combines past and present CAGEs with the remaining NIIN's CAGEs in the FSC to create an IB perspective into the art-of-the-possible. Giving thought to which CAGEs “could” provide equipment helps break away from traditional sourcing constraints, giving way to innovative thinking. Determining which CAGEs “should” provide equipment in the future depends on many factors, such as quality and financial health outlook.

Federal Supply Classifications					
FSC Description		Niins	Cages	Avg rank	Avg weight
5995	Cable, Cord, and Wire Assemblies: Communication Equipment	23	75	4273	4.9
5998	Electrical and Electronic assemblies, Boards, Cards, and Associated t	3	32	4236	7.0
5999	Miscellaneous Electrical and Electronic Components	19	115	5194	3.8
6105	Motors, Electrical	6	47	3336	5.5
6110	Electrical Control Equipment	17	38	1463	10.0
6115	Generators and Generator Sets, Electrical	5	31	3821	5.2
6130	Converters, Electrical, Nonrotating	1	7	1284	8.0
6140	Batteries, Rechargeable	3	28	2597	7.8
6145	Wire and Cable, Electrical	12	81	5208	3.8
6150	Miscellaneous Electric Power and Distribution Equipment	118	199	4146	4.9

Figure 68. Sustainment risk and IB density relationship to FSC

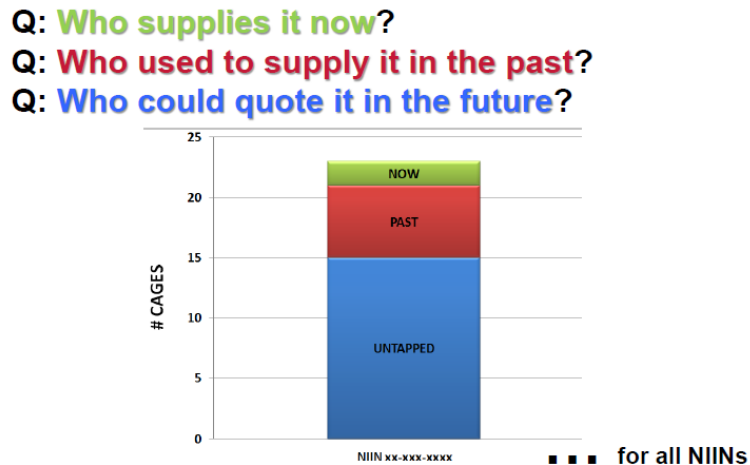


Figure 69. Integrating the future into IB analysis

With so many equipment taxonomies and Defense Logistics Information System (DLIS) codes, equipment support strategies can exhibit patterns that are never leveraged, if IS/IS NOT experimental characterization does not take place. Unfortunately, the logisticians who are versed in the majority of equipment taxonomies are not usually versed in experimental methods [47, p. 115]. Conversely, most of the scientific community who are versed in experimental methods are not versed in the plethora of logistics management codes that make up the equipment and supply chain attributes. This dissertation brings these two worlds together.

Aliasing is implied with analysis like this, however. Aliasing, or confounding, is when a correlation is observed that might lead the observer to falsely conclude causation. As an example, if an observer was ignorant to the seasonal effects of water recreation, they may falsely conclude that the tally of monthly drownings throughout the year is due to the monthly tally of ice cream sales. In this case, the real reason for the observed drowning

pattern would be that more people swim during summer months (Taraman, 2010). When under the influence of aliasing, exploring data patterns can still be useful, even though correlation does not imply causation [145, p. 2].

The exploration of this dissertation began with a macro level screening process balanced with intuition from subject matter experts. The unexplored data trends concealed inside a SERA are vast and only some of which were exploited in the following sections.

4.2.1.1 Characterizing RPI as a Response

Figure 70 shows a graphical summary of the population of LTV NIIN Risk Priority Indicators (RPIs). First, the histogram in the upper left corner of the figure depicts that the population of RPIs resembles a bell distribution truncated at zero on the x-axis. The Anderson-Darling Normality Test values on the upper right side of the figure indicate that the RPI population cannot be considered as a normal distribution, since $p < 0.005$ and the null hypothesis, H_0 , is: the data follows a normal distribution. This makes sense on two accounts: 1) RPIs range from 0 to 1 and 2) an entire platform of NIINs should not have a tendency to center on one particular RPI. A box and whisker plot directly below the histogram depicts the four intervals between the five standard thresholds: minimum, 1st Quartile, median, 3rd quartile, and maximum. The median line separates the blue boxes symbolizing the quartile segments, whereas the asterisks at the right hand side of the box and whisker plot indicate that there are a number of outliers in the data that were not included in the rightmost whisker. This concludes that the highest RPI values are associated with a small number of NIINs.

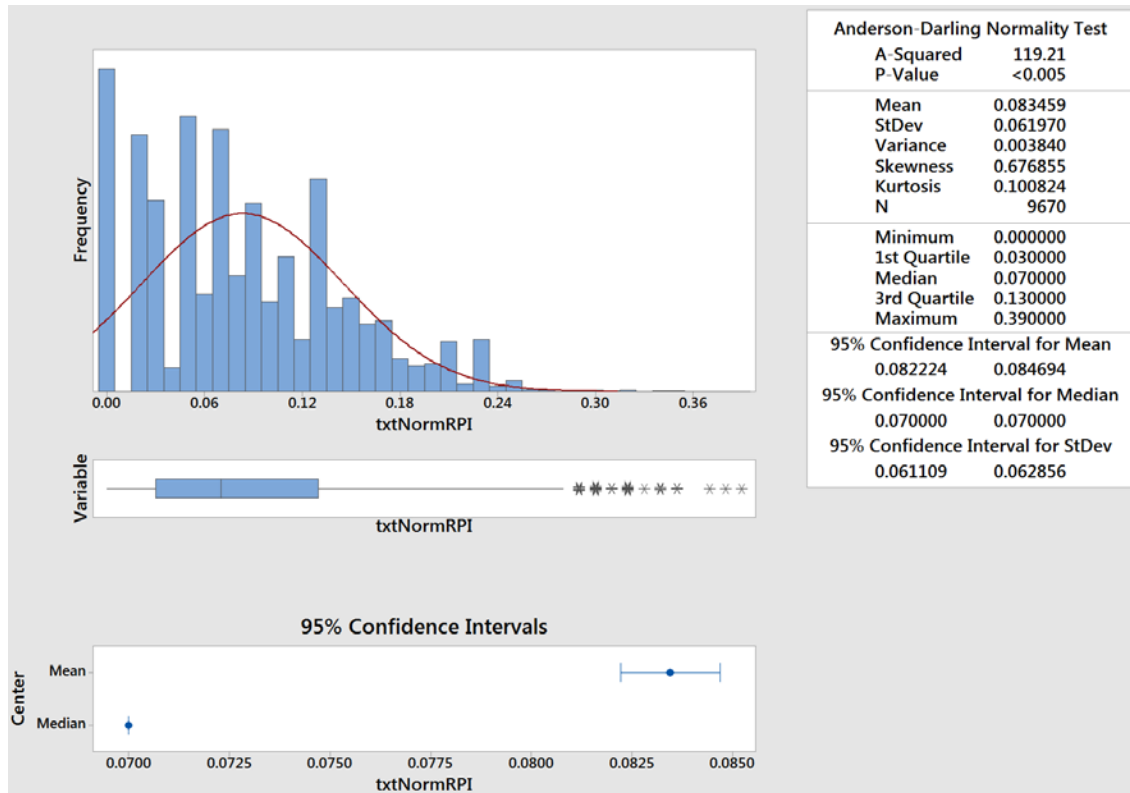


Figure 70. LTV graphical summary of RPI (as if normal)

The truncated nature of the LTV RPI population distribution led to the exploration of a Weibull goodness of fit analysis. However, the RPI values must run through an intermediate natural log algorithm (under most statistical analysis software), before the Weibull fit can take place. Therefore, all zero value RPIs were replaced with 0.0001. This substitution approximated zero within the same granularity as the estimated shape parameter, meeting the algorithm requirement and forcing the adaptation to work. Visually, the superimposed Weibull curve, shown in Figure 71, does not appear to fit the actual histogram. This observation was confirmed by the low P-value and probability plot of Figure 72.

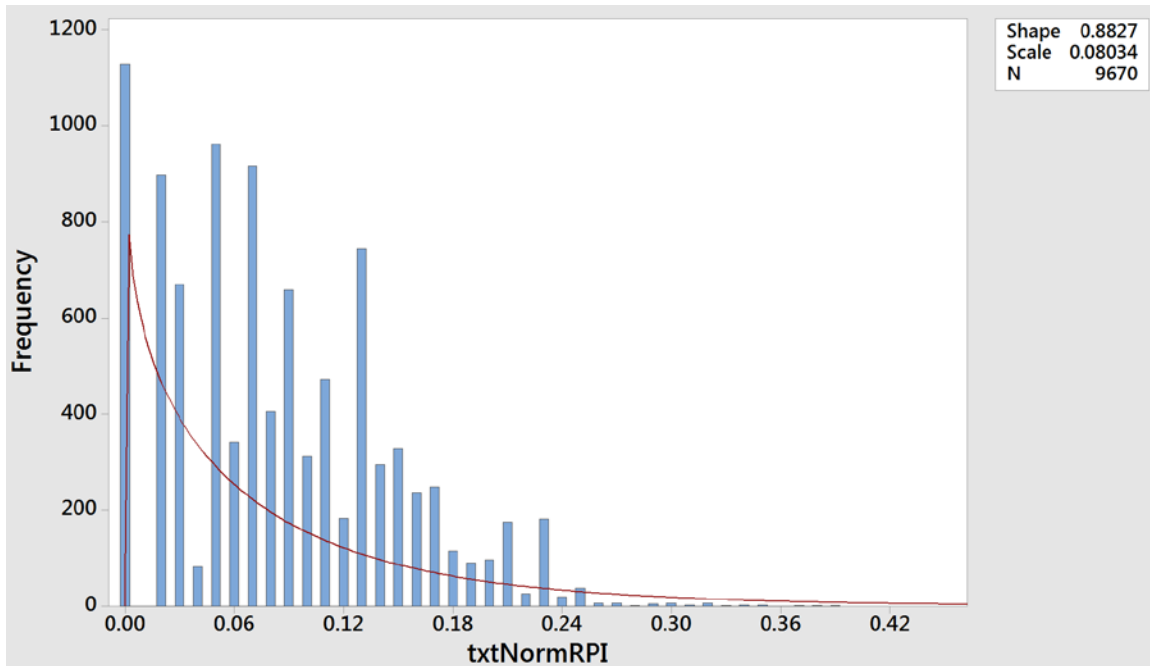


Figure 71. LTV histogram of RPI vs. Weibull

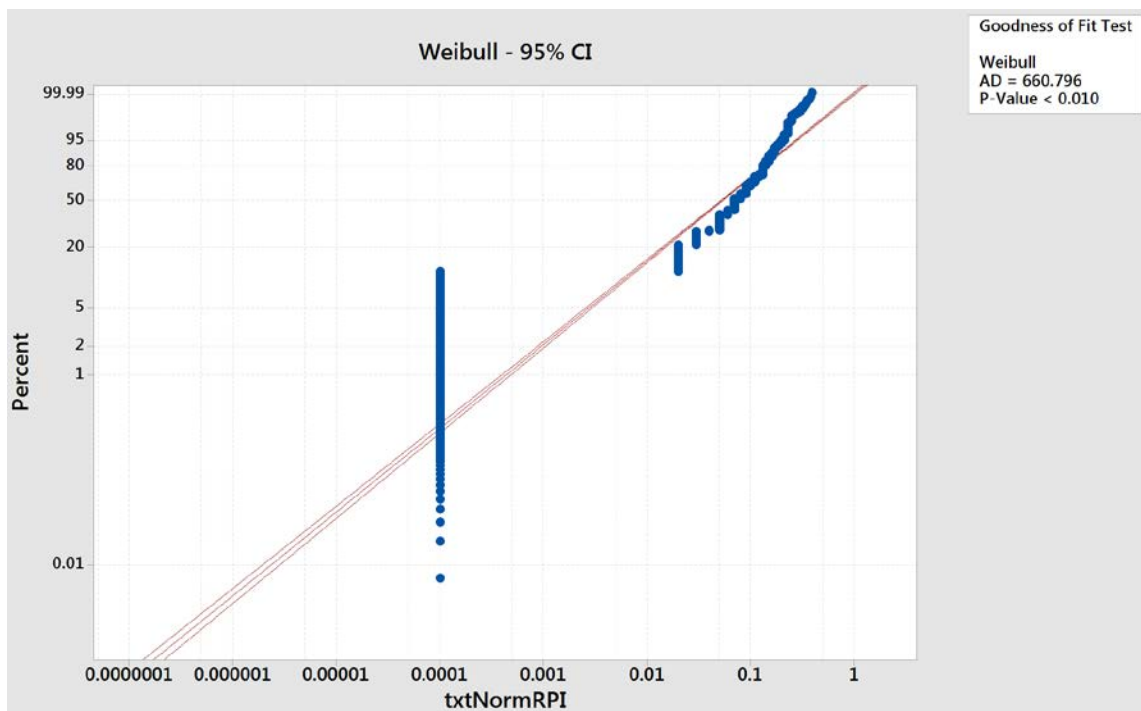


Figure 72. LTV RPI Weibull fit test

Further exploration of possible fitting to lognormal, exponential, and gamma distributions also resulted in P-values below any reasonable acceptance threshold (> 90% confidence).

4.2.1.1.1 RPI vs. FSG and FSC

The first correlation experiment sought a relationship between LTV RPIs and Federal Supply Group (FSG). In other words, are LTV RPIs randomly dispersed among all the LTV FSGs, or is there a pattern? Figure 73 shows a box plot of RPI vs. FSG, depicting each FSG's interquartile RPI relationship, mean (crosshairs symbol), median (grey dot symbol), and outliers (asterisk symbol), where:

1. an RPI value is deemed an outlier if it is $1.5 \times \text{IQR}$ from the end of the interquartile range (IQR) and
2. the whiskers extend out to the largest respective RPIs that do not qualify as outliers

What can be concluded from the box plot is that the FSGs with large (> 400) numbers of NIINs binned under them, such as FSG 25, 47, 53, and 59, have some of the largest ranges and include multiple outliers. As expected, the FSGs with very few (< 3) number of NIINs binned under them, such as FSG 12, 14, 63, and 65, display as mere dots. The takeaway, however, is that the RPI versus FSG box and whisker plot proves to be an effective visual analytic when communicating multiple aspects of a platform's equipment profile. Further enhancements could include: rank ordering the x-axis to integrate the Pareto relationship communicated in Figure 66 and displaying the corresponding NIIN count for each FSG as a data label.

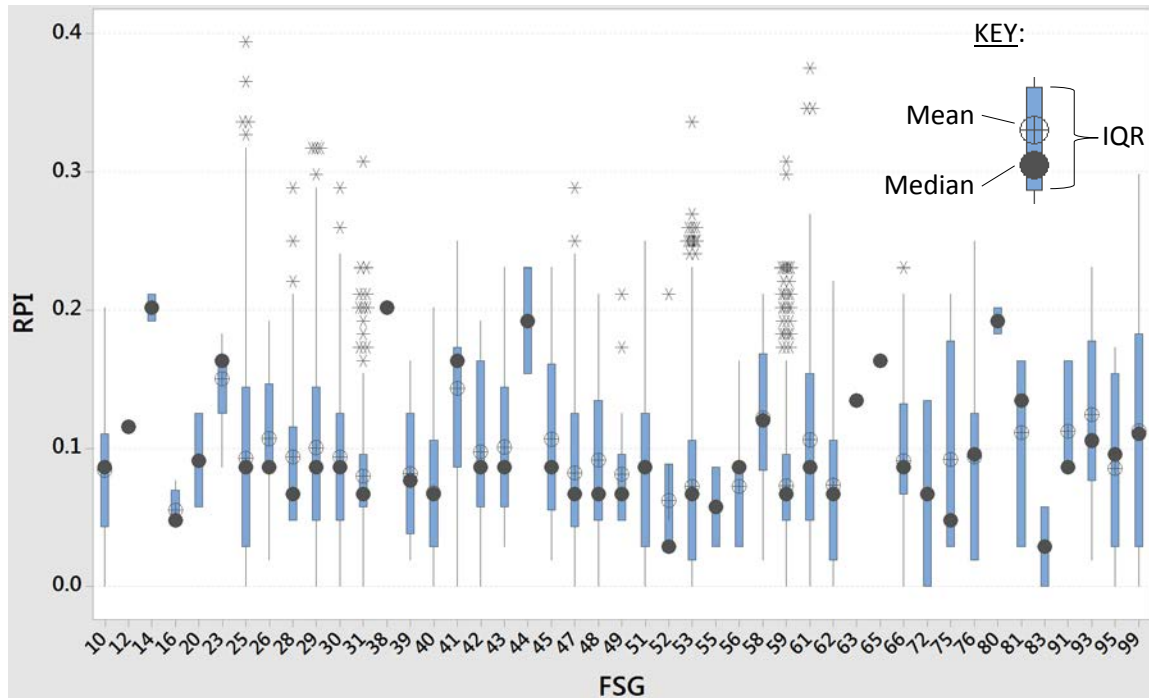


Figure 73. Box plot of LTV RPI vs. FSG

A similar analysis was conducted on RPI versus FSC. Since there are 154 FSCs represented in an LTV SERA, however, the x-axis becomes too congested to reside in a single box plot.

4.2.1.1.2 RPI vs. AAC

As introduced in section 3.3.7, Acquisition Advice codes (AACs) are assigned to NIINs to denote how, where, and under what restrictions NIINs are to be acquired. The list of all possible AACs and their definitions was expected from the SERA and is shown in Table 5. There are AACs that directly identify unsupported NIINs, such as NIINs with AAC = T, V, X, or Y. Sometimes the support strategy is to *not* sustain certain equipment. Therefore, there is inherent noise in AACs T, V, X, and Y that should *not*

necessarily be considered as a DMSMS concern. Quantifying this noise is beyond the scope of this research.

Table 5. AAC definitions

<i>AAC</i>	<i>Definition</i>
A	Service/Agency-Regulated. Issue, transfer, or shipment controlled above the ICP level.
B	ICP Regulated. Issue, transfer, or shipment is controlled by the ICP.
C	Service/Agency Managed. Not subject to specialized controls other than those imposed by the individual service
D	DOD Integrated Materiel-Managed, Stocked, and Issued. Not subject to specialized controls other than those im
E	Other Service-Managed, Stocked, and Issued. Not subject to specialized controls other than those imposed by th
F	Fabricate or Assemble (Non-Stocked items).
G	GSA/Civil Agency Integrated Materiel Managed, Stocked, and Issued.
H	Direct Delivery Under a Central Contract (Vendor Stocked items).
I	Direct Ordering from a Central Contract/Schedule (Non-Stocked Items).
J	Not Stocked, Centrally Procured Items (Non-Stocked Items). IMM/Service centrally managed but not stocked ite
K	Centrally Stocked for Overseas Only. Main source is local purchase or direct ordering from a central contract/sch
L	Local Purchase (Non-Stocked Items).
M	Restricted Requisitions - Major Overhaul. Items which for lack of specialized tools, test equipment, etc., can be us
N	Restricted Requisitioning - Disposal. Discontinued items no longer authorized for issue except on the specific app
O	Packaged Fuels (Non-Stocked Items). DLA-managed and service-regulated.
P	Restricted Requisition - Security Assistance Program (SAP); items only for SAP.
Q	Bulk Petroleum Products. DLA-managed.
R	Restricted Requisition - Government Furnished Material (GFM).
S	Restricted Requisitioning - Other Service Funded; subject to specialized controls of the funding military service.
T	Condemned (Non-Stocked Items). Item is no longer authorized for procurement, issue, use or requisitioning.
U	Lead-Service Managed. As a minimum provides procurement, disposal, single submitter functions.
V	Terminal Item. Identifies items in stock, but future procurement is not authorized.
W	Restricted Requisitioning - Special instructions apply (non-stocked items).
X	Semi-Active Item - No replacement (Non-Stocked items).
Y	Terminal Item (Non-Stocked Items). Future procurement is not authorized.
Z	Insurance/Numeric Stockage Objective Item. Nominal quantity stocked.

The distribution of AACs for the NIINs of three major TACOM platforms is shown in Figure 74. One of the most frequently observed AACs for a NIIN is “D”, which means the NIIN has a stable enough demand to be stocked by the Defense Logistics Agency (DLA). On the other hand, an AAC of “J” means the NIIN is not stocked, but can be

ordered through a number of procurement methods that typically involve additional lead time.

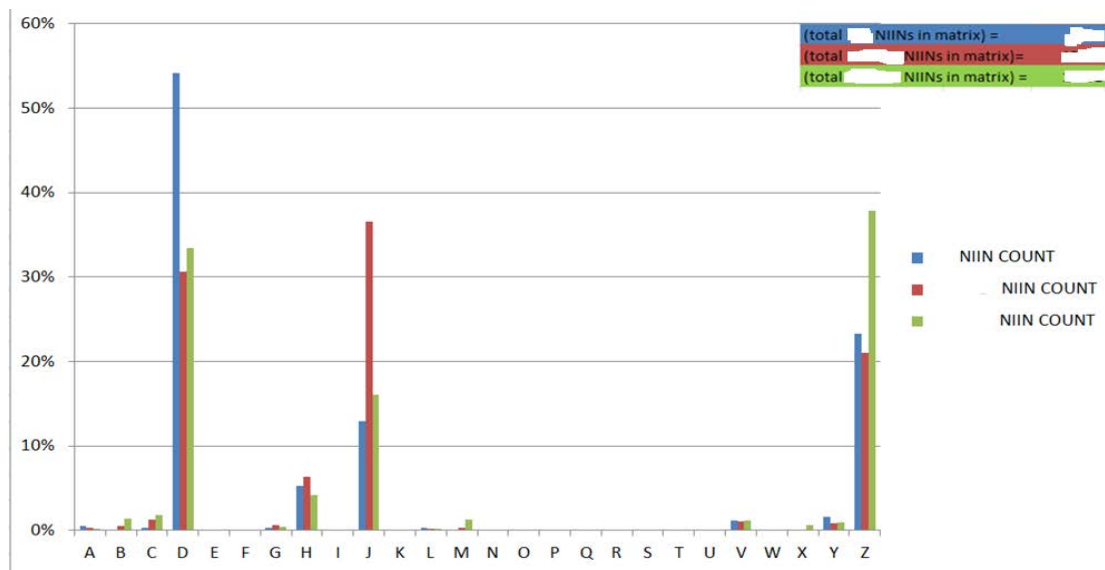


Figure 74. AAC distribution across three major platforms. (Legend suppressed for anonymity)

Figure 75 shows the result of screening to see if higher LTV RPIs correlate to particular AACs. In this case, any NIINs that exhibited a missing AAC after data mining were given an AAC of zero, by default. Unfortunately, the only visual conclusion that can be drawn is that the NIINs coded with “D” seem to be split into two groups: one group of outliers exhibiting relatively high RPI values (> 0.2), and another group consisting of the first three quartiles exhibiting relatively low RPI values (< 0.2). This means that DLA stocks a group of NIINs that exhibit twice as much risk indication as NIINs under the same AAC. Therefore, allocating risk mitigation resources towards the higher RPI NIINs, as opposed to the lower RPI NIINs, is justified.

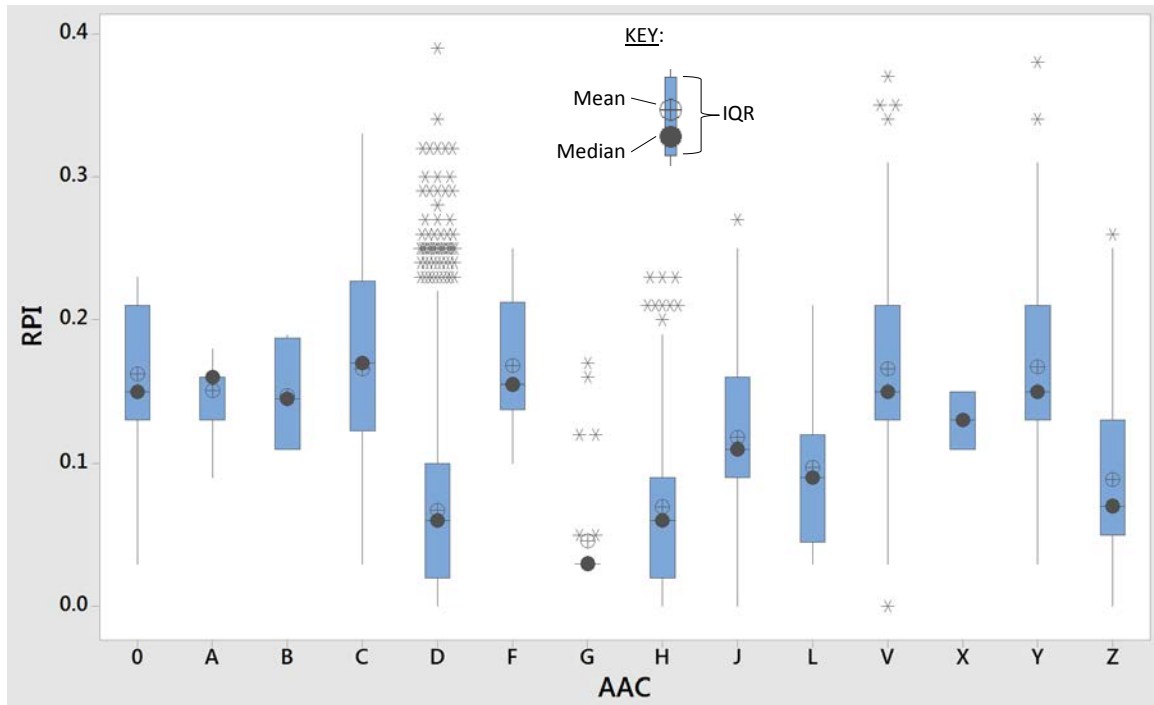


Figure 75. Box plot of LTV RPI vs. AAC

4.2.1.2 Characterizing 339 Events as a Response

The DoD defines validation as:

The process of determining the degree to which a model or simulation and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model [146]

The notion that aspects of the SERA serve as a model to indicate real world DMSMS event possibilities needed to be validated. Therefore, a plan was devised to treat the presence, or lack of, a past 339 event as a dichotomous response to independent variables associated with each NIIN in the LTV SERA. Being able to validate the modeling

capability of using SERA data in this fashion would give organizations the opportunity to proactively mitigating their own risk through the use of M&S.

Only 3% of the LTV NIINs had DLA Form 339s issued against them, between 20 April 2013 and 20 Mar 2016, as depicted in Figure 76. The timeframe reflects three complete years of data, from the time the data was mined. It is important to note that 98% of all provisioned LTV NIINs are managed by DLA, so the majority of the population of NIINs were eligible to become 339s, yet only a small percentage actually did.

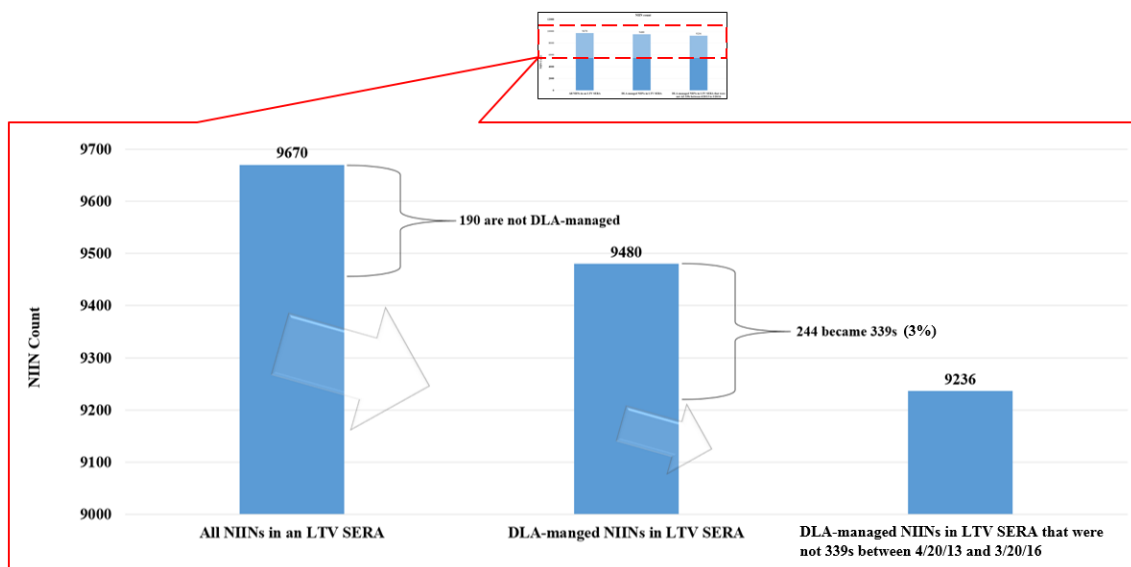


Figure 76. Proportion of LTV NIINs that became 339s

The notion that 339s indicate DMSMS can be seen in Figure 77. The figure captures the DLA Reason Codes for issuing TACOM 339s from 2009-2016, the timespan under which 339s were monitored closely by TARDEC's Industrial Base Engineering Team (IBET). The Reason Codes are as follows:

1. ALT (Administrative Lead Time), also known as Award Lead Time or Pre Award Referral: the Reason Code assigned to 339s when the time to complete equipment contracting paperwork exceeds the minimum acceptable lead time for a demand profile. Excessive ALTs can be attributed to factors such as having to initiate new contracts, due to previous suppliers going out of business, and supplier certification lapses.
2. PLT (Production Lead Time), also known as Post Award Referral: the reason code assigned to 339s when the time to manufacture and deliver equipment under a valid contract exceeds the minimum acceptable lead time for a demand profile. Excessive PLTs can be attributed to factors such as commercial demand priority tying up available capacity. This can also be attributed to the procrastination of sub-tiers to supply the relatively low volumes of materials and componentry associated with the defense market.
3. RSW (Requisition Strategy Workflow), also known as Release Strategy Workflow: the reason code assigned to 339s when certifications or inputs are required, as part of a materiel management action, under a given support strategy. The RSW reason code often reflects information disconnects between DLA and a command, or even support strategy coordination deficiencies within commands.
4. PQDR (Product Quality Deficiency Report): the reason code assigned to 339s used to document a quality issue with a NIIN. Quality issues documented within the PQDR system oftentimes indicate a lack of a supplier's six sigma capability [110, 147].

5. Other is the reason code assigned to 339s when an analyst feels the reason requires a custom input of justification.

Many 339s have been processed by TARDEC's Industrial Base Engineering Team (IBET) and the underlying reasons for 339 issuance thoroughly researched, since 2009, and found to be indicators of DMSMS forces at play. For example, excessive equipment prices often cause 339s due to suppliers not wanting to do short military production runs yielding low return on investment. Note how the ALT and PLT add up to over 50% of all 339s in Figure 77, signifying that the IB response to demand causes DLA to issue 339s as requests for engineering support. The requests for help are oftentimes to affirm a new support strategy or approve a needed supplier [148, p. 42, 149, pp. 6, 10].

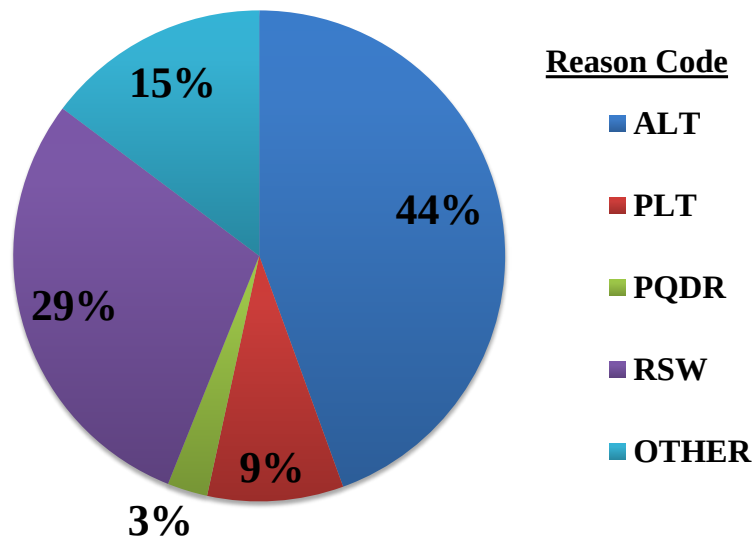


Figure 77. Reason Codes for 339s

4.2.1.2.1 339 Events vs. RPI

Since RPI is the attribute in the SERA that represents the overall sustainment risk of a NIIN, validating a NIIN's RPI against a dichotomous 339 response was a logical first test, since 339 events indicate real-world requests for sustainment support help with the “management and procurement of an item for its entire life cycle” [149, p. 10].

Validating that 339 NIINs are part of a different population than that of non-339 NIINs is the heart of the validation. The strategy was to designate SERA attributes as independent variables in an experiment to see whether the 339 NIINs could be distinguished from the remaining non-339 NIIN population.

It was presumed that NIINs experiencing 339 events would show higher RPI values, but the data revealed an opposite trend. Figure 78 compares normally-fitted RPI distributions, between the LTV NIINs that became 339s (in blue) versus the NIINs that did not (in red), between 20 April 2013 and 20 Mar 2016. Since 339 NIINs only constitute 3% of the total data, it was difficult to observe any distinctions between the red and blue frequency histograms on the left side of the figure. However, changing over to a density histogram on the right side of the figure was found to have the unexpected effect of magnifying the RPIs of the NIINs that became 339s, making it easier to contrast with the non-339 histogram. The density histogram was calculated from the frequency histogram where the area of each bar in the density histogram was constructed to represent the proportion of NIINs that fall within the respective RPI bin. Therefore, the only difference between the frequency and density histograms, is the scale of the y-axis. In other words, the chance that a value lies within a certain interval is directly

proportional to the frequency. The more values observed within a certain interval, the greater the chance that any observed value lies in that interval. The distribution of the 244 NIINs that became 339s was later found to be non-normal, via Anderson-Darling test ($p = 0.016$), as was the distribution of the 9236 NIINs that did not become 339s ($p < 0.005$). Therefore, inferential statistics based on the data fitting normal distributions cannot be used with confidence.

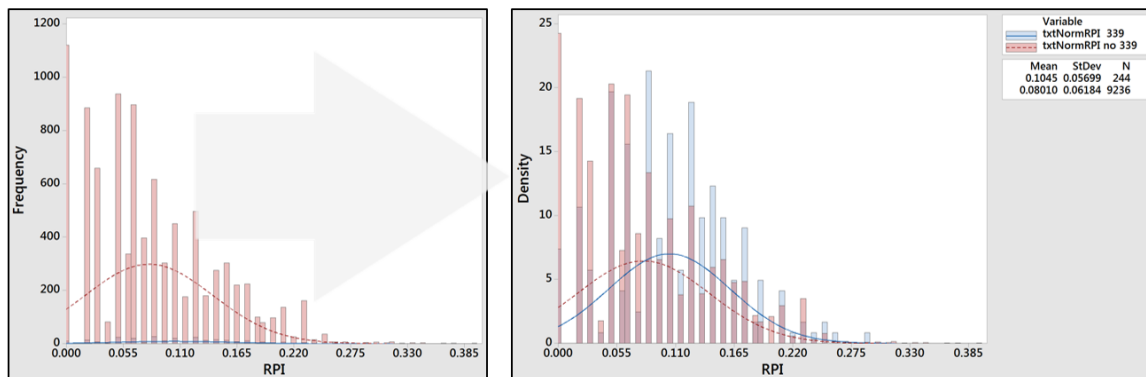


Figure 78. LTV RPI histograms comparing normal fits of 339 RPIs vs. non-339 RPIs

The shapes of the histograms, in conjunction with their non-normal determination, prompted a histogram comparison under a Weibull fit. Again, a transformation from a frequency histograms to density histograms was performed to equalize the visual handicap induced by the disparate histogram frequencies of the dichotomous response, as shown in Figure 79. Comparing the two response curves, an apparent RPI difference is observed, thereby, constituting more work. Also, the Weibull fit appears to represent the lower RPI values (< 0.06) a little better than the previous attempt at a normal fit. Although, the Weibull curves appear to decay too quickly, as RPI values increase. The distribution of the 244 NIINs that became 339s was found to be non-Weibull ($p < 0.01$ at 95% confidence), as was the distribution of the 9236 NIINs that did not become 339s (p

< 0.01), as shown in Figures 80 and 81, respectively. Therefore, this particular phase of analysis could not conclude that eligible NIINs (i.e. DLA-managed) with higher RPIs have more tendency to become 339s than eligible NIINs with lower RPIs.

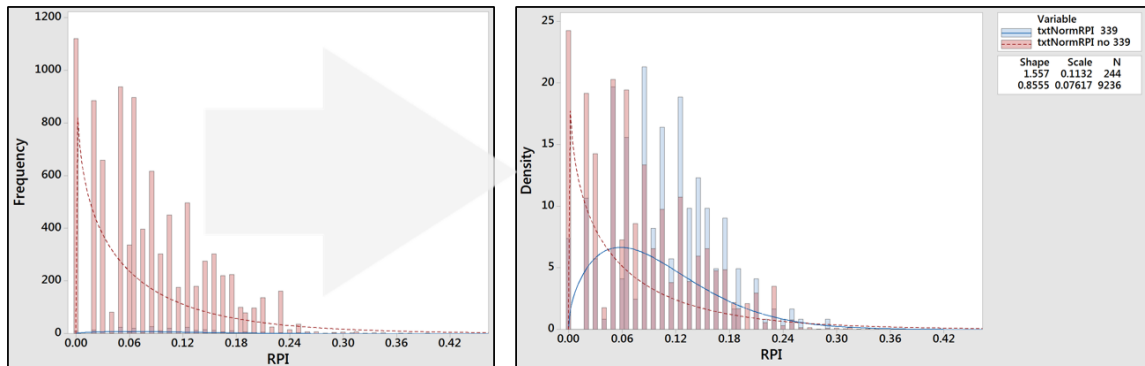


Figure 79. LTV RPI histograms comparing Weibull fits of 339 RPIs vs. non-339 RPIs

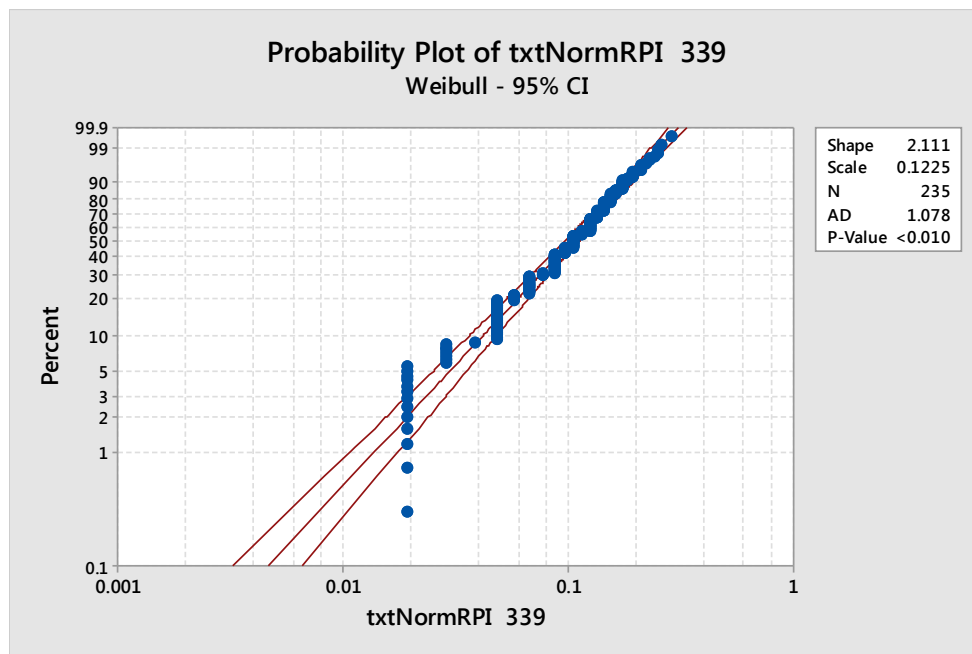


Figure 80. LTV probability plot of 339 NIIN RPI vs. Weibull

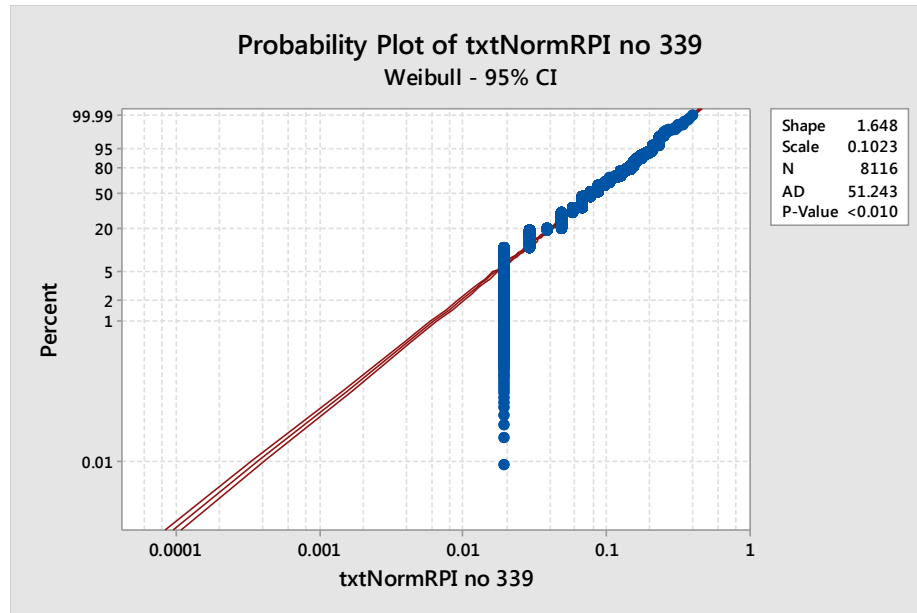


Figure 81. LTV probability plot of non-339 NIIN RPI vs. Weibull

4.2.1.2.2 Correlation of 339 Events vs. SERA Factors

A correlation matrix between the LTV SERA risk indicator flags, RPI, 339 presence, and individual 339 reason codes was generated, as shown in Table 6. Since each 339 is attributed to exactly one of the six reason codes, a dummy variable coding scheme was used to categorize the 339 events into an array of dichotomous reason code states. Note that a sixth reason code called Non-Procurable Item (NPI), normally considered part of the Other reason code, was included as its own column in the correlation matrix for additional visibility. The null hypothesis was that no correlation exists between any of the variables, using the 95% confidence interval test statistic that: if $p < 0.05$, reject the null hypothesis. Although the correlation matrix tests all variable pairs, the RPI and SERA flags were treated as the predictor variables and the presence of a 339 and the presence of an individual reason code served as the dichotomous output variables for each of the LTV NIINs in the analysis. Recall the SERA flags discussed in section 3.3.8.

Overall, the correlation matrix did not expose any strong relationships between variable pairs that were not already understood. Only three variable pairs had a $p < 0.05$ with Pearson correlation coefficient > 0.5 (highlighted in green in the matrix):

1. The ALT reason code (i.e. ALT: 1) versus the presence of a 339 (i.e. 339: 1) variable pairing,
2. The Single Valid Supplier flag (i.e. txtWt1Grp) versus RPI (i.e. txtNormRPI) variable pairing and
3. The Top 10% Open Maintenance Work Orders flag (i.e. txtWtWOLastYrTop) versus Top 10% Closed Maintenance Work Order flag (i.e. txtWtWOClosedTop) variable pairing

The higher correlation of the ALT reason code to the presence of a 339 was due to ALT being the most popular reason for issuing 339s. All flags were expected to show statistically significant correlation to RPI, regardless of Pearson correlation coefficient magnitude, yet the Hazardous Material (i.e. txtHazWt) and Shelf Life (i.e. SLCWt) flags exhibited p -values > 0.05 . This observation challenges the credibility of the correlation matrix to identify significant correlations in this data set with precision. In another example, the correlation matrix determined that only a strong correlation coefficient > 0.5 exists with the RPI-Single Valid Supplier flag pair. Finally, the reason why the Top 10% Open Maintenance Work Orders flag shows a relatively high correlation with the Top 10% Closed Maintenance Work Order flag is that active NIINs commonly have open work orders along with a history of closed work orders. Therefore, having both flags contribute to the calculation of RPI is unnecessary.

Table 6. LTV SERA vs. 339 Reason Codes Correlation Matrix

	339: 1	NPI: 1	PQDR: 1	PLT: 1	OTHE: 1	RSW: 1	ALT: 1	txCageCodeWt	txAACWt	txRiskWt	txWtDPUnavail	txWtHaz	txWtSLC	txWtNor	txWt1Grp	txWt0Or1WeapSys	txWtRiskMed	txWtRiskUnk	txWtDPLtd	txWtWOClosedTop	txWtWOLastYr	txWtWOLastYrTop	txWtPBO	txWtRand	txWtCWTTop10Pcn	txWtNoDemand	txWtCWTTop10Pcn
NPI: 1	0.126																										
	0																										
PQDR: 1	0.268	-0.001																									
	0	0.931																									
PLT: 1	0.31	-0.001	-0.002																								
	0	0.921	0.832																								
OTHER: 1	0.483	-0.002	-0.003	-0.004																							
	0	0.877	0.742	0.703																							
RSW: 1	0.466	-0.002	-0.003	-0.004	-0.006																						
	0	0.881	0.75	0.713	0.567																						
ALT: 1	0.589	-0.002	-0.004	-0.005	-0.007	-0.007																					
	0	0.85	0.688	0.642	0.469	0.485																					
txCageCodeWt	0.048	-0.003	-0.006	-0.007	-0.012	0.103	0.016																				
	0	0.765	0.526	0.464	0.254	0	0.115																				
txAACWt	-0.008	-0.003	0.011	-0.007	-0.001	-0.01	-0.005	-0.005																			
	0.424	0.779	0.261	0.492	0.912	0.302	0.606	0.592																			
txRiskWt	-0.012	-0.003	0.012	-0.007	-0.01	-0.01	-0.004	-0.02	0.015																		
	0.255	0.788	0.222	0.511	0.305	0.323	0.669	0.049	0.128																		
txWtDPUnavail	0.028	0.001	-0.017	0.003	0.016	-0.01	0.047	-0.048	0.014	-0.04																	
	0.006	0.896	0.088	0.749	0.108	0.32	0	0	0.179	0																	
txWtHaz	-0.005	-0.003	-0.006	-0.006	0.022	-0.01	-0.012	-0.019	0.006	-0.017	-0.061																
	0.606	0.796	0.583	0.526	0.034	0.341	0.228	0.058	0.584	0.088	0																
txWtSLC	-0.001	-0.004	-0.008	0.028	-0.006	0.011	-0.017	-0.006	-0.007	-0.01	-0.061	0.015															
	0.897	0.725	0.455	0.006	0.566	0.272	0.101	0.582	0.489	0.333	0	0.132															
txWtNor	0.057	0.001	0.005	0.002	0.044	0.028	0.034	0.176	0.2	0.133	0.413	0.015	0.015														
	0	0.896	0.654	0.825	0	0.005	0.001	0	0	0	0	0.145	0.133														
txWt1Grp	-0.018	-0.009	-0.018	0.008	-0.022	0.003	-0.009	-0.063	0.023	-0.002	0.189	-0.048	-0.032	0.564													
	0.07	0.398	0.073	0.439	0.033	0.759	0.358	0	0.026	0.84	0	0	0.001	0													
txWt0Or1WeapSys	-0.007	-0.005	-0.008	-0.021	-0.029	0.017	0.014	0.176	0.172	0.06	0.017	-0.081	-0.041	0.394	0.258												
	0.47	0.618	0.415	0.038	0.004	0.09	0.168	0	0	0	0.098	0	0	0	0												
txWtRiskMed	0.009	-0.003	-0.006	-0.007	0.041	-0.01	-0.004	-0.02	-0.001	-0.018	-0.008	0.008	0	0.11	-0.038	0.069											
	0.374	0.791	0.574	0.516	0	0.329	0.687	0.052	0.904	0.08	0.429	0.441	0.991	0	0	0											
txWtRiskUnk	0.007	-0.001	-0.002	-0.002	0.026	-0.003	-0.004	-0.007	-0.006	-0.006	-0.003	-0.006	-0.008	0.023	-0.007	0.026	-0.006										
	0.48	0.927	0.847	0.823	0.011	0.737	0.672	0.504	0.531	0.548	0.806	0.563	0.43	0.023	0.519	0.01	0.553										
txWtDPLtd	-0.003	0.012	0.014	-0.019	-0.004	-0.007	0.005	-0.049	0.065	-0.044	-0.305	-0.034	-0.039	0.167	0.044	-0.073	-0.017	-0.01									
	0.777	0.237	0.157	0.065	0.706	0.475	0.633	0	0	0	0.001	0	0	0	0	0.103	0.321										
txWtWOClosedTop	0.107	0.012	0.046	0.029	0.123	0.026	0.018	-0.044	0.026	-0.016	-0.035	0.018	0.068	0.279	-0.085	-0.143	-0.007	0.034	-0.018								
	0	0.247	0	0.004	0	0.01	0.082	0	0.01	0.109	0.001	0.079	0	0	0	0	0.487	0.001	0.076								
txWtWOLastYr	0.075	-0.004	0.045	0.017	0.084	0.014	0.017	-0.102	0.002	-0.034	-0.09	0.044	0.012	0.056	-0.172	-0.223	-0.04	0.001	-0.007	0.425							
	0	0.716	0	0.088	0	0.16	0.102	0	0.809	0.001	0	0	0	0.242	0	0	0	0.893	0.522	0							
txWtWOLastYrTop	0.128	0.02	0.071	0.019	0.156	0.017	0.027	-0.029	0.02	-0.007	-0.023	0.003	0.065	0.254	-0.072	-0.092	-0.006	0.033	0	0.698	0.309						
	0	0.051	0	0.064	0	0.101	0.009	0.004	0.055	0.491	0.025	0.794	0	0	0	0	0.53	0.001	0.982	0	0						
txWtPBO	-0.003	-0.002	-0.003	-0.004	-0.006	0.013	-0.007	-0.002	0.019	-0.01	0.002	0.001	0.019	0.197	0.006	0.099	0.011	0.027	-0.03	0.162	0.101	0.18					
	0.738	0.88	0.748	0.711	0.563	0.209	0.481	0.853	0.056	0.318	0.809	0.919	0.063	0	0.532	0	0.276	0.008	0.003	0	0						
txWtRand	0.031	-0.006	0.003	0.006	0.022	0.019	0.016	-0.043	0.005	-0.021	-0.071	0.085	0.013	0.269	-0.09	-0.093	-0.02	0.017	-0.013	0.383	0.317	0.275	0.119				
	0.002	0.524	0.781	0.577	0.034	0.058	0.127	0	0.634	0.039	0	0	0.203	0	0	0	0.046	0.095	0.201	0	0	0	0				
txWtCWTTop10Pcn	0.019	0.018	0.001	0.026	0.018	-0.011	0.008	-0.019	0.025	0.033	0.036	-0.019	0.03	0.207	0.075	0.118	0.023	0	-0.042	-0.054	-0.085	-0.029	0.001	-0.061			
	0.059	0.072	0.938	0.011	0.073	0.272	0.441	0.065	0.013	0.001	0	0.06	0.003	0	0	0	0.024	0.976	0	0	0	0.005	0.918	0			
txWtNoDemand	-0.024	-0.007	-0.015	-0.011	-0.019	-0.005	-0.006	0.076	-0.05	0.016	0.123	-0.039	-0.008	0.376	0.175	0.212	0.055	-0.002	0.009	-0.11	-0.253	-0.078	-0.027	-0.112	-0.083		
	0.017	0.475	0.129	0.268	0.058	0.631	0.552	0	0	0.106	0	0	0.458	0	0	0	0	0.852	0.4	0	0	0	0.008	0	0		
Cell Contents:																											
Pearson correlation																											
P-Value																											

To examine any possible platform-to-platform differences, Abrams equipment logistics data was also analyzed for correlation. Abrams 339 events were gathered over a larger timespan, as compared to LTV 339s, as illustrated in Figure 82. Note that, in both cases,

only 339 events occurring after the establishment of the LTV and Abrams risk indicators were examined in the analysis, as indicated by the position of the yellow arrows relative to the timeline. This was to illustrate that the 339 events being analyzed had no influence on the establishment of the generic risk indicators of the LTV and Abrams SERAs.

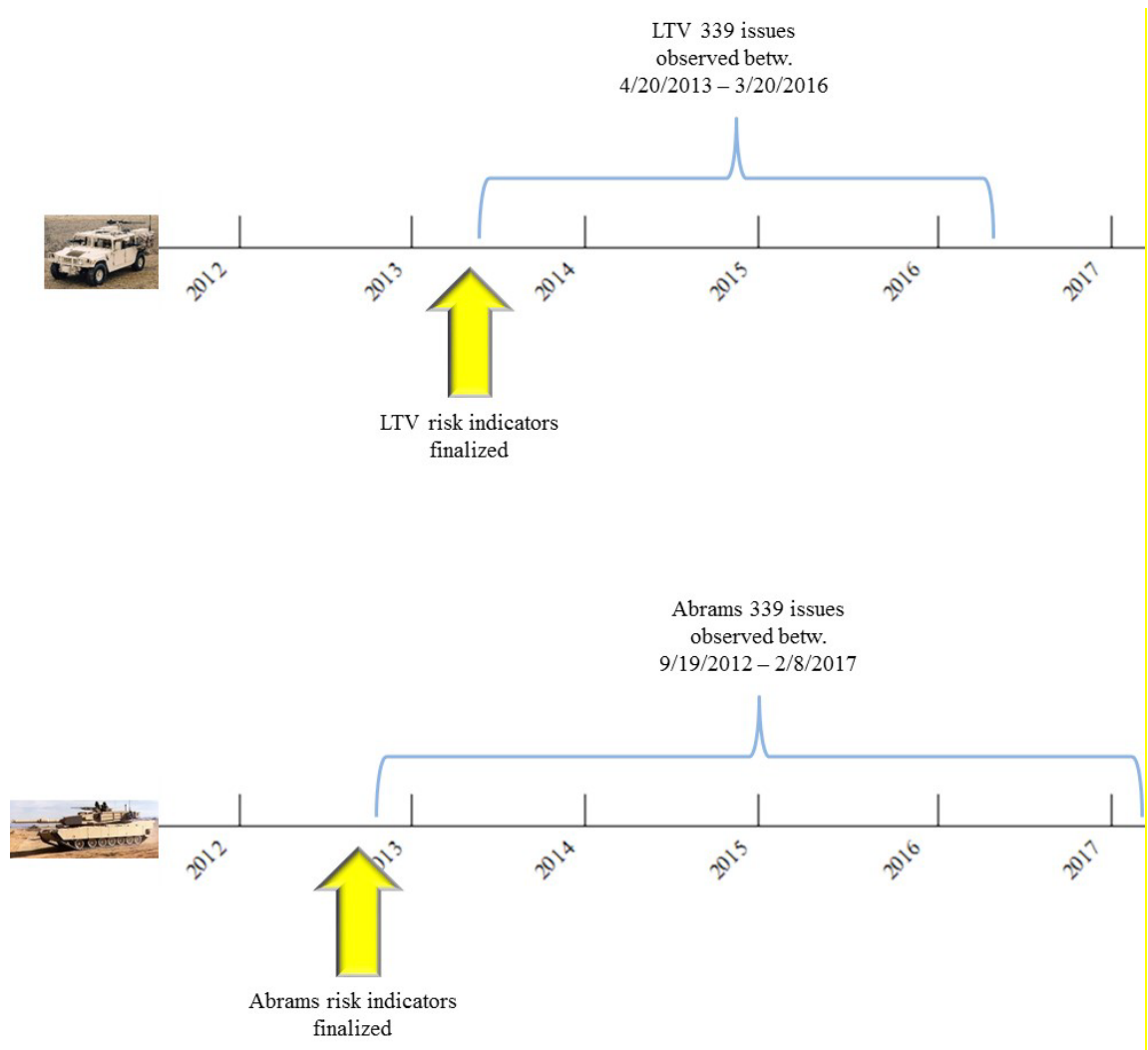


Figure 82. Span of LTV and Abrams correlation analysis

Similar to the LTV platform, no strong correlation was found between 339 events and the Abrams SERA risk indicators. The correlation matrix for the Abrams data is included in Appendix C. Overall, the ability of the Pearson correlation coefficient and the p-value of

the correlation matrix to detect inherent correlations between variables in the LTV and Abrams data sets is unconvincing. For example, even though inherent correlation exists between any RPI value and its makeup of flag weights, not all RPI-flag variable pairs in the LTV correlation matrix exhibited p-values less than 0.05, nor did they exhibit strong Pearson coefficients. Therefore, just because a Pearson coefficient or p-value falls short of some threshold does not always mean that an underlying relationship is absent. However, the influence that sufficient sample size and flag weight might have on the correlation matrix needed to be examined further.

To better understand the effect of flag frequency on p-value and Pearson coefficient for each RPI-flag pair, Figure 83 was created. The blue columns represent the number of times any one particular flag was tripped in the LTV SERA. Arranging the blue columns in descending order and comparing them to their corresponding RPI-paired Pearson coefficients (in orange) confirmed that the Pearson coefficients do not favor flags with a high frequency of samples. As the figure emphasizes, all RPI-flag pairs examined were found to be statistically significant with $p < 0.05$, except for the Shelf Life (i.e. RPI-txtSLCWt) and Hazardous Material (i.e. RPI-txtHazWt) pairs marked with an orange “x”. However, none of the RPI-flag pairs exhibited strong Pearson coefficients > 0.5 , except for the Single Valid Supplier (i.e. RPI-txtWt1Grp) pair.

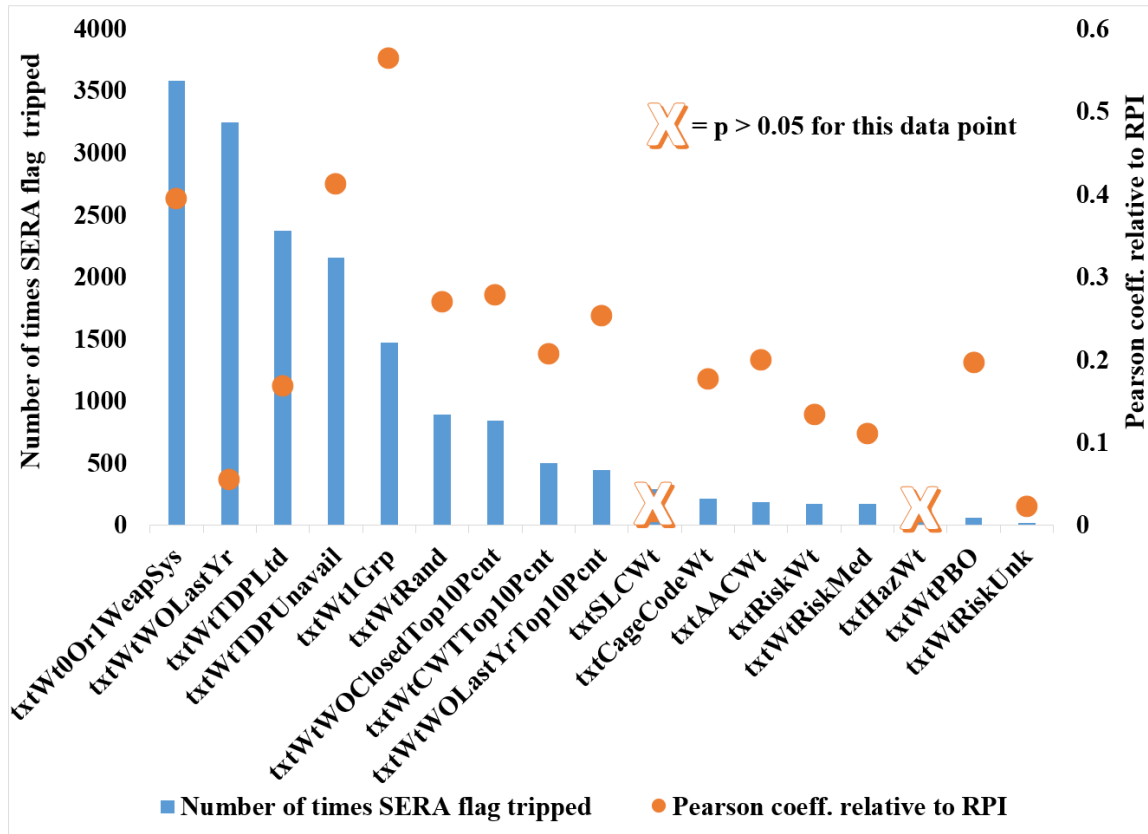


Figure 83. LTV flag frequency vs. Pearson correlation to RPI

The only other flag attribute that influences its resultant RPI calculation, besides its frequency, is a flag's weight. Therefore, examining each flag's weight with respect to its RPI-paired Pearson coefficient and p-value offered the only remaining explanation for why the correlation matrix exhibited significant and strong correlation between some RPI-flag pairs, but not others. Figure 84 illustrates this final examination. Flags, depicted as green columns, were rank ordered by weight in comparison to their respective Pearson coefficients (in orange). As can be seen in the figure, the significant p-values and strong Pearson coefficients do not favor flags with higher weights.

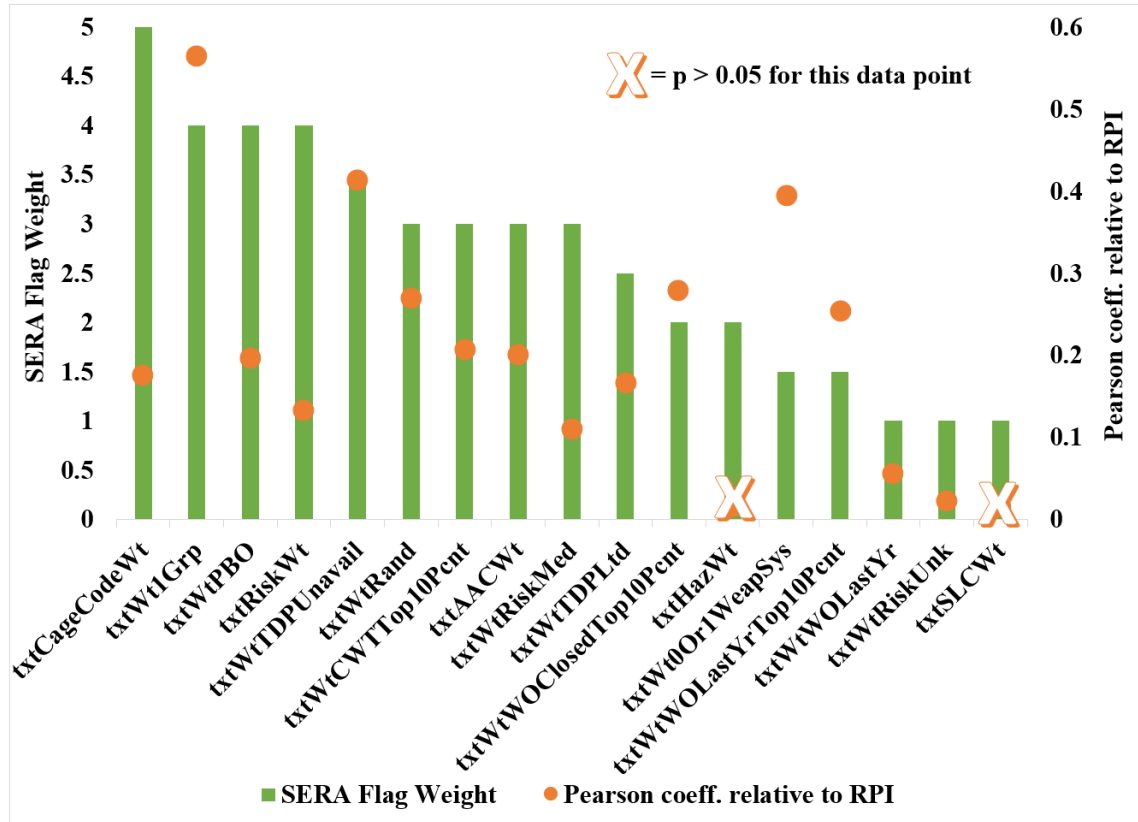


Figure 84. LTV flag weight vs. Pearson correlation to RPI

It should be noted that the Pearson coefficient and p-value thresholds with which analysts make model quality determinations are quite sensitive to “how” paired variables might be inherently related. Examining the dummy variable coding scheme used to classify the LTV 339 events by reason code illustrates this point, as shown in Figure 85. The grey columns represent the number of times any one particular reason code was used to justify a 339 event. Arranging the grey columns in descending order and comparing them to their corresponding 339 event-paired Pearson coefficients (in orange) confirmed that the p-values and Pearson coefficients do, in fact, favor reason codes exhibiting higher frequencies. As the figure emphasizes, all 339 event-reason code pairs examined were found to be statistically significant with $p < 0.05$. However, none of the 339 event-reason

code pairs exhibited strong Pearson coefficients > 0.5 , except for the 339 event-ALT pair, which accounts for 35% of all 339s in the analysis. In fact, the manner in which the 339 events are inherently related to the dummy variable reason coding scheme dictates what frequencies produce a strong Pearson coefficient of > 0.5 . As indicated by the dashed gridline line in the figure, a reason code would have to account for at least 25% of all 339s in order to make the cut for what is considered to be a strong and significant correlation in this data set. Comparing this result with that of the previous analysis involving an inherent normalization relationship between variable pairs is evidence enough to conclude that the correlation matrix, by itself, is unreliable when applied to this particular data set.

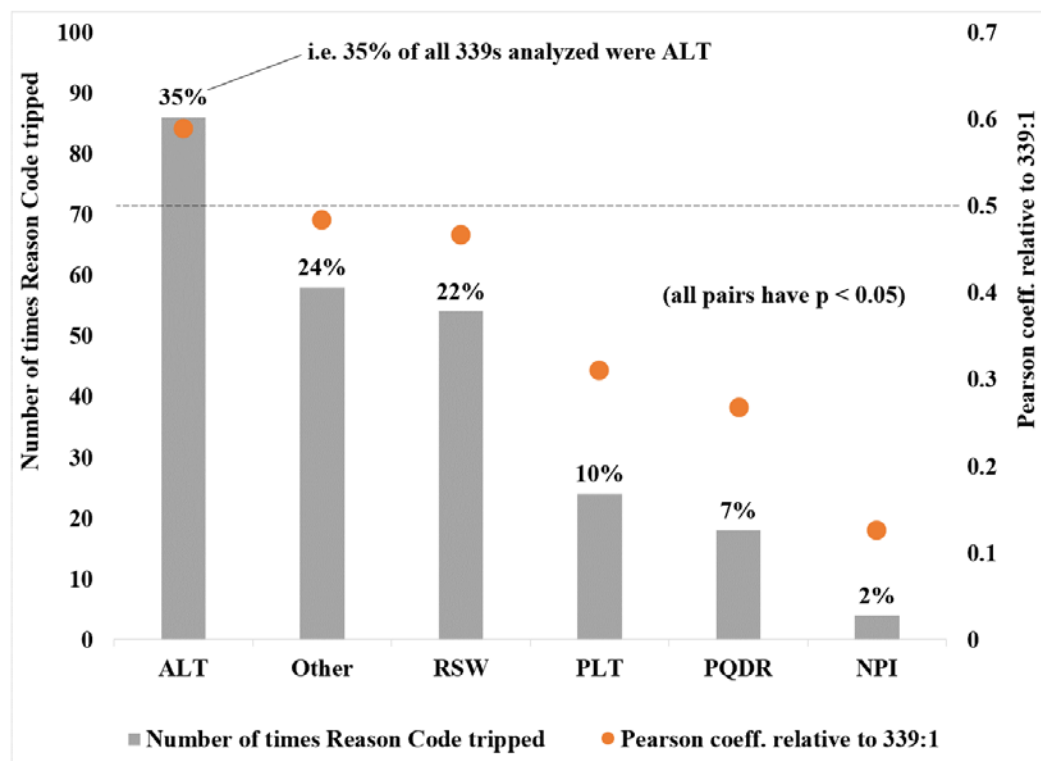


Figure 85. LTV reason code vs. Pearson correlation to 339 event

In summary, the small sample of NIINs that experienced 339 events only accounted for 3% of all the NIINs in each respective platform analyzed, as shown as blue pie slices in Figure 86. In each case, the NIINs with 339 events exhibited the same range of RPIs as did the NIINs that did not experience 339 events. Although the corresponding blue distribution of RPIs initially appeared distinguished from that of the red RPI distribution, the observed differences were found to be statistically insignificant for the LTV and Abrams data sets.

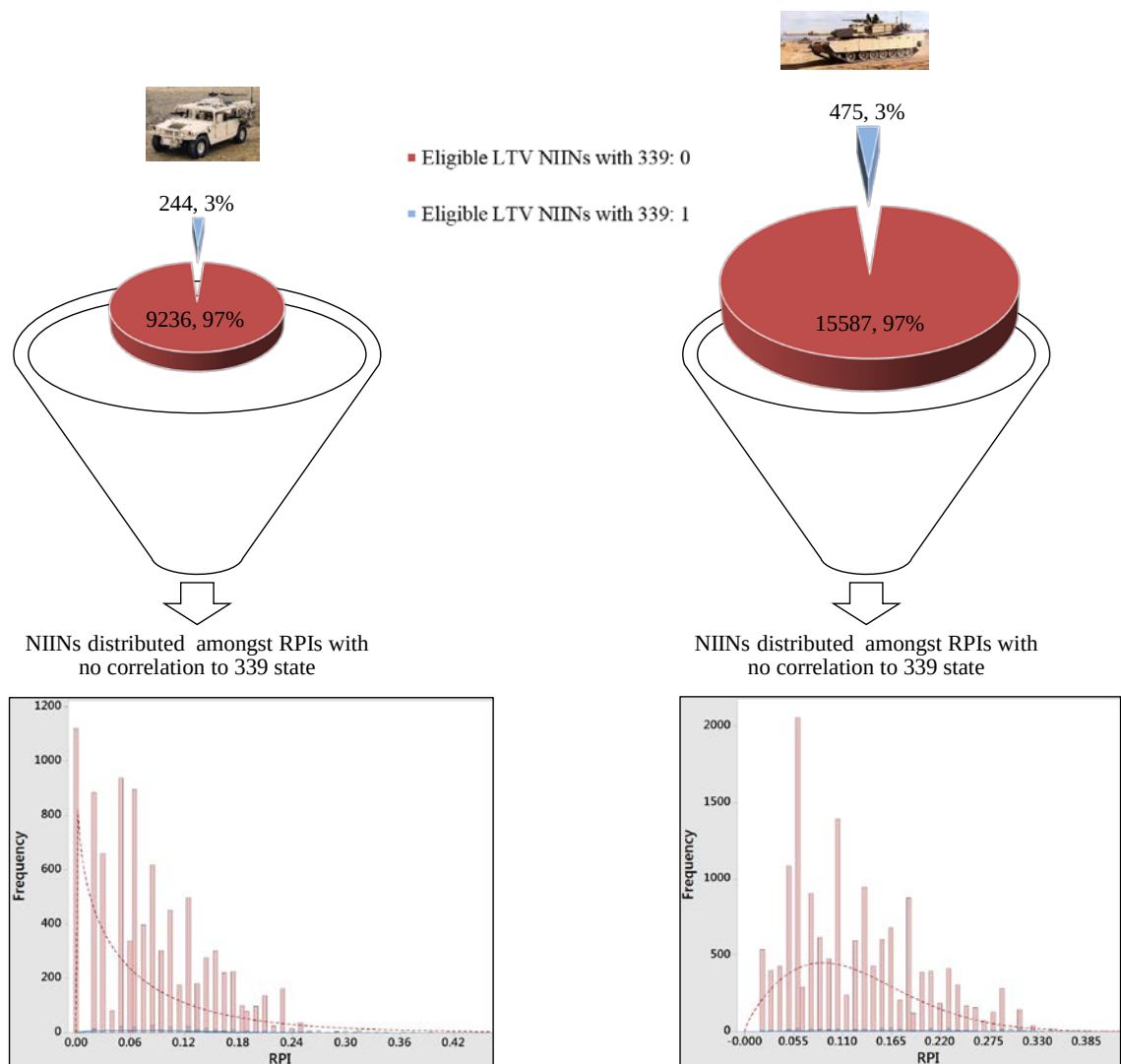


Figure 86. Depiction of LTV and Abrams NIIN proportion to 339 and RPI distribution

The low correlation discovery between the LTV and Abrams SERA flags and 339 events is disappointing but not surprising. The diverse connotation that exists with the word “risk” among many industries does not always warrant a statistically significant correlation to corresponding issues downstream of the analysis, in order for a risk assessment to be deemed useful [150, 151, p. 3]. The longstanding Failure Modes and Effects Analysis (FMEA) tool that is used to assess risks for many industries illustrates this point [152, 153]. Similar to the SERA, an FMEA involves subject matter experts (SMEs) assigning weights and scores to risks, in order to prioritize the risks in preparation for mitigation implementation. With FMEA, scores are assigned to the likelihood, consequence, and detection of risks that may or may not ever manifest as real issues in the future. Although widespread and considered as an essential element of any control plan, it has long been accepted that “there are significant methodological challenges in validating FMEA” [154, p. 9]. Detection methods, alone, are criticized in the literature for being unreliable [151, p. 1, 155]. This is one of the reasons why the SERA does not include a detection score, nor does the SERA involve the multiplication of any likelihoods or consequences, prior to the summation of a NIIN’s total weight score. Many DMSMS events effecting equipment readiness exhibit risk indicators that go undetected right up to the point of a company going out of business [7].

The value of tools like FMEA and SERA is that they provide valuable information that could not otherwise be leveraged, in order to identify defects in a strategy or systems design [156, p. 2, 157, 158]. The SERA is a direct answer to Army Regulations that mandate the integration of “industrial base planning into all phases of the acquisition

system's life cycle. Relevant information will be gathered and maintained in order to describe the current industrial base, identify critical sector, document major shortfalls, and identify trends" [29, pp. 29, 35, 19]. The scores used in tools such as FMEA and SERA are meant to guide teams to implementing mitigations for potential events that "could occur, but will not necessarily occur" [156, pp. 59, 99]. Therefore, it is commonplace for these tools to lack correlation to events that actually occur. Further research is warranted if a correlation to 339 events is desired, as new SERA flags continue to be discovered, while existing flags are categorized. Better training on assigning consistent reason codes to 339s and even experimenting with new sets of reason codes is recommended to refine the association between 339s and DMSMS events. The overall knowledge gained from this section of research is that logistic regression is an appropriate technique to trial dichotomous DMSMS risk indicators against the presence of real-world DMSMS events moving forward. Many more opportunities for trend exploration, beyond a general analysis, exist within the logistics and industrial base data of the SERA.

4.2.1.2.3 Logistic Regression of 339 Events vs. SERA Factors

When dealing with dichotomous predictors and responses in trying to predict a group membership, logistic regression is often a recommended analysis technique [145, p. 30]. One of the reasons for this is logistic regression does not assume that the variables follow any particular distribution, nor is the technique limited to continuous or discrete data types [145, pp. 23, 439]. This is appropriate, since the SERA flag predictors are considered ratio type data with dichotomous distribution states. Specifically, with a

binary logistic regression model, the probability of encountering a 339 event is based on a nonlinear function of the best linear combination of predictors:

$$\hat{Y}_i = \frac{e^u}{1+e^u} \quad (\text{Eq. 7})$$

where $\hat{Y}_i$ is the estimated probability that the i th case ($I = 1, \dots, n$) encounters a 339 event and u is the usual linear regression equation:

$$u = A + B_1X_1 + B_2X_2 + \dots + B_kX_k \quad (\text{Eq. 8})$$

with constant A , coefficients B_j , and predictors, X_j for k predictors ($j = 1, \dots, k$).

Conversely, $1 - \hat{Y}_i$ is the estimated probability that the i th case ($I = 1, \dots, n$) does not encounter a 339 event.

The linear form of the regression equation, therefore, is in terms of the *logit* (or $\log_e$) of the odds of encountering a 339 event divided by the odds of not encountering a 339 event:

$$\text{logit}(\pi) = \ln\left(\frac{\hat{Y}}{1-\hat{Y}}\right) = A + \sum B_jX_{ij} \quad (\text{Eq. 9})$$

The maximum likelihood method of estimating coefficients is used to find the best linear combination of predictors to maximize the likelihood of obtaining the observed outcome frequencies. Similar to how the correlation matrix was generated in the previous section, any blanks that resulted after data mining and calculating the SERA flag sub-scores were replaced with zeros. Only five SERA flags exhibited a $p < 0.05$ in the initial binary logistic regression model. Therefore, the model was rerun including only those five flags, as shown in the Minitab Session Window screenshots in Appendix D. The model's low R-squared value of 6.61% concludes that the LTV SERA flags are a poor predictor of 339 events.

4.2.1.2.4 339 Events vs. AAC Rates of Change

Monitoring changes in the AAC for different classifications of equipment, in conjunction with other signatures of logistics behavior, was hypothesized to offer insight into sustainment maturity, when taken in context with the respective platform strategy on which the equipment is used. Specifically, capturing the variation in AAC change intervals, was thought to offer clues into predicting sustainability. Theoretically, the AAC for a typical NIIN is expected to evolve through particular AAC states, beginning with “D” when the NIIN is in high demand (such as in wartime). When lower demands cannot justify stocking, the NIIN typically dwells under “J”, “X”, or “Z”, until reaching the end of its useful life as “V” or “Y” (recall section 4.2.1.1.2).

For example, Figure 87 shows the AAC state changes for a vehicle heater that started in a semi-active demand state and oscillated back and forth at a high rate of change between stocked and non-stocked states under a terminal item determination. Graphically, the AAC rates of change resemble relay chatter, between 2006 and 2010. In terms of acquisition analysis, however, frequent chatter can be a sign of active management and scrutiny, which is often a DMSMS deterrent, since DMSMS events often occur due to equipment not being actively monitored by analysts.

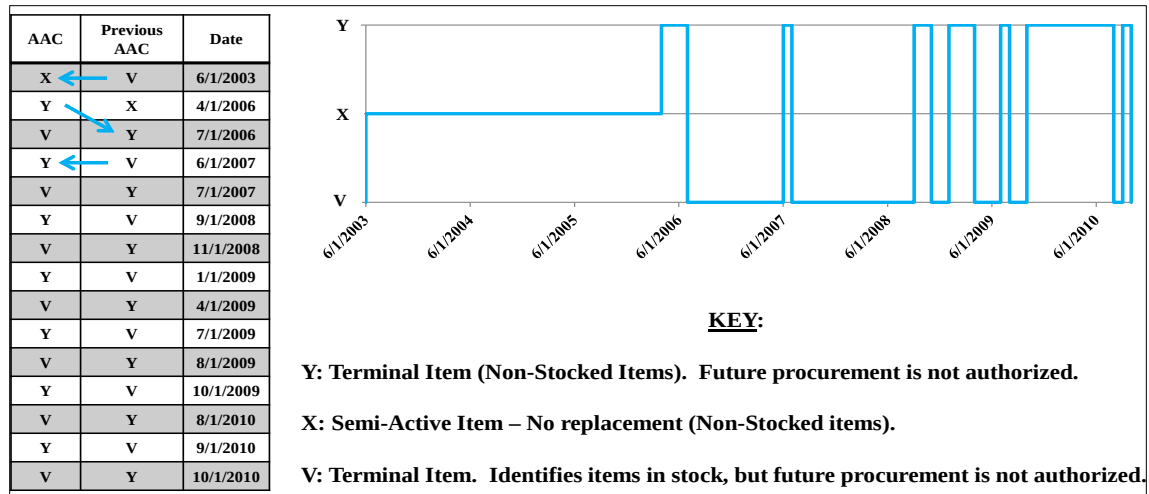


Figure 87. AAC state changes for LTV heater

The number of AAC state changes between a randomly chosen set of NIINs that became 339s was examined against a set of NIINs that did not experience any 339s between December 2001 and December 2014. This period starts with the first year for which AAC state changes were archived and commences with the year the analysis was conducted. The raw results are illustrated in Appendix E, where AAC states A-Z were coded as 1-26 along the y-axis. Figure 88 summarizes the raw results in a dot plot, where the set of 339 NIINs were coded with a 1 and the set of non-339 NIINs were coded with a 0. The non-339 NIINs encounter more cases of AAC state changes than do 339 NIINs. Again, this could be attributed to more active management of the NIIN by DLA analysts. NIINs that are under more analyst scrutiny are less apt to be mismanaged, as in the case of NIINs not assigned to a demand planner that may have stagnant, or outdated, AAC states [159, 160]. Also, all NIINs in this analysis experienced at least one AAC stage change over the period examined, proving that some level of materiel management was in place. Dot plots were used to characterize and compare the data sets, since the AAC state

change counts were ordinal. Also, after previously encountering ill-fitting normal and Weibull distributions during aforementioned attempts at data characterization, displaying the raw, individual samples as dots, vertically separated into two different panels, created a simple lens with which to graphically compare the data.

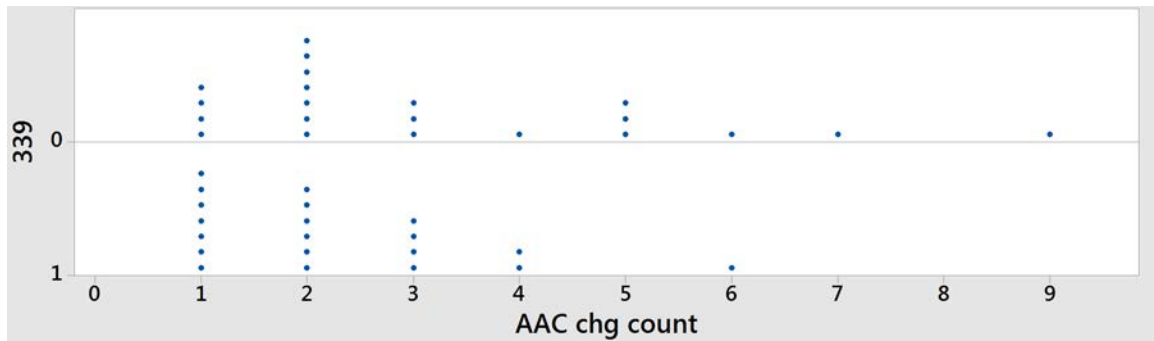


Figure 88. AAC state change dot plot

Another approach was explored that involved pre-binning the AAC states into two sub-groups (i.e. clusters), prior to plotting, to try and induce further characterization and amplify visual distinctions between 339 NIINs and non-339 NIINs:

1. The first cluster (N-Z) involved AAC states that include inherent DMSMS indicators,
2. The second cluster (A-M) involved AAC states that do not include inherent DMSMS indicators

The results of this particular analysis are illustrated in Appendix E. Note how much more the dichotomous state cluster changes stand out, when compared to deciphering state changes between 26 AACs. Figure 89 summarizes the results of the AAC state cluster change experiment. In this case, there were 5 NIINs whose intra-cluster AAC state changes resulted in a zero cluster change count. Also, the cluster change dot plot has the

effect of equalizing the 339 NIIN and non-339 NIIN data sets in terms of their AAC cluster change counts in the counts ranging from 0-3, whereas the cluster change counts ranging from 4-7 reveal even more distinction between the data sets. This is a significant discovery in the search for validation, since it relates two accurate representations of the real world within a single model: the first representation being the presence of a 339 response and the other representation being the objective count of AAC state cluster changes as an independent variable.

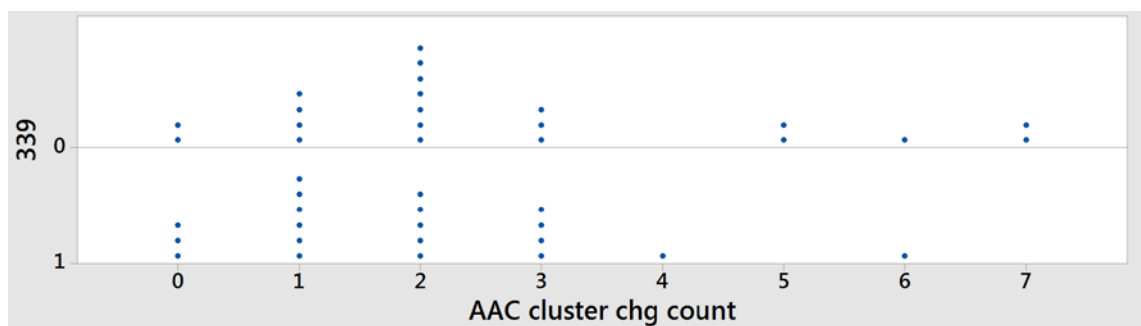


Figure 89. AAC state cluster change dot plot

Again, the use of inferential statistics to determine whether the AAC state cluster change count distribution of 339 NIINs is statistically different from that of non-339 NIINs was not warranted, since the data did not follow known distributions. Figures 90 and 91 show the failed fit test results for the AAC state change data sets and the AAC state cluster change data sets, respectively. An attempt at a Weibull fit on the AAC state cluster change distributions was not possible, due to the presence of some zero value cluster changes. Overall, applying the AAC state cluster change characterization method shows promise. Perhaps collecting more samples under future study could either: 1) produce resemblance to known distributions, warranting use of inferential statistics or 2) add confidence to observing a difference in distributions, by mere eyeball test.

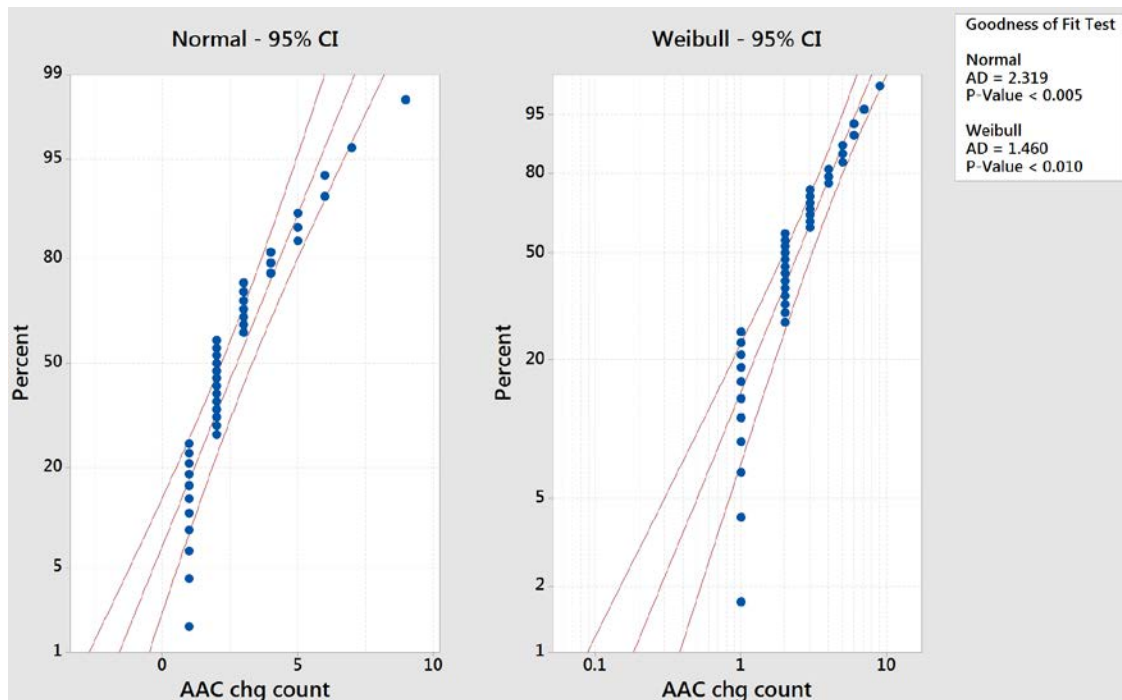


Figure 90. Probability plots for AAC state changes (normal vs. Weibull)

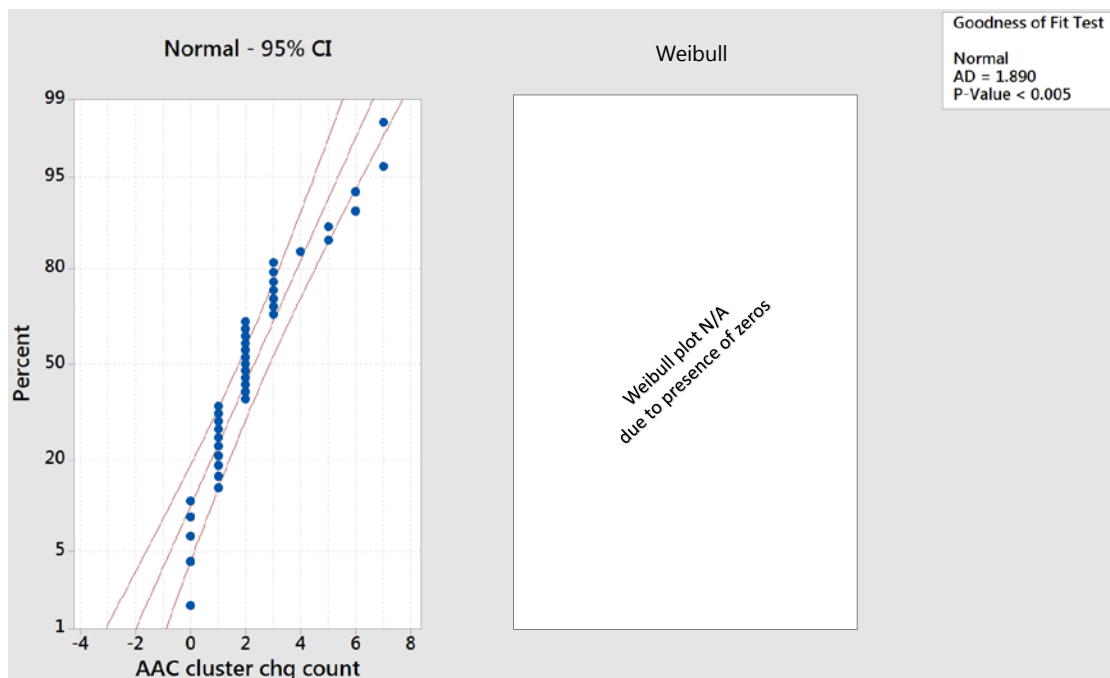


Figure 91. Probability plots for AAC state cluster changes (normal vs. Weibull)

4.2.1.3 Characterizing 339 Resolution Time as a Response

Instead of dwelling in correlation analysis that only involves a reactive DMSMS response that is discrete, such as a NIIN experiencing a 339 event or not, validation using a continuous, reactive DMSMS response was desired. Therefore, a continuous response that correlated to a 339 event was researched. It was found that some teams of analysts record the man-hours spent resolving 339s assigned to them. Therefore, if a NIIN never encountered a 339 event, it would not have any man-hours of 339 resolve time associated with it. Therefore, a source of continuous man-hour data was discovered that exhibited 100% correlation with a sample of dichotomous 339 events under the respective team's domain of platform NIIN responsibility. Again, a dot plot was used, as shown in Figure 92, to initially view the distribution of the candidate response, prior to attempting a fit of the data to a known distribution. The sample of time spent resolving 339s included outliers that were orders of magnitude greater than most of the sample, as in the 339 cases of Figure 92 that were recorded as taking over 80 hours to resolve. Personal experience in resolving 339s supports this occasional phenomenon.

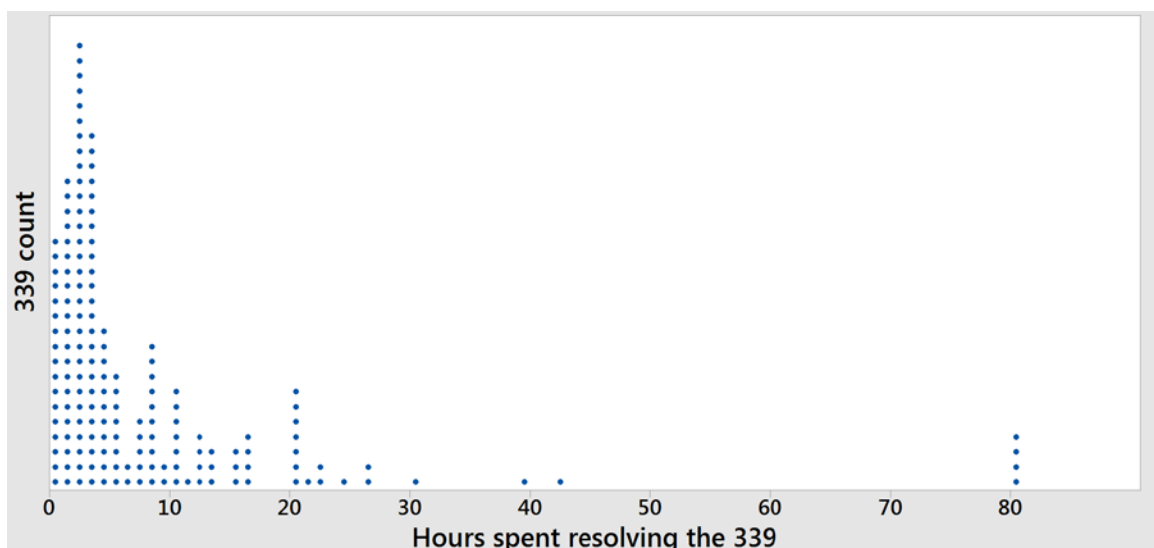


Figure 92. LTV dot plot of 339 hours

Even though the discovery of continuous DMSMS response data was encouraging, multiple attempts to characterize the dot plot of Figure 92 under known distributions failed, as shown in Appendix F.

Although there is no indication that higher risk situations consume more resources to mitigate than lower risk situations, a possible correlation between the two continuous responses introduced in this research (i.e. 339 resolution time and Total Weight or RPI) was tested, as shown in Figure 93. Total Weight was used as the predictor in this case, instead of RPI, because the 339 hours were originally associated with summed flag scores. The distinction is transparent, since the two metrics are proportional to one another. Unfortunately, no correlation was found here either (R-squared = 0.00%).

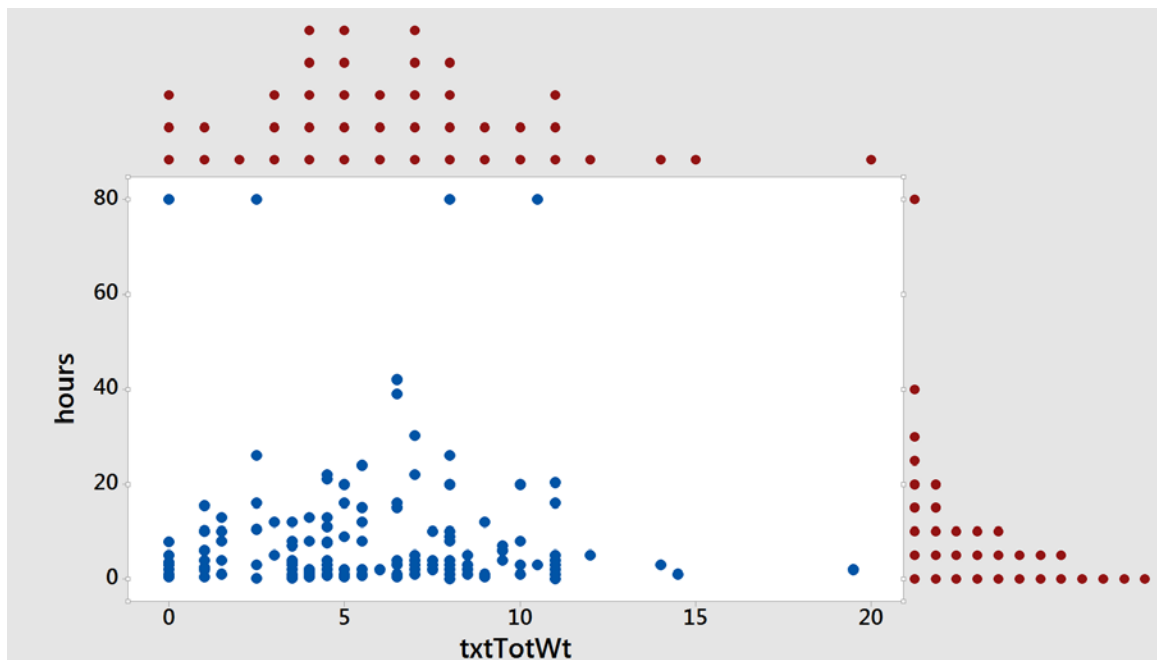


Figure 93. LTV marginal plot of 339 hours vs. Total Weight

The lesson learned during this portion of the research was that the marginal plot serves as an efficient visual analytic. This is due to the marginal plot's ability to display the dot plots of each factor on the same figure as the regression itself. Adding fit statistics and curve overlays could improve on this efficiency even further.

4.2.2 SERA Factor Dimensionality Reduction

Since multiple attempts at regression between SERA factors and DMSMS responses proved unsuccessful, a principal components analysis (PCA) was performed on the SERA flags to determine whether a dimensionality reduction was warranted. In the context of the SERA, this translated to replacing the group of existing SERA flags with a new measurement system. The new measurement system features a reduced set of orthogonal “superflags” that are linear combinations of the original flags. Because there are less flags capturing the same amount of variance, the superflags are considered to be an improvement to the overall assessment facet of the SERA. The superflags “are thought to reflect underlying processes that have created correlations among variables” [145, p. 612]. This new measurement system made possible with PCA also offers a cascade of mutually orthogonal axes that are rank-ordered in descending order of largest variance of superflag scores. The PCA design corresponding to each subsection of a sensitivity analysis containing four factors is shown in Figure 94. The first factor encompasses the three platforms that were studied: LTV, Bradley, and Abrams. The second factor included two different domains of independent variables: one that included the 339 event response as an independent variable and the other which did not. This was done as a sanity check to see what effect inherent noise would have on the results. The third factor represented another sanity check to see what effect inherently correlated independent variables would have on the results. The final factor included the two ways with which to deal with missing data (i.e. blanks): one level replaced all blanks with the low level of each flag (i.e. zeros) and the other level replaced all blanks with the high

level of each flag (varied from 1 to 5, depending on flag type). The PCA results for the entire sensitivity analysis, including the full factorial of treatments, reside in Appendices G through I. Figure 94 highlights the treatment thread, in green, that produced the model of representative superflags. An explanation of how the PCA ran best for the green-highlighted treatment thread follows.

1. The LTV SERA risk matrix containing 61 attributes for each NIIN was exported to a 9670 X 62 array with NIIN labels residing in the first column.
2. A column was inserted that contains the dichotomous 339 response for each NIIN that assigns a 1 to NIINs that have had 339s in the past and a 0 to NIINs that have not.
3. The array was filtered to retain only the columns of flags that are inherently independent from one another, resulting in a 9670 X 11 array. The reason for this was to remove as much covariance noise from the set of independent variables as possible. For example, retaining inherently dependent flags like: a) No Demand in Past 3 Years and b) Top 10% Open Maintenance Work Order (MWO) in past 12 Months for Non Mission Capable Items would only introduce unnecessary aliasing into the model, since a demand would have to be present, in order for a subsequent MWO to even exist.
4. Missing flag sub-scores in the array were replaced with zeros (the low level of all dichotomous flag sub-scores).

5. The dichotomous 339 response was excluded from the PCA-targeted array, but was used as a color grouping to see whether the new superflags could help distinguish 339 NIINs from non-339 NIINs.

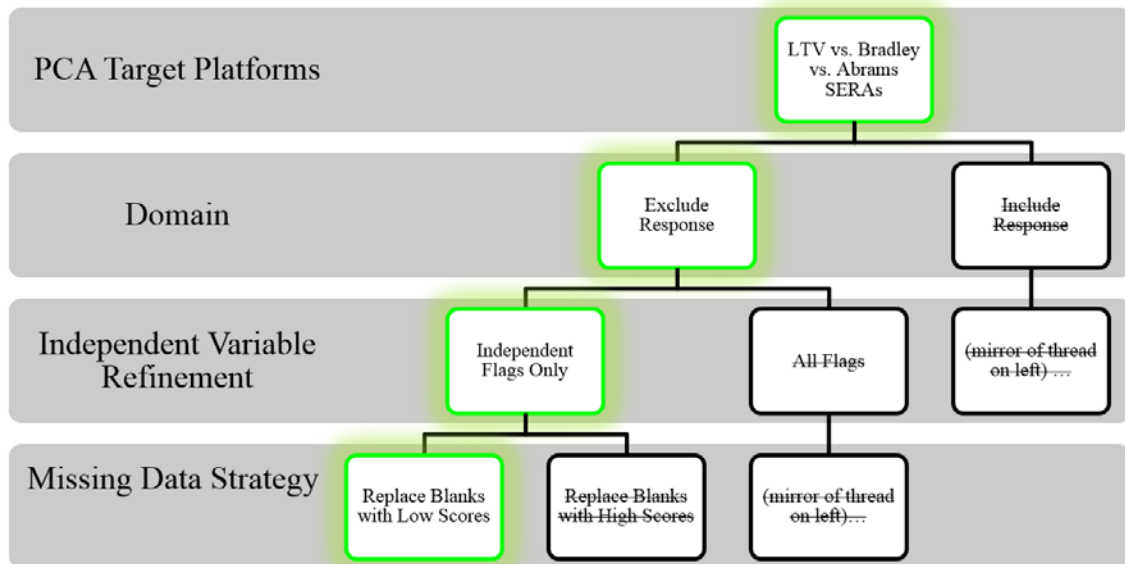


Figure 94. PCA design

The PCA identified four principal components that represented a cumulative contribution ratio threshold of 80%, as shown in the Pareto chart of Figure 95. This research set the threshold at 80% to represent the top principal components, similar to other researchers using PCA for dimensionality reduction [161, p. 424]. In other words, the top four principal components represent the characteristics of the original data enough to account for 80% of the total variance of all the principal components, as measured on the secondary y-axis. In comparison to the ten incumbent SERA flags that served as the baseline for this experiment, reducing the dimensionality down to four superflags is an improvement.

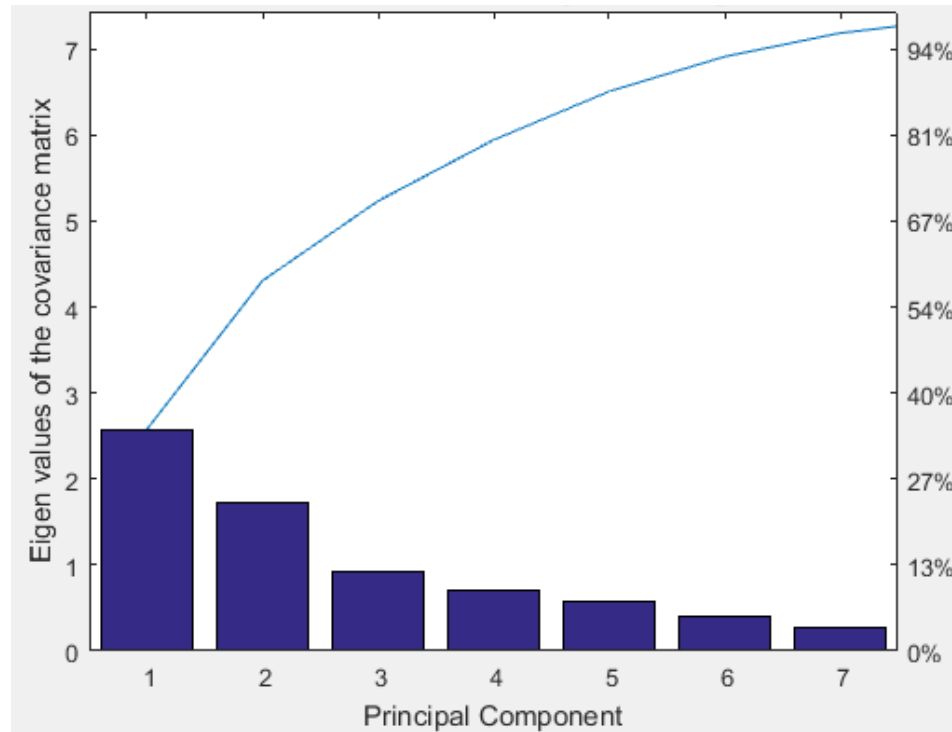


Figure 95. Contribution and cumulative contribution ratios excluding dichotomous response on only the flags that are inherently independent and blank scores set to low level

The corresponding 3-D plot of the principal component scores relative to the top three principal component axes, representing 35%, 23%, and 12% of the variance, respectively, is shown in Figure 96. The set of scores that represents the 339 NIINs (shown in red but hardly visible) shows no visual separation from the set of scores that represents the non-339 NIINs (shown in blue). Although the superflags represent the SERA risk variance more efficiently, their practicality is limited if they cannot help predict DMSMS events.

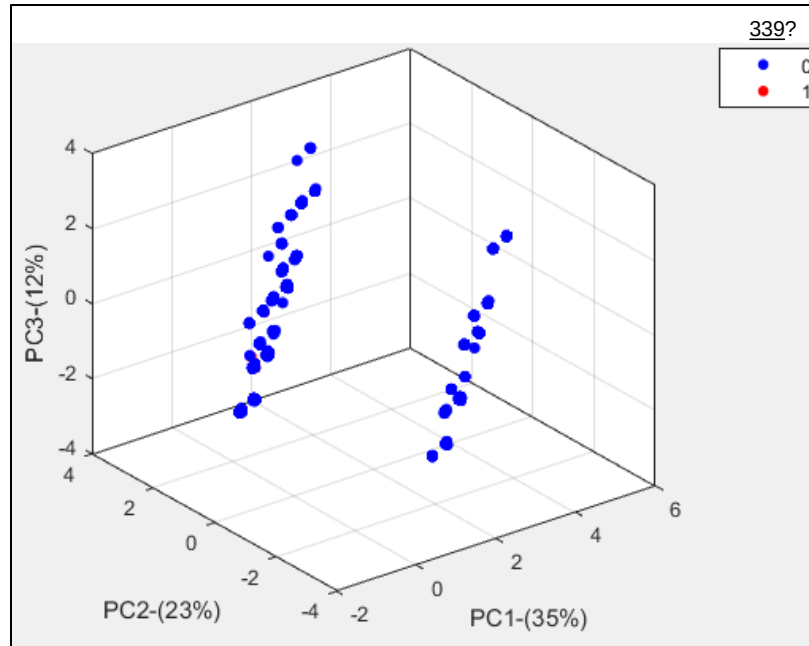


Figure 96. Principal components scores excluding dichotomous response on only the flags that are inherently independent and blank scores set to low level

The overall PCA sensitivity analysis is summarized in the Multi-vari of Figure 97, with accompanying key in Table 7. The Multi-vari displays the number of principal components required for each treatment to reach a cumulative contribution ratio threshold of 80%, as illustrated by the 24 circular symbols. The green symbol represents the overall effect for the quadrant of treatments, whereas the magenta symbol summarizes the effect of each level of factor B. In all cases, between 4 and 6 principal components were able to represent at least 80% of the overall variance. Factor C was the only significant factor found in the sensitivity analysis. This is portrayed in Figure 97 as the data markers (as measured by the vertical axis) jump from 4 to 6 principal components, as read from the two leftmost quadrants to the two rightmost quadrants (i.e. from C=1 to C=2).

Table 7. Multi-vari coding key

<u>Factor, k</u>	<u>Level, p</u>
A = Platform	1 = LTV 2 = Bradley 3 = Abrams
B = Domain	1 = exclude 339 response 2 = include 339 response
C = IV Refine	1 = filter out correlated flags 2 = all flags included
D = Blanks Strategy	1 = blanks replaced with zeros 2 = blanks replaced with flag high value

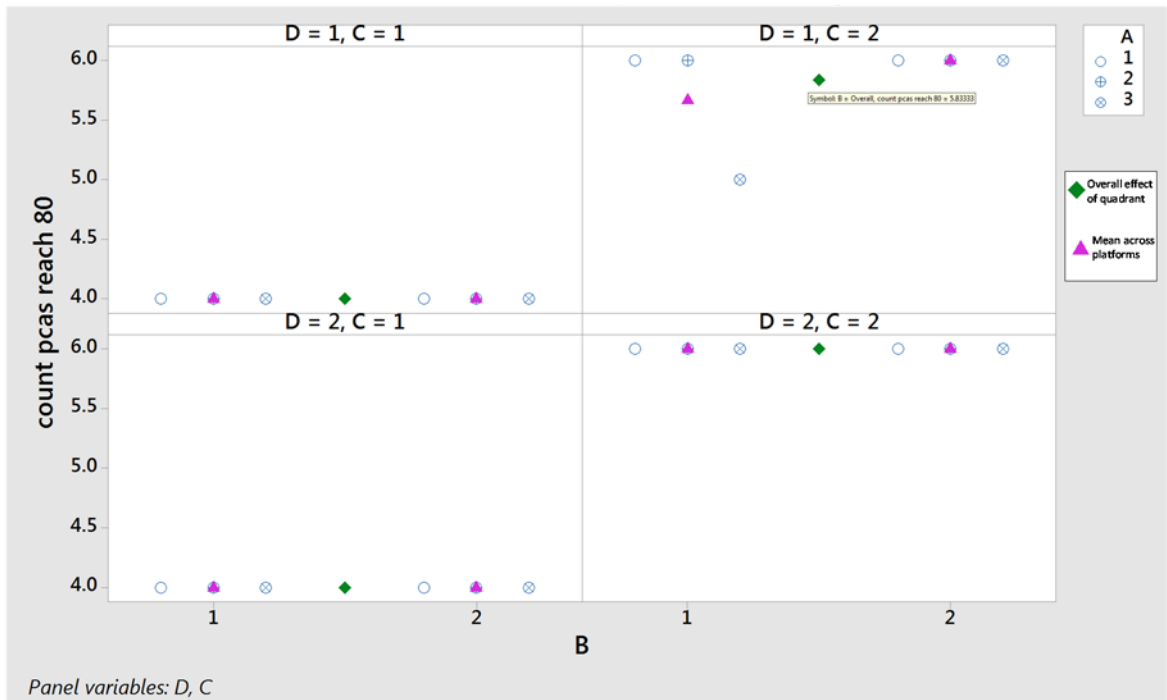


Figure 97. Multi-vari of PCA eigen value sensitivity between LTV, Bradley, and Abrams

4.3 SERA Application Conclusion

The SERA RPI does not correlate to the presence of 339s or 339 resolution time. Also, higher SERA RPIs do not favor any particular FSG, FSC, AMDF price, or AAC. More exploration is warranted, regarding how well AAC state changes correlate to the presence of 339s (or other DMSMS indicators).

Although this research did not demonstrate any DMSMS-prediction capability, the SERA is valuable in that it:

1. Provides the data to analyze sustainment support strategies moving forward and
2. Serves as an educational tool proliferating the logistics engineering philosophy across disciplines

In addition, the SERA's ability to generate a rank-ordered list of equipment RPIs does serve to prioritize and efficiently allocate risk mitigation resources. Applying the SERA to generate lists and visual analytics has been deemed value-added by the TACOM Lifecycle Management Command (LCMC), as evidenced by the fact that multiple Program Managers (PMs) have requested SERAs and SERA use is part of the Abrams Lifecycle Sustainment Plan [162].

Principal Components Analysis (PCA) demonstrated that a reduced set of SERA superflags exists that account for 80% or more of the total independent variable covariance. Plotting the scores of the superflags offers a new visual analytic with which to view DMSMS risk. Also, a sensitivity analysis confirmed that the type of platform does not influence the number of principal components, nor does the inclusion of

response noise, nor whether blank data is replaced with low levels or high levels of a SERA flag sub-score.

In conclusion, the analyses conducted in this section has advanced the state-of-the-art of logistics engineering. Equipment and industrial sources of supply have a variety of attributes that can continue to be screened for logistics patterns, using M&S. Out of 21 sustainment risk indicators in a SERA, each with three unique states, $10,460,353,203$ (i.e. 3^k) theoretically different “risk signatures” are available for exploration [163].

Experimenting with:

1. How many actual risk signatures exist on a platform and
2. How the risk signatures change over time, could still provide additional insight into pre-DMSMS behavior that could be used for mitigation, before equipment design decisions are made that lock in potentially caustic sustainment support strategies for decades.

In March 2017, a proposal to further develop the risk-versus-issue distinctions between SERA and DMSMS events accompanied an entry in the Commercial Technologies for Maintenance Activities (CTMA) Technology Competition run by the National Center for Manufacturing Sciences (NCMS) and the Office of the Secretary of Defense for Maintenance Policy and Programs. Competing in and being nominated for competitions like the CTMA Technology Competition could result in the U.S. Army achieving the same caliber of success that the U.S. Navy experienced, during their cleanup of 100% of the achievement awards at the 2015 DMSMS

Conference [164, pp. 29-33]. By elevating the scrutiny of SERA to the level of the Joint Chief of Staff of the Logistics Directorate (J4), the future direction of SERA inside and outside of TARDEC will be challenged like never before. Pending the results of the 2017 CTMA Technology Competition, an opportunity exists to fund SERA R&D into the future, while evolving SERA into more of a predictive M&S tool.

5. RESULTS OF APPLYING MODEL-BASED SYSTEMS ENGINEERING THROUGH AN ENTERPRISE LENS

5.1 Prototype Acquisition Design enabling Technology Transition

After being educated in the new assessment and analysis capabilities of the SERA, senior executives at TARDEC still often responded with: “So what?” The reason for this was partly due to leaders being anxious to start mitigating the risks that the SERA highlighted. Innovative solutions were desired to break away from the daze that sophisticated analysis often provokes. Mitigation solutions pertaining to domains beyond TARDEC, and even beyond the U.S. Army, were encouraged by TARDEC’s Chief Scientist [38]. Therefore, the following four out of five phases of DMSMS risk mitigation were taken into consideration: Identify, Assess, Analyze, and Implement, as shown in Figure 98. It is important to note that making the organic industrial base (OIB) part of the implementation design under an improved risk mitigation framework enables the DoD to leverage even more of the OIB services and capabilities referenced in Appendix F under the Analyze phase of Figure 98 [165].

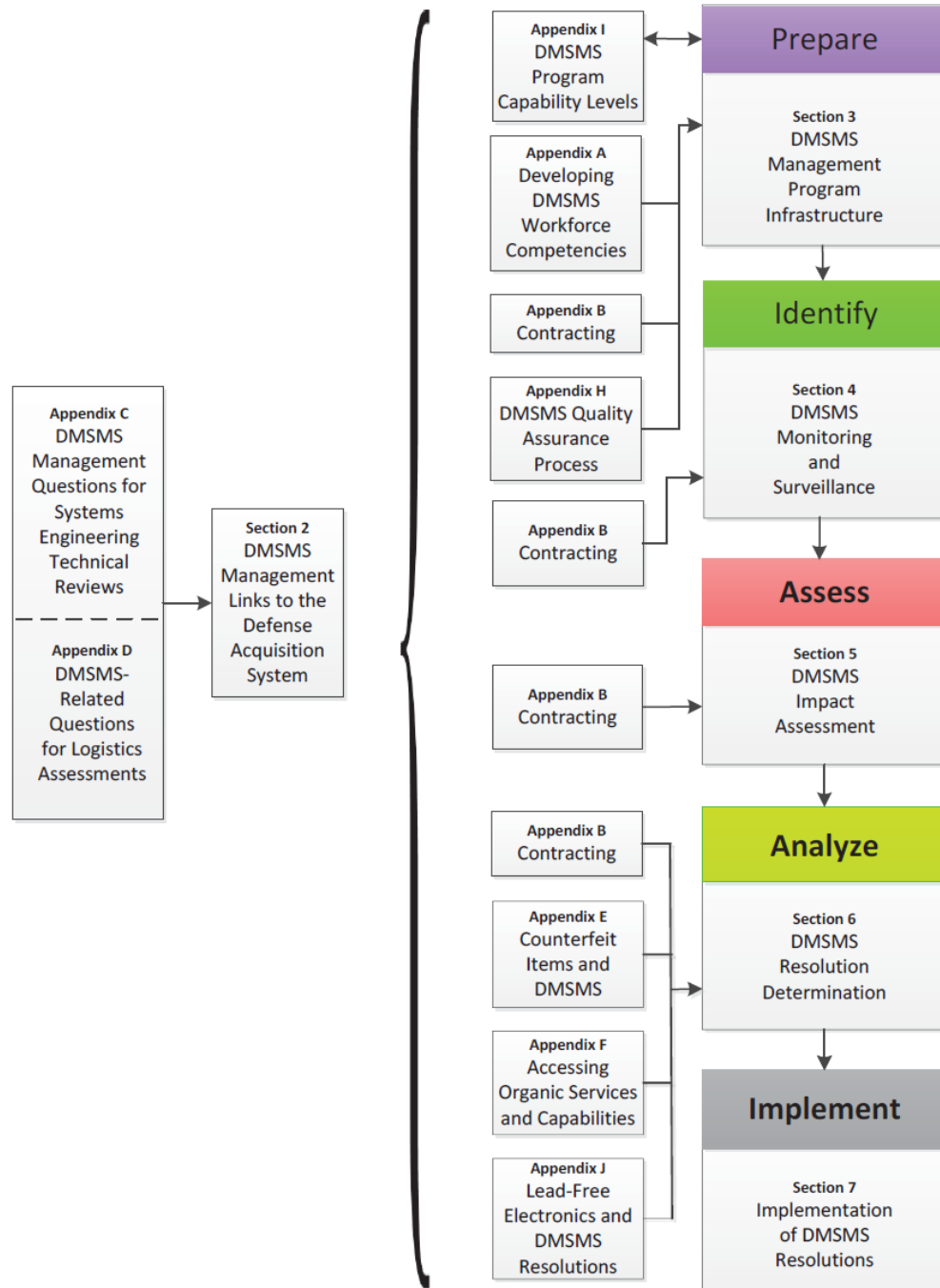


Figure 98. DMSMS risk management phases [47, pp. 12, 46]

Since contracting influences the first four phases of the DMSMS risk mitigation process and is commonly the most frustrating aspect of acquisition, it was clear that attacking the

contracting problem, under the guise of solution implementation, would provide the most added value within an R&D organization like TARDEC.

5.2 Constructing the Defense Mobility Enterprise Model

Traditional FAR-based contracting policies overly constrain the exchange of requirements and capabilities between government and industry and “restoring the face-to-face meetings between customer and supplier would result in better coordination and greater understanding of current and future needs on each side as in commercial business” [2]. Moreover, enabling university-industry research collaboration has been shown to increase innovation output and was an important aspect of establishing a new business model [166]. Choosing to continue to operate under the authority of the 10 U.S.C. 2371 Section 845 Other Transaction Agreement (OTA), like the Defense Ground Robotics Alliance (DGRA) and the benchmark Defense Ordnance Technology Consortium (DOTC), was a clear choice, since it enabled industry to be “a partner in future technology planning”, allowing “a freer exchange of information between industry and its customers” [2]. Designing an enterprise model that offered the freedom and discipline of a properly run OTA that covers a DoD-wide ground systems domain, including manned and unmanned configurations, would “ensure that the military services and industry focus research and development on competitive design and development” [2]. In fact, a senior DoD leader said that *competition* is the one word that explains why the OTA authority continues to exist [167].

Advancing key prototype acquisition tasks, upstream, before funds are even released by Congress leverages the decoupling principle in that project funding is completely decoupled from the R&D acquisition process, until an award is ready [113]. In addition, permitting a Distribution C communication environment allows government researchers to “provide draft technical requirements to industry early and involve industry in funded concept definition” [10]. Distribution C is not considered public-releasable information. Instead, it is the level of information that a government contractor typically receives [121]. In other words, a Distribution C environment permits a higher granularity of exchange of requirements and capabilities information, between the DoD and industry, respectively.

Expanding beyond the DGRA and Robotics Technology Consortium (RTC) to include manned ground systems research was desired. However, such a change constituted a new OTA and formal name changes. To boldly distinguish the new business model from the old one that involved only unmanned systems research, the name Defense Mobility Enterprise (DME) was chosen to give one name that emphasizes “mobility” as the heart of the ground domain under an enterprise lens with which to view the future of prototype R&D acquisition. Therefore, the DME encompasses:

1. The participating U.S. Government researchers and project managers (formerly called the DGRA),
2. The participating industry and academia members (formerly called the RTC), and
3. The new OTA that binds the domain, people, and process together under one legal authority

After the DME was launched, starting in July 2014, the DGRA became the Vehicle and Robotics Alliance (VRA), the RTC became the National Advanced Mobility Enterprise (NAMC) and the new OTA was coined the Ground Vehicle Systems OTA (GVS OTA), as portrayed in Figure 99.

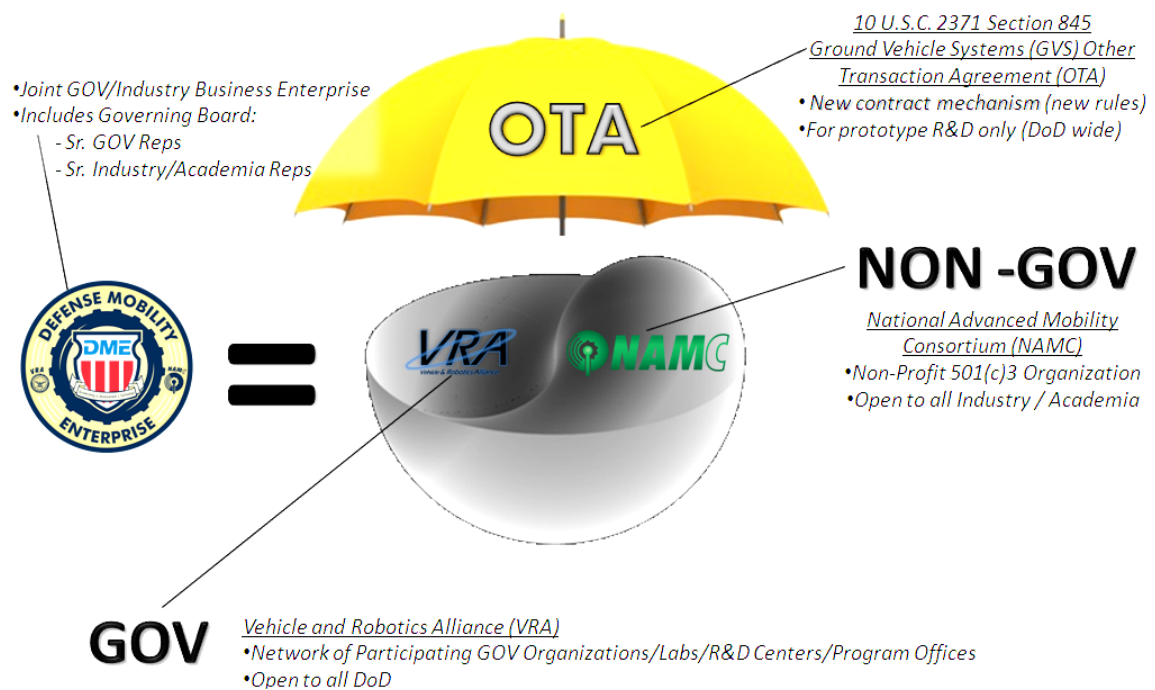


Figure 99. Defense Mobility Enterprise composition

Integrating an education aspect was one of the main objectives of the contracting model's creation. The education aspect was a lesson learned from implementing the SERA in that users will be more willing to accept a new paradigm if there is an immediate benefit to them with low investment. This lesson learned is also evidenced by the success of:

- * Apple's Genius Bar (customer service via human interaction),
- * YouTube (people's attraction for video instruction),

* The smartphone app market (enticing all ages and disciplines to constantly input data and gather information, during all hours of the day)

Coaching users through different levels of understanding and providing trustworthy and entertaining applications to simplify their experience was something that users appreciated. Users expressed their appreciation by nominating all three VRA Program Office (VRA PO) members for the 2015 TARDEC Director's 20 Award, during the peak of the educational facet of the model's rollout. DME education started during the initial seconds of introduction and a simple "back of the business card" approach to explaining the DME to newcomers was manifest, by printing Figure 99 on the back of actual VRA PO business cards. The mission was to run as many projects through the DME business model as possible, in order to quickly mature the new prototype acquisition system. With hundreds of problem resolvers working through a lean contracting model, a plethora of technology transfer solutions could be cooperatively staged, minimizing the implementation time for a particular technology transfer mitigation.

An appreciation for the aforementioned aspects of new business model implementation was gained after collaborating with Terry Lavios, app developer and founder of Lavios Designs LLC, between 2009 and 2011. Applying the lessons learned from collaborative workshops under the mentorship of Mr. Lavios confirmed that a richness comes when graphic metaphors are incorporated into models with which users have personal experience [168, 169, p. 31]. In the spirit of experimentation, DME education was purposely associated with consultation over cups of coffee. This association was

leveraged in the first level of model abstraction portrayed in Figure 100. Getting audiences to understand Figure 100 was the goal of every meet and greet. The reason for this lies in: 1) the competition and communication made possible by the White Paper Phase and 2) the strategic planning and resource allocation aspect of the Basket. Coined as the “Coffee Analogy”, Figure 100 summarizes the key points of the DME Annual Cycle process in just a few metaphors. The coffee grounds and filter metaphor emphasizes how the White Paper Phase acts as a filtration process that narrows the competition down to concentrated solutions deemed most important to DoD programs. The coffee pot metaphor associates morning beverage readiness with the OTA best practice of staging highly rated R&D project proposals in a repository, known as the Basket, for eventual consumption by the VRA community. This conceptual model supports “the design of an object-oriented system begins not with the task to be performed, but rather with the aspects of the real world that need to be modeled in order to perform that task” [56, p. 26].



Figure 100. Coffee analogy

Capturing user attention with the Coffee Analogy prompts users to zoom into the next level of model abstraction. Enticing users to be disciplined enough to follow a formal process flow, entering/exporting information to/from a single model, is the ultimate goal. The low level process flow is shown in Figure 101. The process is explained as follows:

1. A schedule of annual cycle deadlines is published,
2. The VRA announces their prototype R&D project needs/requirements to the NAMC, by entering them into the Broad Area Announcement Information Delivery System (BIDS) database,
3. The VRA and NAMC participants for a particular project are encouraged to have proprietary conversations, discussing a NAMC member's capabilities toward a particular project. NAMC members have the opportunity to submit a three page White Paper on the project to the respective VRA researcher(s),
4. The White Papers are reviewed and evaluated by the VRA researchers. NAMC members then use these evaluations, along with any feedback the NAMC member may have received during the proprietary conversation period, to decide whether investing further in the process is likely to generate a return on investment. Oftentimes, if a White Paper does not meet VRA requirements, the NAMC member chooses to forgo proceeding any further in the process. However, a NAMC member is welcome to use any constructive criticism given by the VRA, during the White Paper Phase, to realign their company strategy or make different internal R&D (IR&D) decisions to be more competitive. Since the NAMC is already a government contractor, technical conversations can be more accurate. Under traditional FAR contracting, it is unfair for the government to give specific

requirements information to a select few. NAMC membership, on the other hand, is continuously competed, open to any R&D company or academic institution that wishes to join, given they meet standard military contractor requirements, such as receiving a certified Military Critical Technical Data Agreement (form DD2345).

5. An Annual Plan is then approved,
6. The Annual Plan is then published containing all the projects that endured the White Paper phase and wish to attract full project proposals moving forward,
7. NAMC members then decide whether or not to submit full project proposals to the VRA through BIDS,
8. The VRA researchers evaluate the NAMC proposals for their respective project(s),
9. The VRA researchers select what is to be done with each proposal submitted under their project(s): a) either the proposal gets selected for negotiation and award (requiring a detailed scope of work), b) the proposal gets placed in the Basket for possible funding in the future, or c) the proposal does not get selected for funding or the Basket, due to a poor rating for not meeting requirements (rare)

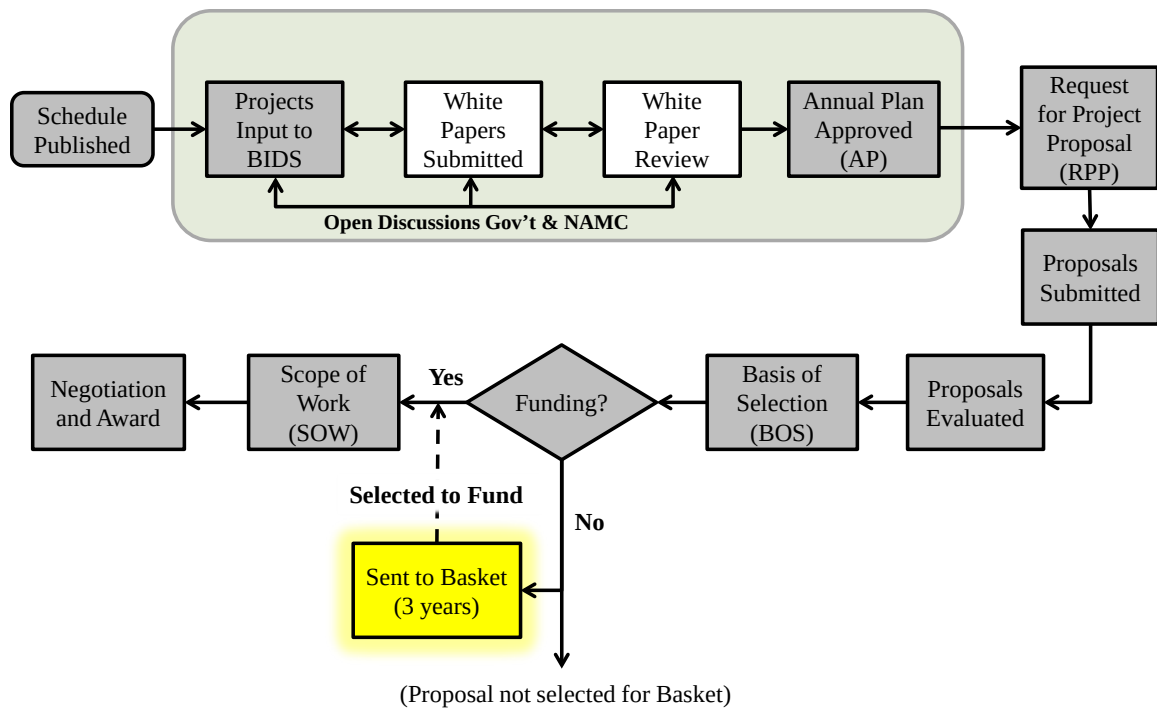


Figure 101. DME Annual Cycle process flow chart (low granularity)

A significant increase in the level of user interaction with the model occurs between the second and third levels of abstraction, or, as a user zooms into the next level of process flow granularity. Decomposing the process flow to a swim lane diagram format allows much more information to be transferred to the user, as shown in the version 5 release in Figure 102. Specifically, the DME Swim Lane Diagram tells a DME user “Who” does “What” tasks, “When” tasks are due, and “How” tasks are executed successfully. The swim lane diagram format also serves a pivotal role in establishing a model-based systems engineering environment in that it naturally depicts a roadmap of varying levels of abstraction that can be parametrically linked to other information technology (IT) systems. Also, enterprise performance metrics can start to be gathered easily, due to the definitive intervals that exist between any two steps in the process flow. The swim lanes

of Figure 102 are listed as: the Agreements Officer Representative (AOR), the VRA PO, Army Contracting Center New Jersey (ACC-NJ), the NAMC, and the NAMC member.

The milestones along the header pertain to the DME Annual Cycle schedule that was published in the beginning of the process. The individual methods for each step are taught through popup windows containing meta data that includes hyperlinks to video tutorials, templates, forms, and best-of-the-best (BOB) and best-of-the-worst (BOW) examples of completed forms, for user reference.

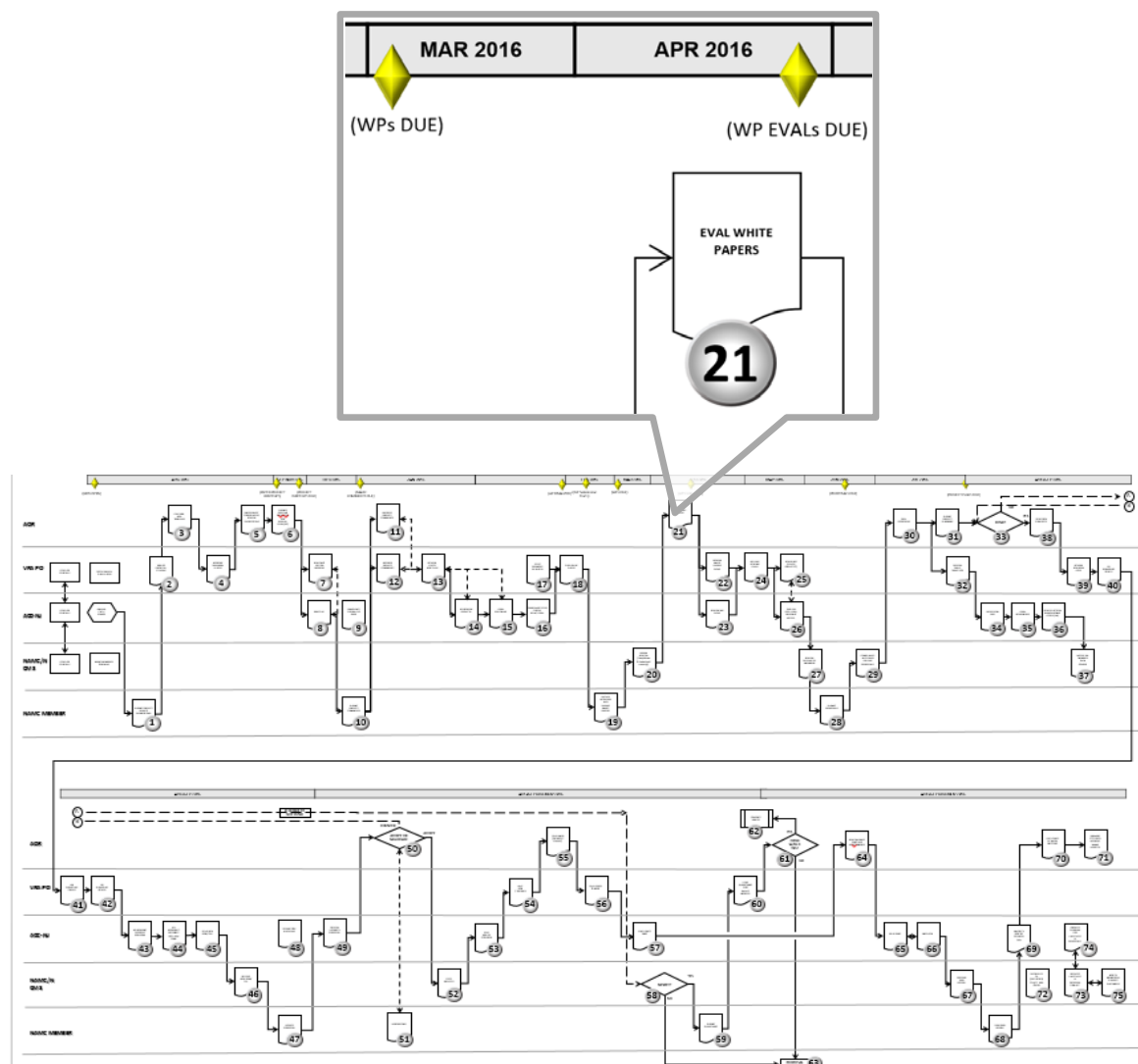


Figure 102. DME Annual Cycle Swim Lane Diagram (high granularity)

The use of milSuite, a government-off-the-shelf (GOTS) application referenced in Chapter 2, provided the capability for mass distribution and secure communication of the process. A screenshot of an embedded training video that was launched from within a previous release of the DME Swim Lane Diagram is shown in Figure 103. The extensive use of milSuite tapped into the association that many users already had with social media, actually permitting users to seamlessly travel from a macro-level space towards a low-level space within a single DME framework - a key systems engineering aspect discussed in Chapter 2 and recommended in the literature [170]. Working with users and monitoring their throughput and productivity was an insightful experience as to how ready the community is for a parametric infrastructure.

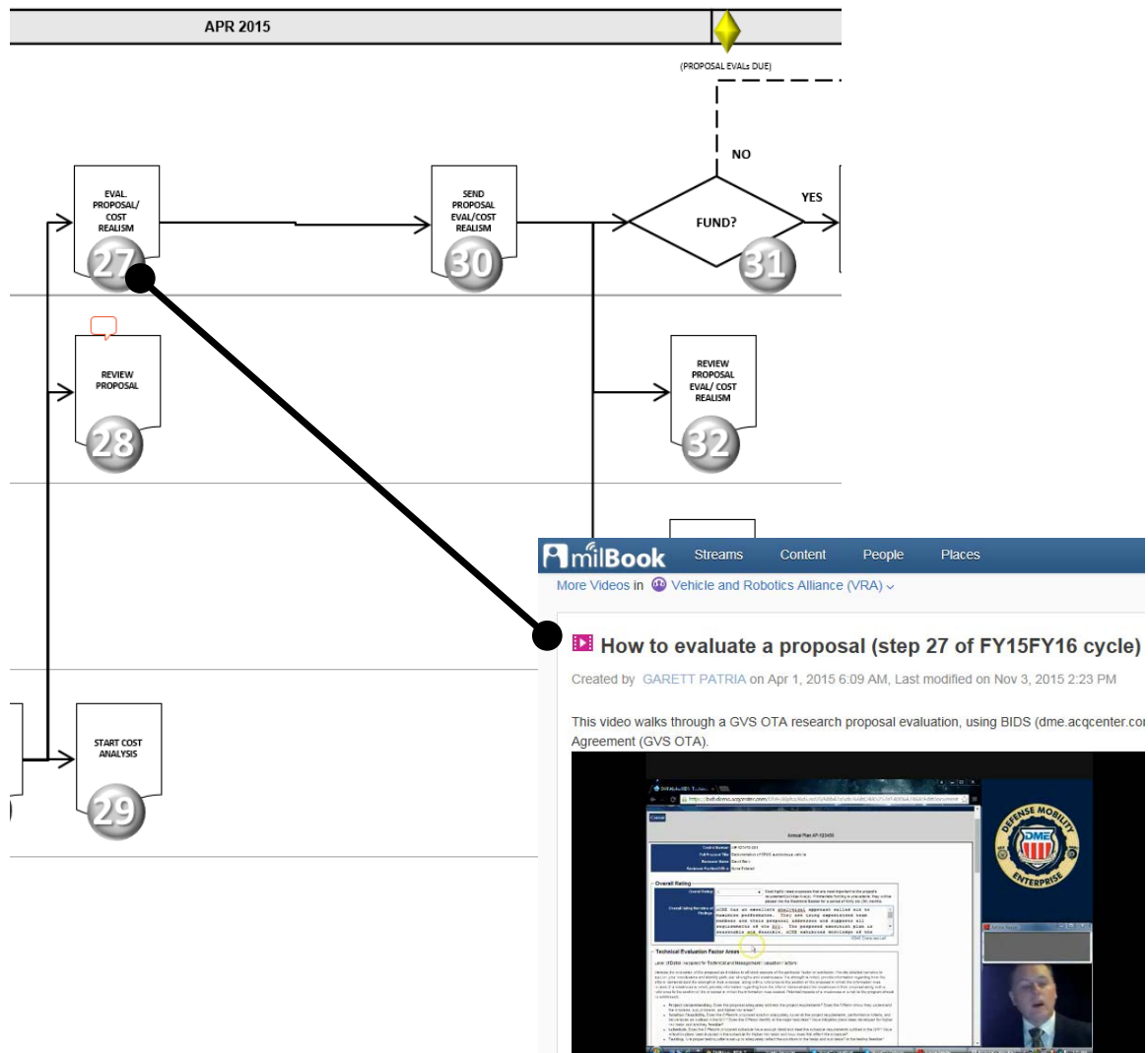


Figure 103. Training videos parametrically linked to DME Swim Lane Diagram tasks. BIDS interface used with permission.

The fourth level of model abstraction created was the discrete event simulation (DES) designed to be generated from the same Visio source file that exports the DME Swim Lane Diagram to PowerPoint. It is important to note the extensive use of commercial-off-the-shelf (COTS) software, like PowerPoint, with which users are already familiar. Figure 104 illustrates the work in process (WIP) queue that sits on top of the proposal evaluation module (step 27) within the DES model. Animating each R&D project as its

own entity traveling through the flow, advertising stagnation at the bottlenecks, and displaying the calendar date ticking away in the foreground helped realize the capacity of the new acquisition system’s pipeline. This confirmed that “visualization is the major contributor to a model’s credibility, which in turn leads to acceptance of a model’s numeric outputs” [171]. Together, the swim lane diagram format and the DES animation encouraged visual kaizan, so that throughput and productivity could be optimized [172].

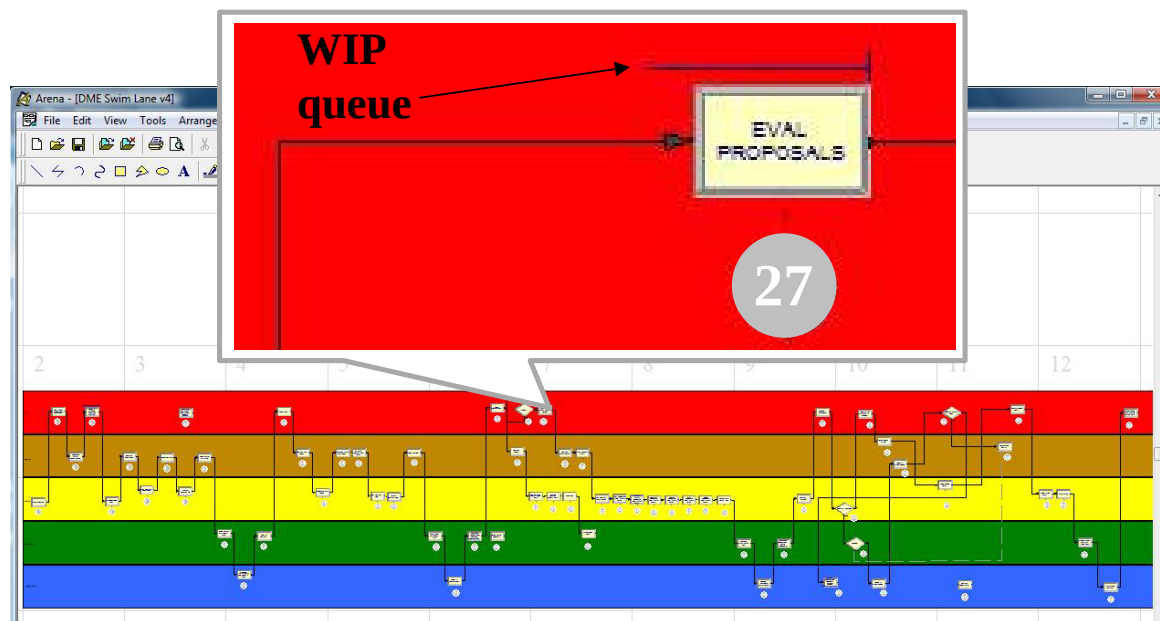


Figure 104. DME DES model

Many other interfaces were conceptually modeled as parametric I/O to COTS software, common in most office environments, as Figure 105 illustrates. The upper left thumbnail of Figure 105 shows a portion of the list of R&D projects in the DME pipeline, where each project is managed by color coding it by who (i.e. which swim lane) is responsible for advancing the project to the next step in the flow. This list is reviewed formally twice per week in teleconferences which include the VRA PO, ACC-NJ, and NAMC. In this example, the projects highlighted in the tan colored rows of the spreadsheet correspond to

Under the DME, resource allocation begins when VRA participants input their project funding forecast, along with confidence levels corresponding to each fiscal year (FY), as shown in Figure 106. The biggest difference with the DME system when compared to traditional FAR contracting is that most of the process tasks are completed in the fiscal year prior to when the project funding is released by Congress. For example, an FY16 Annual Cycle would begin around the FY14/FY15 transition, so that high value projects would be already staged by the summer of calendar year (CY) 2015 (i.e. before FY16 begins on 1 October 2015). This is not to say that FY15 funds cannot be used in an FY16 Annual Cycle. It just means that when the true design intent of the DME process flow is followed, it is possible to obligate funds in the beginning of the fiscal year in which they are released. In addition, for cases when there is expiring funds, the DME process flow advances the contracting work so far upstream, that the expiring funds can be obligated within a few months.

File Edit View Favorites Tools Help

BIDS
BAA Information Delivery System

Home | To Do List | Annual Plan | Submissions | Search | Logout

Cancel

New Requirement

Research Requirement Information

Status	Draft	
Annual Plan	AP-123456	
Research Area	Mobility	
Requirement	Not yet assigned	
Requesting Govt. Organization		
Title		
POC	Click to Add POC Not yet assigned	
Alternate POC	Click to Add Alternate POC Not yet assigned	
Funding	Funding	Confidence Level
FY14: \$		--Select One--
FY15: \$		--Select One--
FY16+: \$		--Select One--
Summary	Click to Display Definition of Other Transaction Agreement	

Please overwrite this verbiage with a paragraph or two summarizing your research interest and requirements that you want published in the Annual Plan to which interested Consortium Members will respond with white papers and , eventually, actual project proposals. At the end of this Summary field, list the importance of the eight Technical Evaluations Criteria categories on which you will be evaluating project proposals (e.g. Technical is more important than Past Performance which is more important than Schedule which is more important than Cost which is more important than Data Rights. Risk Realization/TRL, Management Area, and Supportability/Maintainability are all equal and are deemed as minimal importance).

Figure 106. BIDS user interface for project formulation. Used with permission.

BIDS output feeds the DME DES and the improved resource allocation visibility that results, by time-stamping the project milestones, as shown in Figure 107. The intervals between any two milestones were collected to build cycle time distributions for various taxonomies, such as Research Area, agency, and VRA researcher experience. The library of distributions served as simulation treatments in the DME DES that were used to observe process bottleneck sensitivity to incoming variation. The DES animation aided in upper management’s understanding of how projects can take so long to get through the pipeline, since many leaders “often misunderstand the fundamental functions of engineering systems and tend to use the average values of engineering characteristics with little enough thought given to variation effects” [173].

Edit History			
Date	Time	User	Action
09/01/2015	8:03:13 PM	Garett Patria	Created Project
09/01/2015	8:10:03 PM	Garett Patria	Submitted Project
09/01/2015	8:22:24 PM	Garett Patria	Rolled back to Draft. Reason: test
09/01/2015	8:30:50 PM	Garett Patria	Submitted Project
09/02/2015	7:10:33 AM	Garett Patria	Removed this project

Figure 107. Example of time-stamped project milestones in BIDS. Used with permission.

The contracting process intervals can be scrutinized even further in a parametric modeling environment, making the process as lean and disciplined as possible.

Constantly refining timing estimates and feeding back actual time-stamp-based intervals into the DES is an important piece of continuous improvement. Permitting the DES to read estimates from (and export allocations to) the daily calendars of team members is one way to involve users who do not normally engage in M&S activities, as illustrated in Figure 108. In this example, the DES accepts task time input that, in order to have a high probability of timely completion, should correspond to resource allocation, such as an appointment in a task owner's electronic calendar. A mature model-based infrastructure would establish a handshake between the DES and employee calendars.

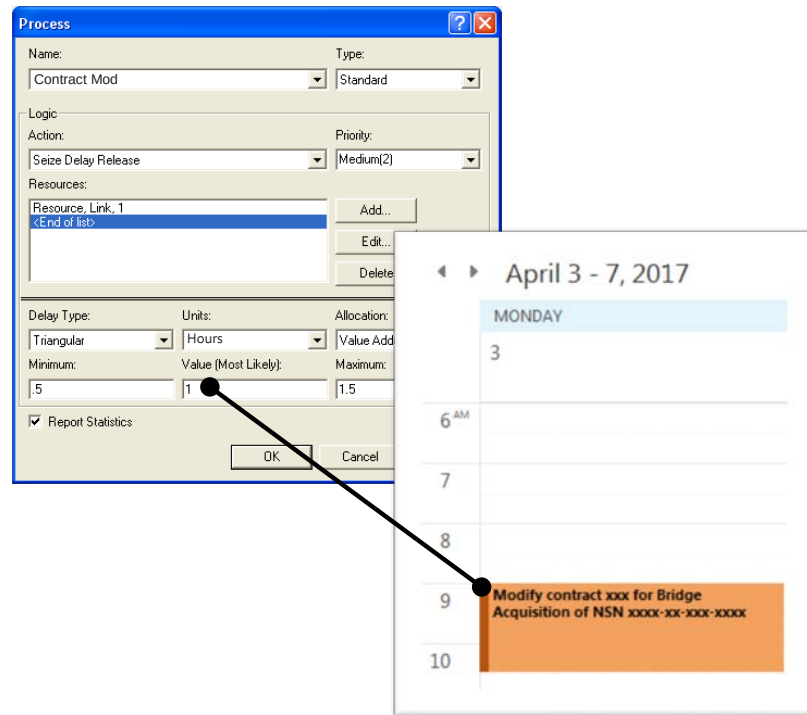


Figure 108. Linking M&S I/O to calendar appointments

Experimentation with how DME scheduling efficiencies effect project status, or swim lane color states, was conducted and a value add (VA) analysis was done on the VRA swim lane. Figure 109 shows the spreadsheet interface that was rolled up into the Schedule module of the DES to observe the behavior of a ten person VRA PO, occupying a swim lane of responsibility, in accordance with a RACI chart, and in synch with actual goals that include overhead work considered non value add (NVA) to DME. The interface of Figure 109 displays: 1) the working hours applied to DME project execution in green and 2) out-of-office (OOO) downtime and hours applied to overhead-type tasks in red. The variable, p , denotes the typical, first shift working hour window, where employees experience the highest influx of DME swim lane tasks for which they are responsible for executing. As can be seen from the figure, the first two employees in the

initial columns, labeled as RACI 1 and RACI 2, apply many more working hours to DME project execution than the other employees, as demonstrated by more green in their respective columns. Reasons for this disparity in value added work output are due to attributes such as work ethic, discipline, resource management, and commitment to the mission.

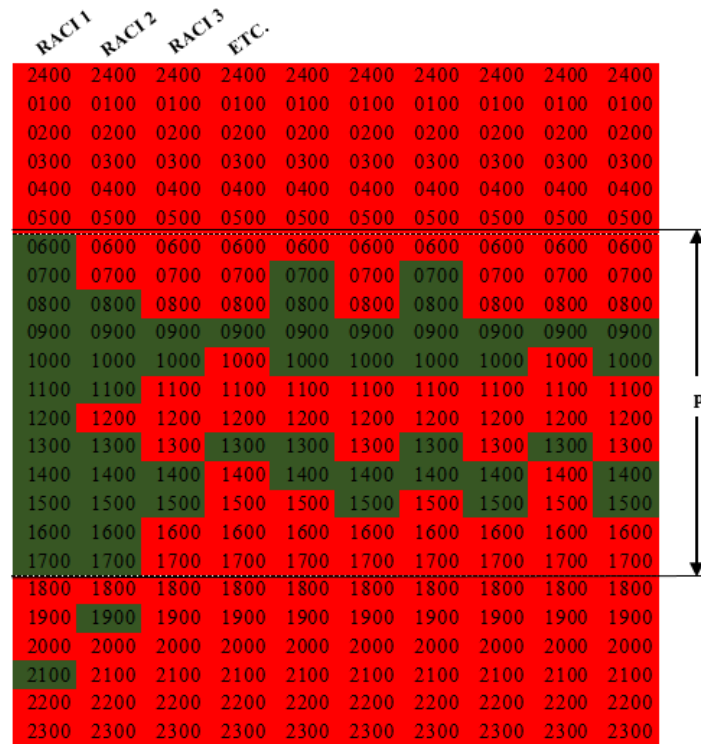


Figure 109. Value-add working hours based on RACI

It was not until the time availabilities of Figure 109 were graphed that the inefficiencies of running a traditional, first shift VRA PO were revealed. Figure 110 shows the results. In this case, the VRA PO was found to only be available to execute their swim lane and RACI responsibilities 23% of the time. After applying effectivity weights to each VRA PO staff member, the effect that performance had on Figure 110's depiction of mere effort was considered to be the true, value add time per day of the program office. This

time was estimated at only 16% of ideal capacity, after taking into consideration attributes such as VRA PO staff member experience and track record of successful work output. In summary, the unveiling of waste and resulting sidebars of resource allocation improvement ideas, brought forth during the construction of the DME model, confirm that model-based systems engineering practices provide value.

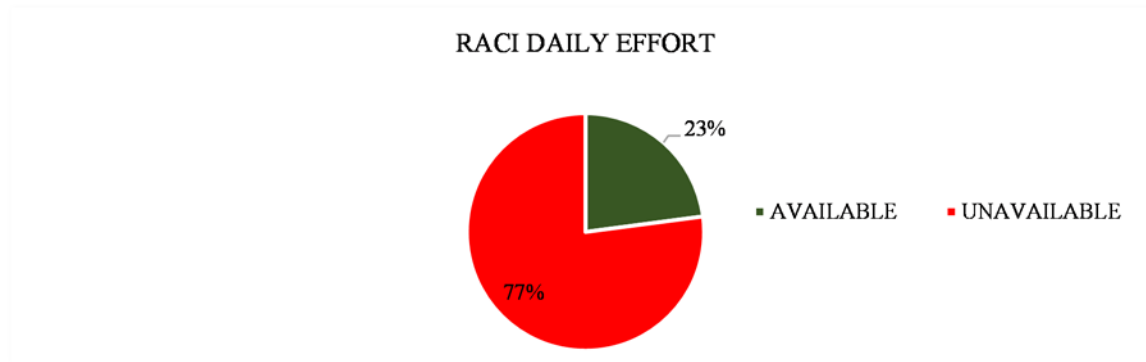


Figure 110. Swim lane capacity in terms of VRA PO availability

5.3 Linking the DME to Sustainment Modeling

The lines of demarcation between a proactive support strategy and a reactive one become blurred when designing a framework like the DME to be used for DMSMS risk mitigation. Creating policies and aligning resources, so that managers can be more agile under reactive circumstances, are deemed as proactive behaviors. For example, being subject to Congressional funds two months before the funds expire brings about a reactive situation, just as does being the recipient of a DLA Form 339. However, channeling the reaction through shopping the DME Basket to either: 1) swiftly obligate expiring funds or 2) kickoff a prototype procurement of substitute equipment that

demonstrates a new technology, simply capitalizes on agile DME provisions established under proactive intentions.

The most important link to make between the DME and sustainment modeling is the connection between incumbent equipment that is subject to DMSMS risk and any corresponding R&D that could result in technology transfer to mitigate DMSMS risk. In addition, educating researchers to look at R&D through an equipment sustainment lens, while getting logisticians to look at sustainment activities through a future technology lens is paramount. Therefore, getting VRA participants used to making the association up front is a major aspect of the conceptual sustainment support strategy model. As Figure 111 depicts, BIDS mainly categorizes DME projects by the Research Areas listed horizontally as tabs along the center of the figure. The Research Areas are: M&S, Autonomy, Collaboration, Platform, Powertrain, Mobility, Survivability, Petroleum and Water Systems (PAWS), Architecture/Security/Modularity (ASM), Payloads, and Testing & Evaluation (T&E). Forcing VRA researchers to click on an Incumbent Equipment button (emphasized by the red arrow in Figure 111), during project entry, pulls in the sustainment aspect via the SERA. VRA researchers then select surrogate equipment that relates the deliverables of their R&D project. The equipment in a SERA includes many attributes, like Federal Supply Class (FSC), which could serve as “technology watch” links, between the sustainment world and R&D world.

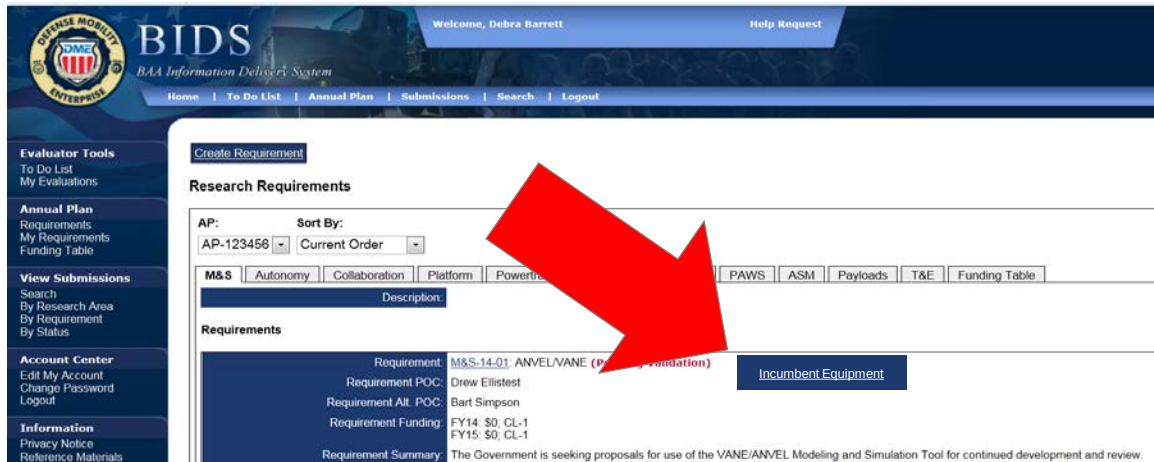


Figure 111. Incumbent equipment input in BIDS. Used with permission.

The technology watch link inside the SERA is illustrated in Figure 112. The SERA uses the visual analytics of the Microsoft Access Relationships interface to depict the hierarchical relationship between various equipment attributes. As an example, the table labeled tblNiin contains multiple data elements, including the NIIN itself. Any one of the data elements in tblNiin has a “many-to-one” relationship with the data elements of the table labeled tblFSC (as depicted by the line segment connecting the two tables labeled with an ∞ and a 1). This makes sense, because a single FSC has “many” NIINs associated with it. The FSC is preceded by the Federal Supply Group (FSG), which is just the first two digits of the FSC and serves as a parent taxonomy. The relationship that the current AAC state table (tblAAC) has with each NIIN in tblNiin is shown in the upper right corner. The relationships captured in this interface can serve as a precursor to getting analysts to start associating risk mitigation classifications, like DME Research Areas, to the sustainment domain moving forward.

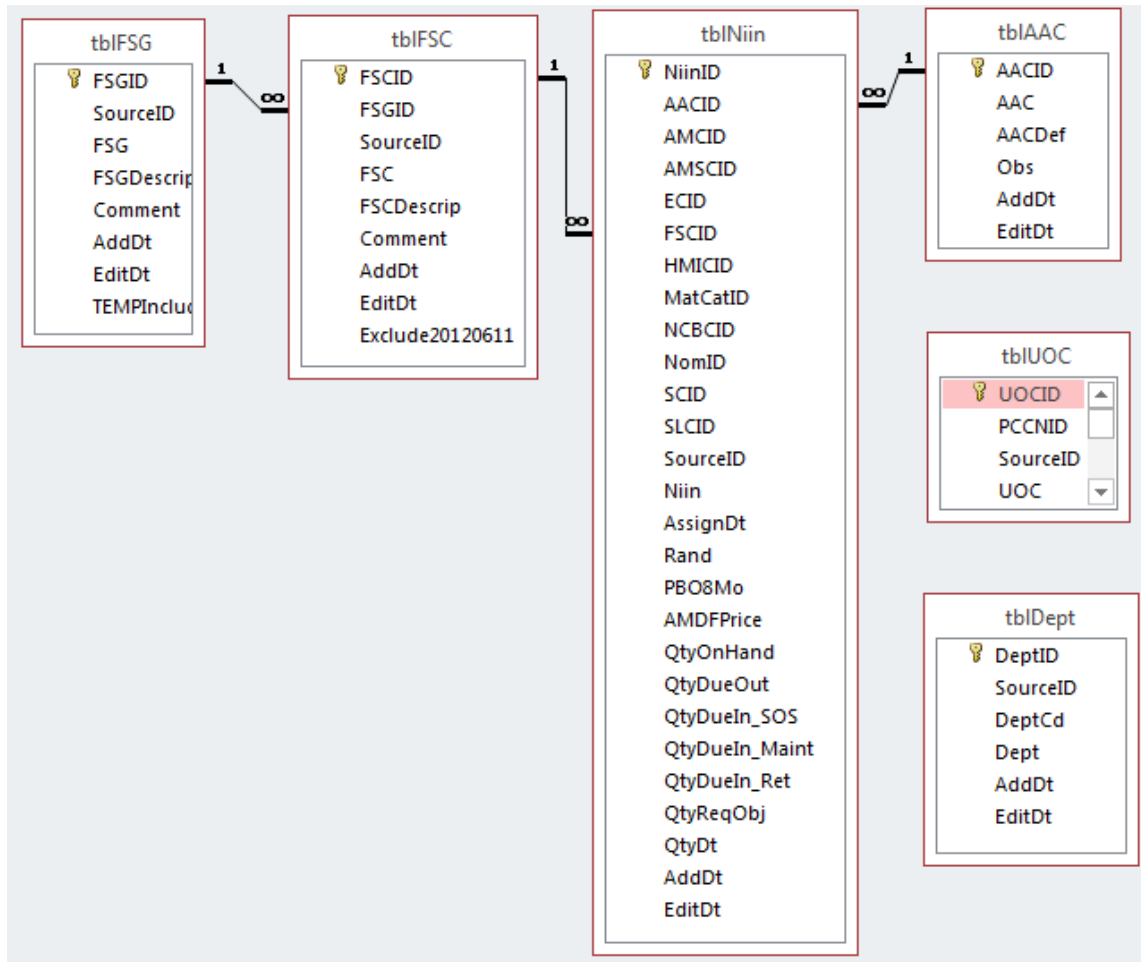


Figure 112. Relational tables of a SERA showing attribute connectivity

Capturing the concepts and relationships presented so far in a SysML backdrop, such as a Parametric Diagram, is shown in Figure 113. Recall from section 1.3 that the objective function of the conceptual support strategy model is to maximize MITS LACK, whose relationship to its t_{DMSMS} and t_{MIT} inputs is defined in the first module on the left of the figure. Following the t_{DMSMS} input thread leads to the lower constraint module where t_{DMSMS} is defined. In this concept, t_{DMSMS} is defined as a function of RPI and two other SERA attributes (denoted by r_{pi} , r_{20} , r_{21} in the figure). The constraint module at the top center of the figure defines RPI as a function of the sum of SERA flag sub-scores

normalized over the maximum possible RPI that an NSN can witness, denoted by r_{max} . Finally, Figure 113 shows how an instantiation module on the right side of the diagram populates variables with assigned values from an external block module (not shown).

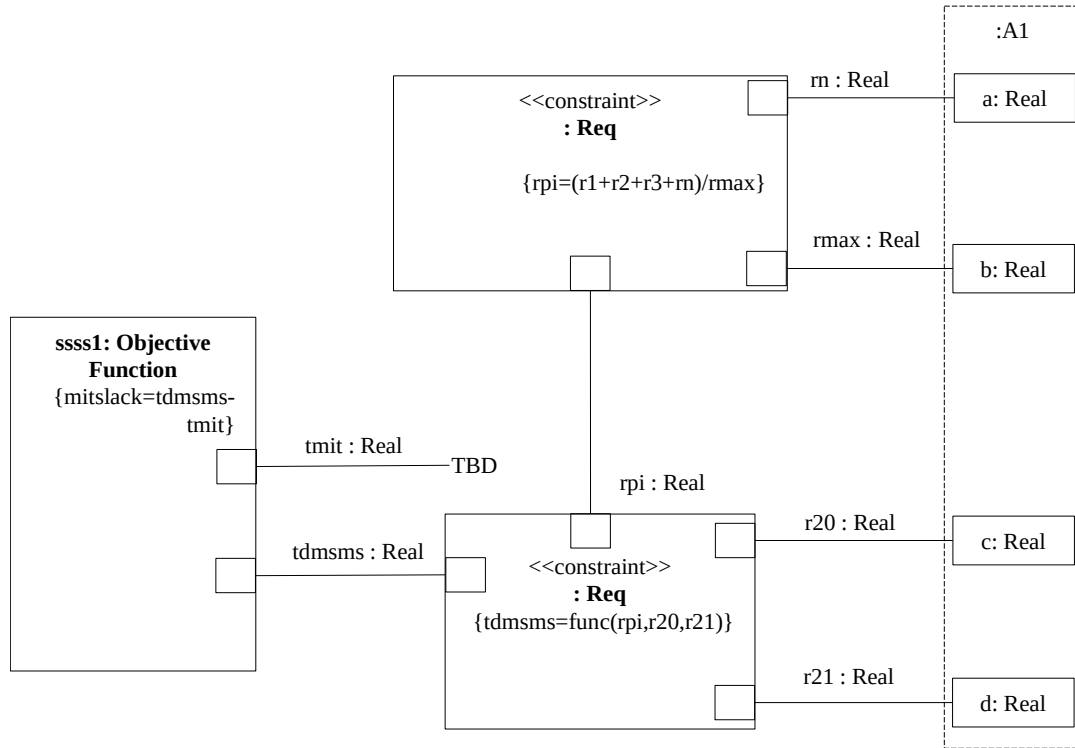


Figure 113. Parametric Diagram relating sustainment and acquisition

5.4 Validation

The adage of “you cannot improve what you do not measure”, coupled with aggressive implementation, has provided the objective backbone for this research, discriminating between true business performance improvement and mere conjecture [63, pp. 109-110, 126, 147]. As theorized, the Lean Six Sigma (LSS) practices used in the implementation of the DME have reduced traditional contracting timelines, in addition to repositioning timelines upstream in the planning cycle. Figure 114 shows a sample of FY15FY16

DME Annual Cycle project intervals, as measured in calendar days. Each stacked bar chart represents a project in the FY15FY16 DME Annual Cycle. Note how the red interval corresponds to the time spent between two distinct milestones (i.e. Proposals Received and Basis of Selection) in the DME Swim Lane Diagram, shown in the upper right corner of the figure. Also note how Figure 114 highlights process variability and bottlenecks, as the length of the bars/intervals fluctuate from project to project. The red interval is attributed to the VRA evaluation of NAMC proposals. The more these intervals can be reduced, the smaller t_{MIT} becomes, in terms of risk mitigation.

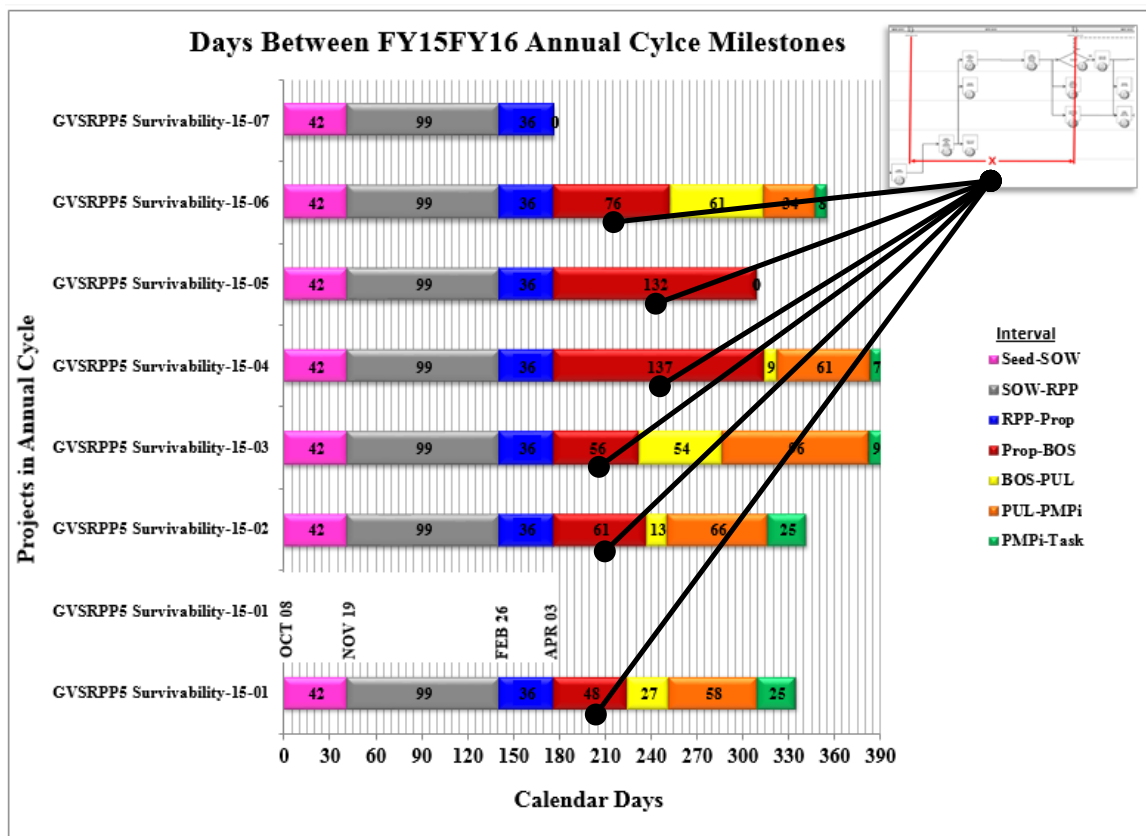


Figure 114. DME contracting intervals feeding the technology readiness piece of t_{MIT}

Rolling all the project timing intervals up into one visual analytic is what Figure 115 portrays. The box and whisker plots of each of the major DME Swim Lane Diagram

intervals allow the VRA PO to assess the performance of an entire enterprise of R&D efforts, by the constituents of t_{MIT} . Again, the bottleneck in this case is clearly the interval between a NAMC proposal being received and when its basis of selection (BOS) is finalized (i.e. left most box and whisker in figure). Visually relating this bottleneck to the process flow, swim lane milestones, RACI responsibility, employee appraisal system, and operational availability of the equipment, for which it mitigates risk, brings the parametric education full circle.

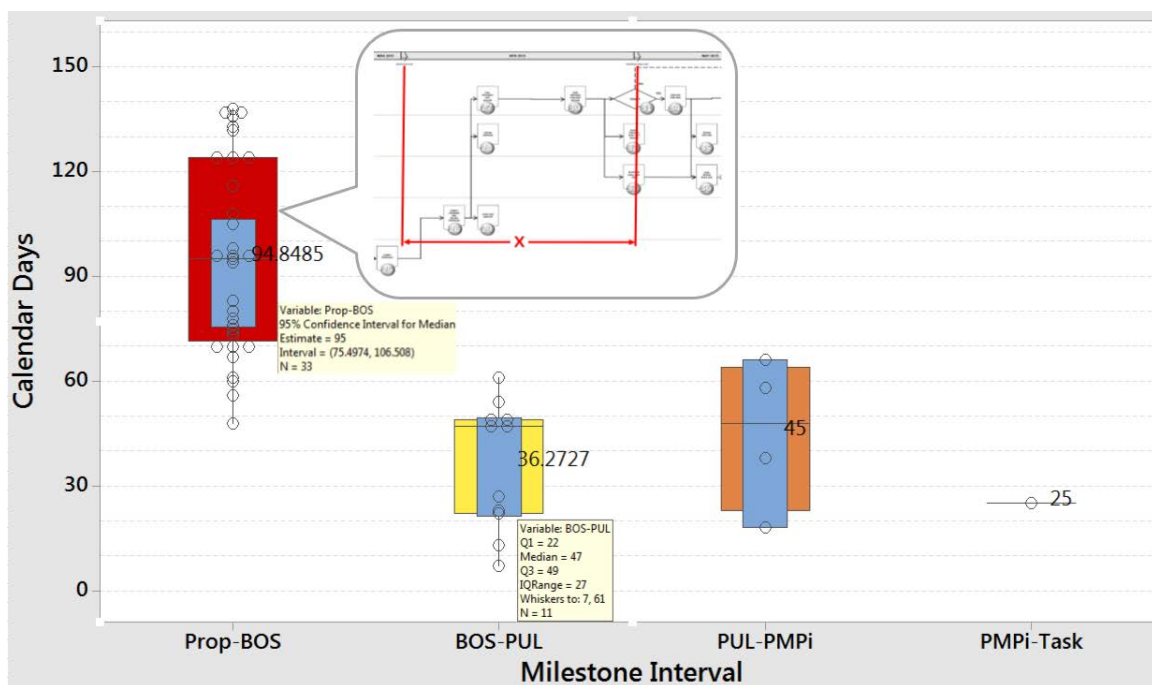


Figure 115. FY15FY16 DME Annual Cycle milestone interval variation (as of 19 Aug 2015)

Prior to applying the research of this dissertation, the S&T funding outlook for FY13 and FY14, under the Defense Ground Robotics Alliance (DGRA), totaled only a few million U.S. dollars at various confidence levels (CL), as shown in Figures 116 and 117: CL1 being 90% or more confident that the estimated funds would be made available for

research, CL2 representing only a 50% confidence, and CL3 being 10% or less. Also, spanning an unmanned-only domain of research, only three Research Areas existed:

Capability and Usage, Platform, and Autonomy.

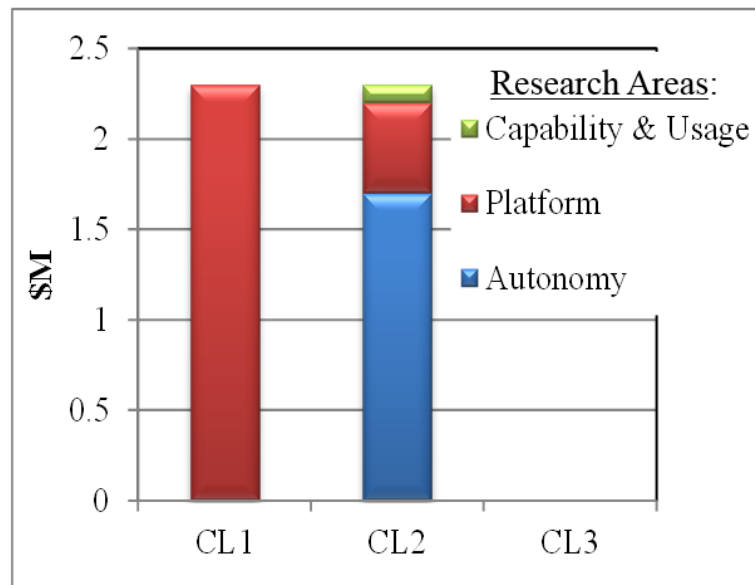


Figure 116. S&T funding outlook for FY13 under an unmanned ground vehicle systems domain

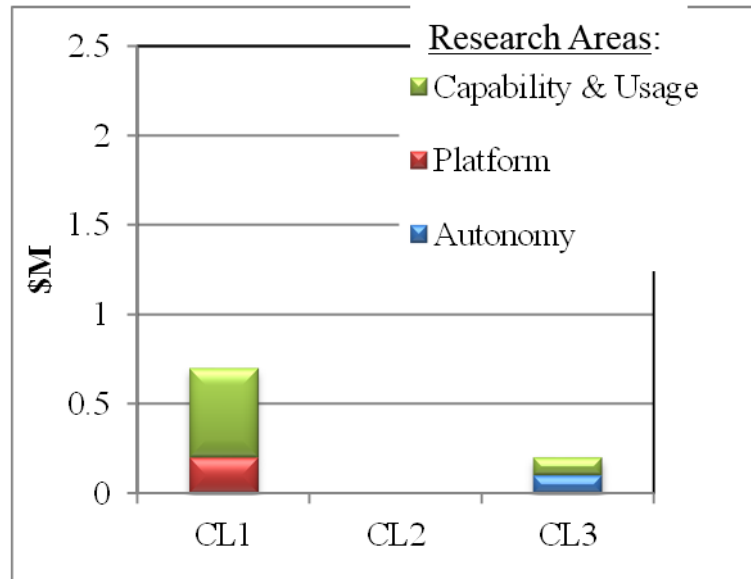


Figure 117. S&T funding outlook for FY14 under an unmanned ground vehicle systems domain

After applying the research of this dissertation, the S&T funding outlook for FY15FY16, under the Vehicle and Robotics Alliance (VRA), totaled over \$100 million U.S. dollars at the confidence levels shown in Figure 118. Under the VRA, the number of Research Areas was expanded from 3 to 11: Testing & Evaluation (T&E), Survivability, Powertrain, Platform, Petroleum and Water Systems (PAWS), Payloads, M&S, Mobility, Collaboration, Autonomy, and Architecture/Security/Modularity.

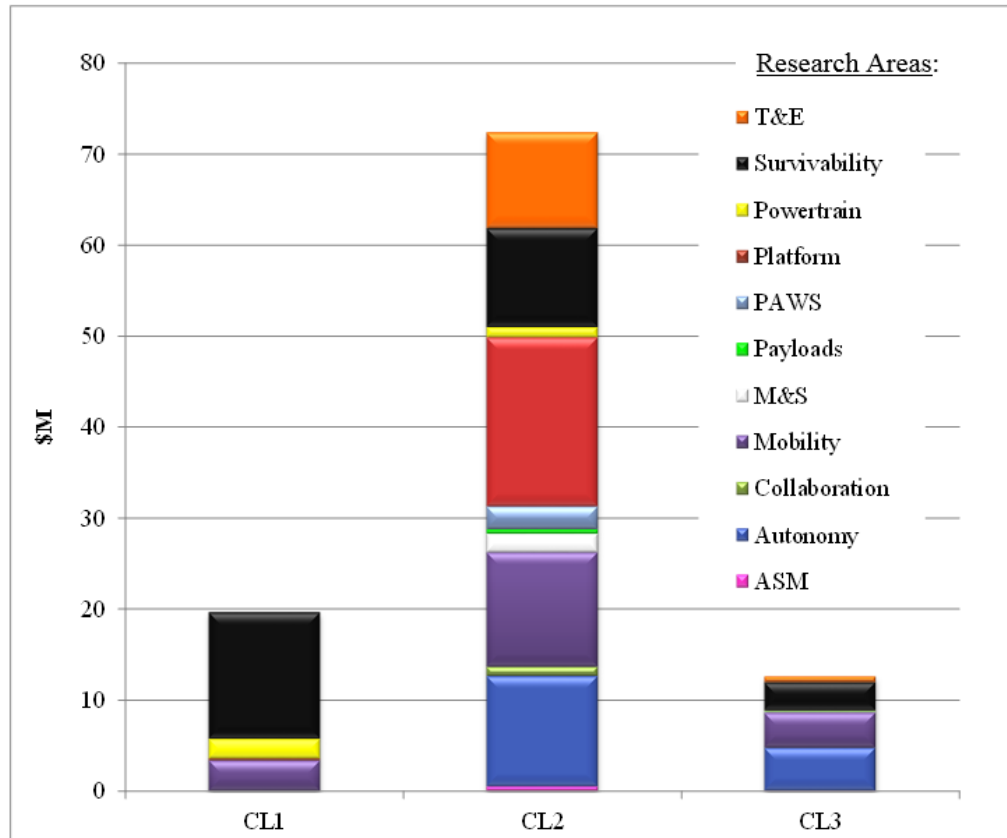


Figure 118. S&T funding outlook for FY15FY16 under an expanded manned + unmanned ground vehicle systems domain

This research has had a profound impact on increasing competition and IB engagement as well, as can be seen in Figure 119. NAMC membership almost tripled from 94 participants to 260 participants in only 2 years. Recalling Figure 69’s depiction of who “could” supply equipment and technology in the future, the effect the DME has had on counteracting diminishing manufacturing sources is remarkable.

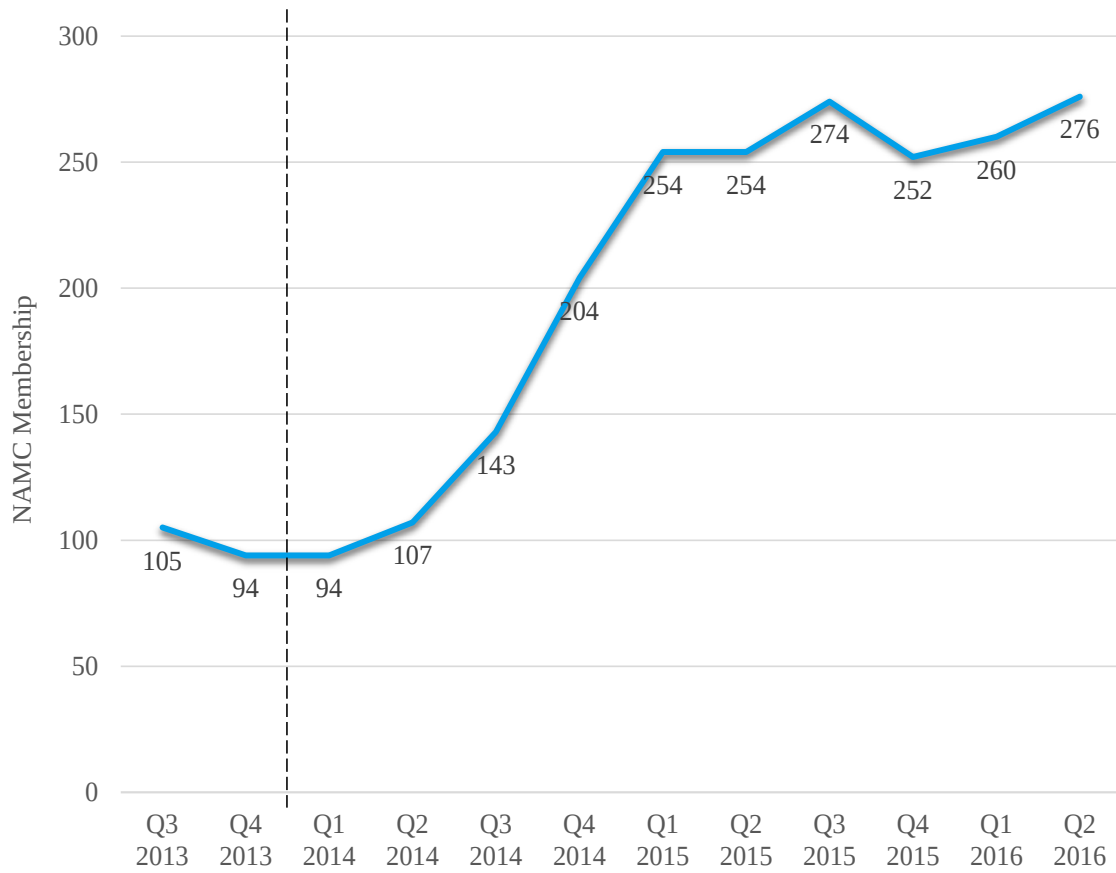


Figure 119. Consortium capacity increase under the Defense Mobility Enterprise. Used with permission.

In terms of the diversity of the NAMC, Figure 120 summarizes the DME's impact on

DMSMS best. The pie chart in the upper right corner shows that two-thirds of the

NAMC membership consists of non-traditional companies and academic institutions.

Non-traditional in this case means that the organization has not had a FAR-based contract

with the U.S Government in the past year valued at over \$500K. In other words, the DoD

is now being exposed to ideas from organizations the DoD has never heard from before.

As the large pie chart shows, over 100 of the NAMC members are both non-traditional

and small businesses. This, in turn, keeps incumbent supplier solutions in check, since

the newcomers are hungry to challenge existing paradigms and prices.

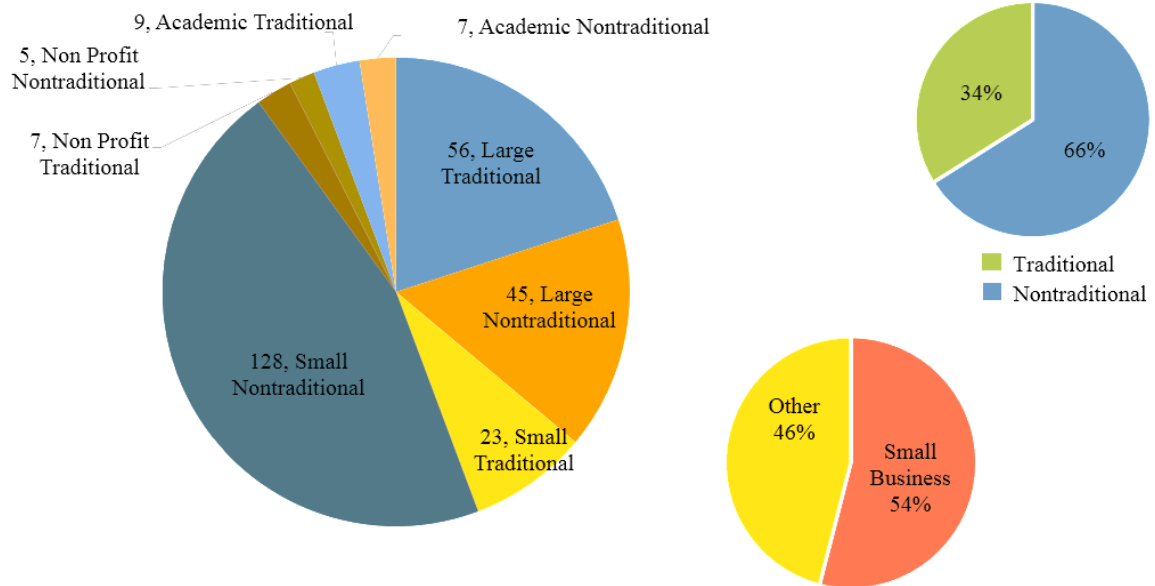


Figure 120. Diversity of National Advanced Mobility Consortium composition (as of August 2016). Used with permission.

Oftentimes, during the generation of a white paper and proposal, small clusters of companies and/or academic institutions will form. Mytelka & Farinelli concluded that collaboration “clusters” amongst diverse companies play a key role in the creation of new products and processes [174]. Three elements of an effective system for innovation were found to be: learning, linkage, and investment – all stemming from local relationships established under the association of a cluster. Mytelka & Farinelli found that stronger vertical relationships between users and producers, analogous to the VRA and NAMC, enabled cost reductions, whereas horizontal collaboration, such as between NAMC members, resulted in faster solution generation.

The DME’s solution generation throughput exceeded expectations. Table 8 summarizes the evolution of solution generation, from projects, through white papers, ending in proposals categorized by Research Area. Although a handful of proposals were funded

immediately (saving expiring funds), most of the 266 proposals received from the NAMC were placed in the Basket. Planning ahead and staging projects ahead of when money becomes available creates agility for researchers and reactive problems solvers that may need alternative equipment solutions in the future.

Table 8. FY15FY16 Annual Cycle output depicting the S&T capacity of the Defense Mobility Enterprise

Research Area	Annual Plan Projects	Whitepapers Received	RPP Projects	Proposals Received
Architecture, Security, and Modularity (ASM)	3	26	1	4
Autonomy	32	158	32	91
Collaboration	2	3	1	0
Mobility	33	101	28	50
Modeling and Simulation (M&S)	11	33	9	23
Petroleum & Water Systems (PAWS)	3	2	2	1
Payload	5	14	5	4
Platform	12	41	11	23
Powertrain	3	14	3	7
Survivability	42	142	33	61
Test and Evaluation (T&E)	2	5	2	2
Total	148	552	126	266

Despite evidence from literature that suggests that formal process is often different from the true sequence engineers actually follow, the DME process has proved that, with discipline, formal process can be enforced and S&T throughput can be drastically improved [175, 176]. As Repenning states, the design of a process must be complemented with experience in process execution, in order to be successful. For example, the right experience, in combination with high productivity, cannot be substituted by simply hiring random people as replacements. Inexperience and low

productivity translates to proverbial fire-fighting, whereas experienced staff tend to be involved in more advance resource planning. In fact, inexperienced staff ends up “starving the ensuing model years to make the one they grow behind on” [175, pp. 286, 296]. As Shainin teaches, true solution implementation validation lies in demonstrating the ability to turn problems on and off [41].

6. CONCLUSION

In conclusion, model-based systems engineering enables the orchestration of logistics and contracting/acquisition information, through working models, to represent sustainment support strategies across multiple platforms. The ground vehicle and robotics sustainment support strategy can be analyzed using the Sustainment Engineering Risk Assessment (SERA) and the Defense Mobility Enterprise (DME). Resource allocation continues to be challenged as new problems and opportunities arise in the sustainment and R&D realms of the DoD. Virtually experimenting with new ways to improve risk mitigation throughput and agility, by widening avenues for technology transition, has proven to be an effective way to add value with little investment [164, p. 30].

Uniting diverse levels of abstraction, through educating users on the many lenses with which to view sustainment support strategies, enables complementary knowledge to be shared across missions. In other words, the state of an entity has a history which is best told from multiple stakeholder perspectives, including inputs from the Science & Technology (S&T), acquisition, finance, and maintenance, disciplines. Having a common software interface, where attributes, inputs, and outputs are parametric, is one of the visions of a utopian systems engineering community and is the heart of a balanced system solution [56, 53, p. 254]. The “ability to pass on systems engineering knowledge of highly specialized military applications distinguishes the aerospace and defense market from the civil market” [2]. Superimposing facets of the conceptual sustainment support strategy model over the Systems Development Environment presented by Friedenthal, Moore, and Steiner is shown in Figure 121 [53, p. 494].

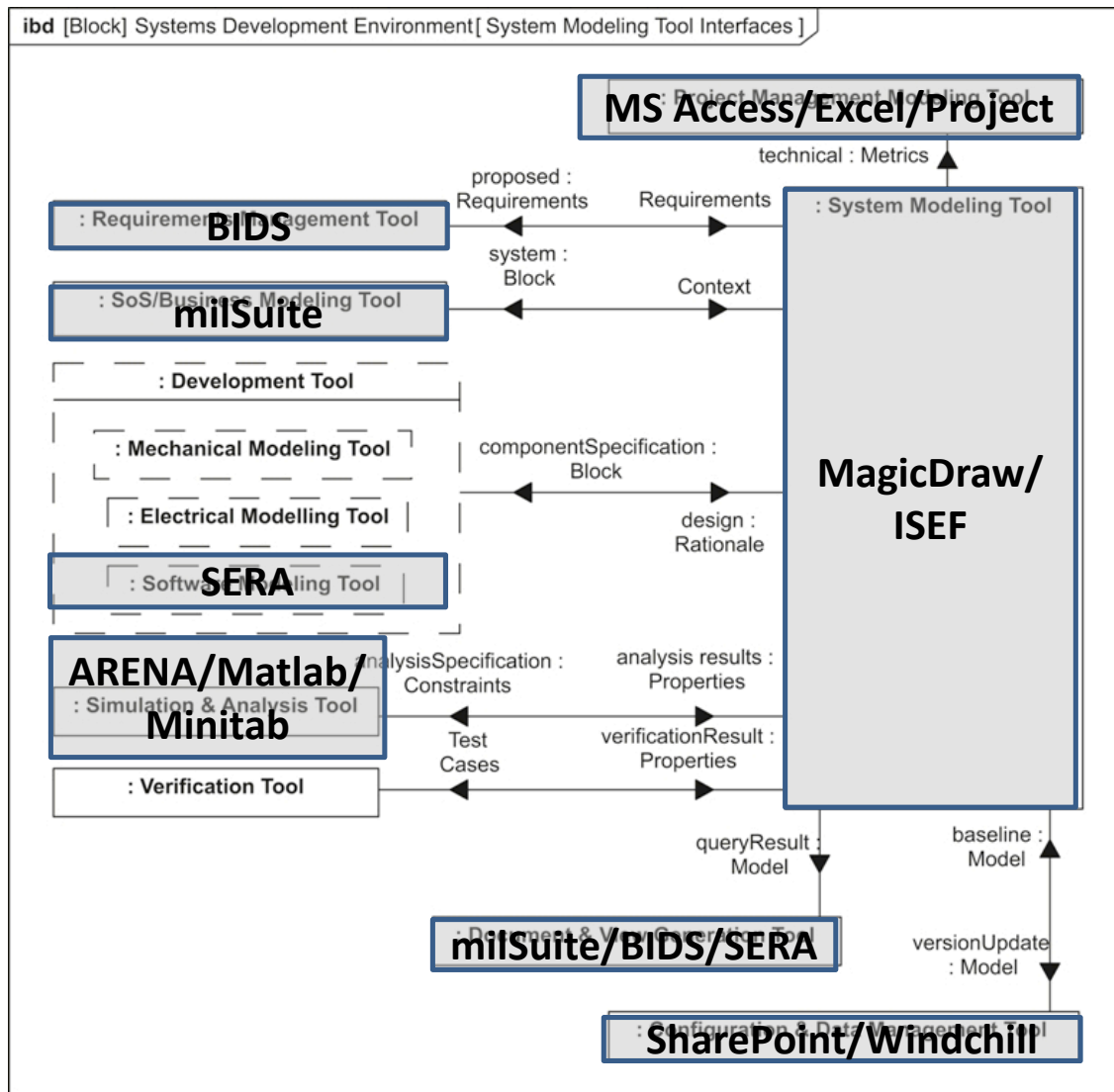


Figure 121. Interfaces between sustainment support strategy modeling tools and DME tools in a systems development environment [54]. Copyright © 2015, 2012, 2009 Elsevier Inc. All rights reserved. Used with permission.

Although some researchers claim that Lean Six Sigma (LSS) has a tendency to stifle innovation and free thinking, opposing researchers advise innovators to “track your trajectory with rigor” [60, 177]. The meticulous LSS practices of this applied research have actually exposed some of the most influential roadblocks to sustainment, prototype acquisition, and productivity. As of 2016, additional platforms, like Stryker and MRAP,

are joining the movement and starting to invest in the enhanced analysis and subsequent risk mitigation offered by the practices of this research. It is likely that the efficiency their investments bring to their respective sustainment support strategies will ultimately make technology overmatch more available to our warfighters.

6.1 Recommendations

Bayesian networks involving conditional probability models may help validate the risk indicator versus issue correlation that was explored in section 4.2.1.2.2 [178].

Monitoring equipment logistics and contracting state change trends for M&S opportunities should be continued to further codify this research, making diverse organization's processes and data more parametric with one another. Incorporating mitigation decision trees, like those shown in Figures 122 and 123, into standard operating procedures (SOPs) is advised.

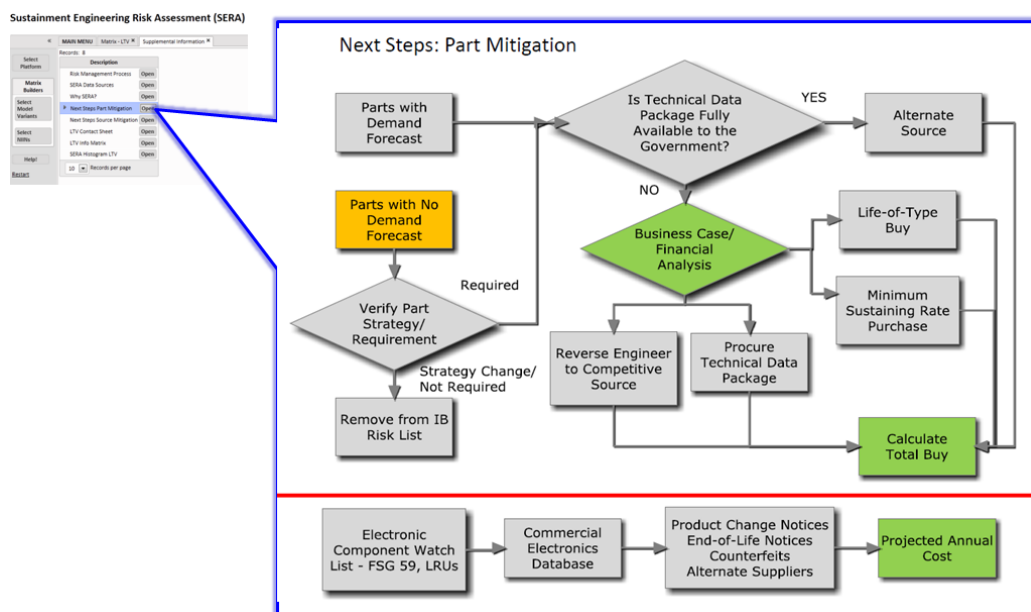


Figure 122. Part mitigation lens of sustainment support strategy

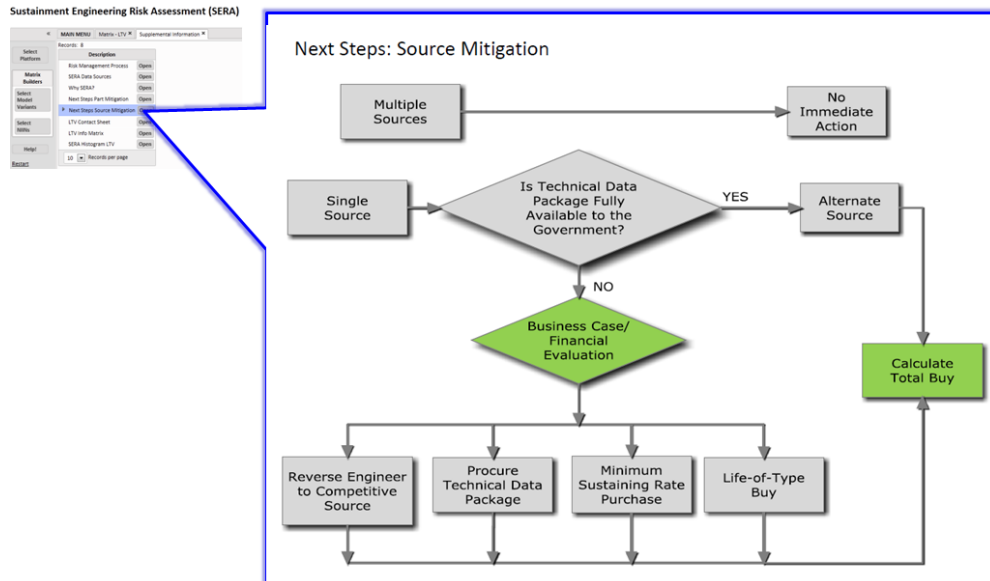


Figure 123. Source mitigation lens of sustainment support strategy

Leveraging government-off-the-shelf (GOTS) tools, like milSuite, that capitalize on the successes of industry, is also recommended. The VRA milBook home page, shown in Figure 124, has proven to be a reliable and effective collaboration portal for the VRA. Many unexplored features still exist within the VRA milBook portal, such as group discussion on a particular technology (as shown in the bottom left corner of the figure), surveying, and polling.

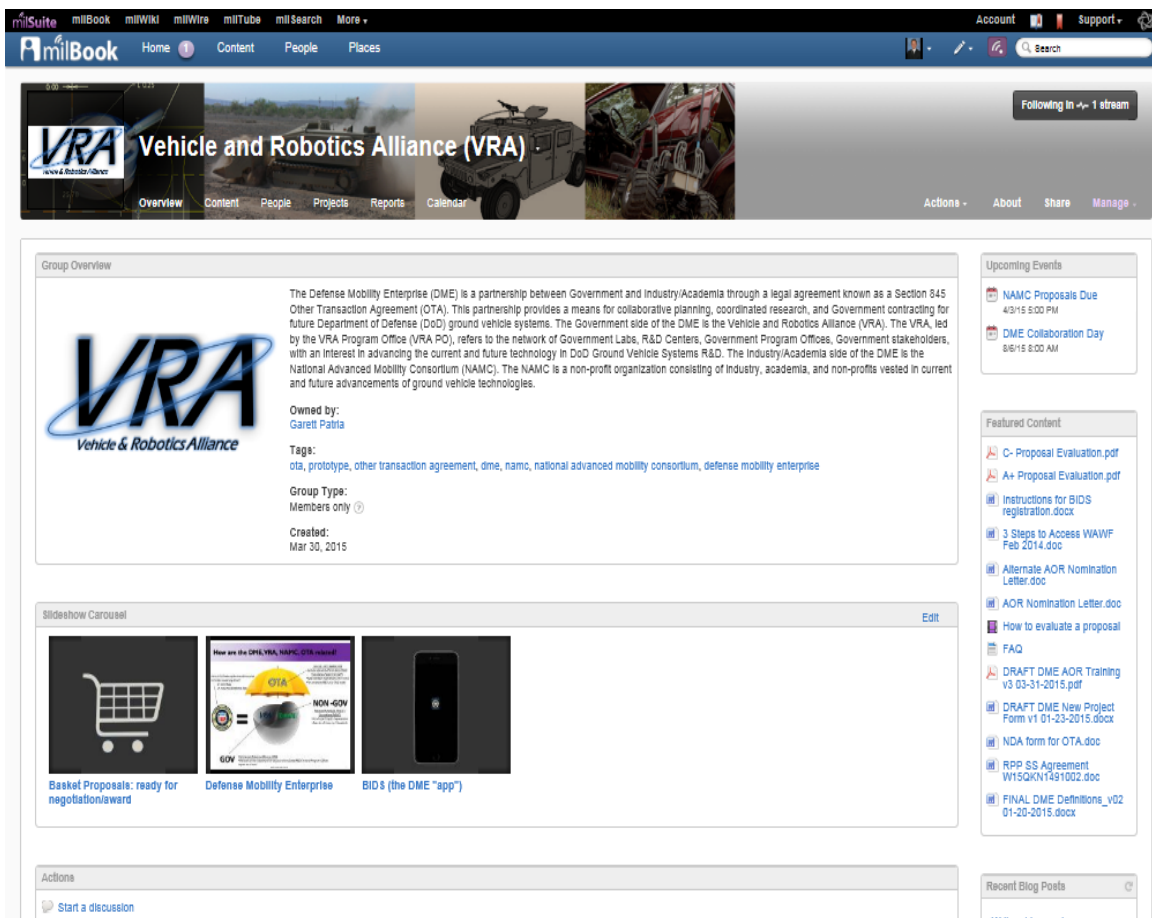


Figure 124. Collaboration lens of the VRA

Exploring capacity and resource allocation simulation alternatives to discrete event simulation (DES) licensing has shown promise, during this research. Figure 125 shows a conceptual example of how a media player visual analytic was created to animate the different states of the DME process throughout the months of an annual cycle. In this example, the dot plots represent the number of DME projects held up at a particular step in the process. Maturing the dot plots to represent the manpower required to complete the tasks by the deadlines could help decision makers lacking DES licenses visualize their resource allocation challenges in a simpler way. Although more experimentation is

needed, it is surmised that “the combination of gaming and simulation offers compelling learning benefits while supporting immersive experiential learning” [179].

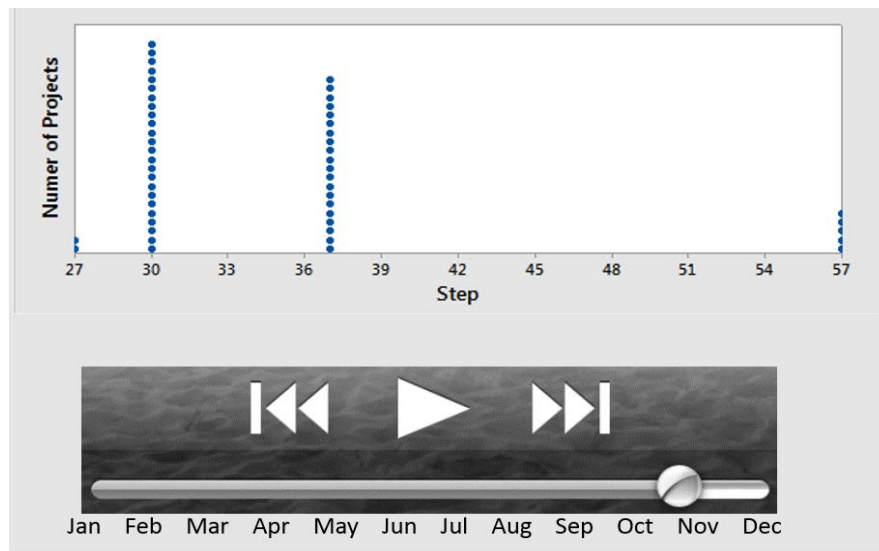


Figure 125. Notional weather radar-style animation haptic

6.2 Future Research

Challenges still exist in monitoring technology readiness efforts, within TARDEC, with hopes to associate them with appropriate NSNs that the technology may someday supersede. Figure 126 shows an example of a coating system R&D project exhibiting different attributes being input by different team members into different software systems - one a GOTS tool (ISEF), and the other a COTS tool (BIDS). It is recommended that any desired capabilities in the Integrated Systems Engineering Framework (ISEF) be parametrically linked to S&T projects in BIDS moving forward, since tradeoffs made in either system “constitute boundary conditions or goals for specialized engineering programs and integrated product support element and concept plans” [17, p. 6].

The screenshot shows the ISEF Desktop interface. On the left is the 'ISEF Explorer' tree. The main window displays a table of requirements for 'Patrol New V Requirements (Capabilities)'. A 'Link Navigator' window is open, showing a diagram with a box labeled 'Ground Vehicle Coating System (GVCS)' linked to a 'Function' box labeled 'Avoid detection'.

ID	Object Number	Node Type	Name	Description
94046	3.1.1.1.1	PerformanceRequirement	While moving	Accelerate from 20 MPH to 40 MPH in 4 sec...
94047	3.1.1.1.2	PerformanceRequirement	On slope	Accelerate from 0 MPH to 60 MPH in 14 sec...
94048	3.1.1.1.3	PerformanceRequirement	Dash speed	Accelerate from a complete stop to 58 MPH in...
94049	3.1.1.1.4	Function	Maintain speed	Meet all vehicle speed requirements at GVN.
94050	3.1.1.2.1	PerformanceRequirement	Forward speed	Maintain a forward speed of 60 mph (outside...
94051	3.1.1.2.2	PerformanceRequirement	Reverse speed	Maintain a reverse speed of 15 mph on level g...
94052	3.1.1.2.3	PerformanceRequirement	Speed on 5% grade	Maintain a sustained speed of 45 mph on 5%...
94053	3.1.1.2.4	PerformanceRequirement	Speed on 40% grade	Maintain a speed of 25 mph on 40% grade on...
94054	3.1.1.3	Function	Traverse grades and slopes	Meet all grade traversal requirements at GVN.
94055	3.1.1.3.1	PerformanceRequirement	Traverse longitudinal slope	Accelerate, start and stop on dry, level s...
94056	3.1.1.3.2	PerformanceRequirement	Traverse side slope	Traverse in either direction, forward and rear...
94057	3.1.1.3.3	PerformanceRequirement	Traverse gap	Traverse a 24 inch deep and 20 inch wide gap...
94058	3.1.1.4	Function	Traverse obstacles	Meet all obstacle requirements at GVN.
94059	3.1.1.4.1	Function	Breach obstacle	Push vehicles or similar objects of GVN from t...
94060	3.1.1.4.2	PerformanceRequirement	Surmount obstacle	Surmount a vertical step 20 inches high in the...
94061	3.1.1.4.3	PerformanceRequirement	Avoid obstacle	Capable of NATO Lane Change at 35 mph.
94062	3.1.1.5	Function	Control vehicle	
94063	3.1.1.5.1	Function	Steer vehicle	
94064	3.1.1.5.2	PerformanceRequirement	Turning radius	
94065	3.1.1.5.3	PerformanceRequirement	Roll stability	
94066	3.1.1.6	Function	Maintain ground clearance	
94067	3.1.1.7	Function	Stabilize vehicle	
94068	3.1.1.8	Function	Share torque	
94069	3.1.1.8.1	Constraint	Disable torque sharing	
94070	3.1.1.8.2	Capability	Torque sharing changes	
94071	3.1.1.8.3	PerformanceRequirement	Torque transmits	
94072	3.1.1.9	Function	Vehicle range	
94073	3.1.1.9.1	Constraint	Recen Patrol Range	
94074	3.1.2	Capability	Survivability	
94075	3.1.2.1	Capability	Don't be acquired	
94076	3.1.2.1.1	Capability	User detectability	
94077	3.1.2.2	Function	Avoid detection	
94078	3.1.2.2.1	Gap	Ground Vehicle Coating System (GVCS)	

Project: Survivability-15 **Ground Vehicle Coating System (GVCS)**

Project AOR:

Project Alt. AOR:

Project Funding: FY15: \$
FY16: \$

Project Summary: The Ground Vehicle Coating System (GVCS) will

Figure 126. Linking ISEF to BIDS

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APPENDIX A

Research Proposal Synthesis

Systems Engineering practices were deployed throughout the synthesis of this research and are known to be effective in developing robust proposals [180]. In particular, this research was the result of a synthesis of three distinct requirements from three interconnected entities, as depicted in Figure 127 below:

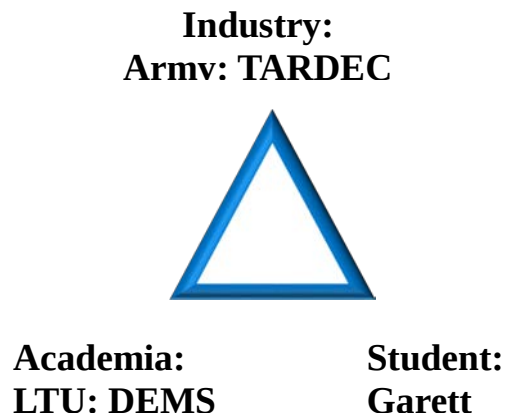


Figure 127. Triad of dissertation requirements

Stefanopoulou recommended that doctoral research should embody a blend of lead roles and agreements between: the industry sponsoring the research, 2) the academic institution fostering the education, and 3) the doctoral student offering their talents and interests [181]. Therefore, the following documented vision and mission statements (corresponding to the three entities of Figure 127) were used as a gauge to pre-check the relevance of the subject matter:



**Tank Automotive Research
Development and Engineering Center
(TARDEC)**

Vision:

Be the recognized Department of
Defense leader for ground systems and
combat support systems technology
integration and systems-of-systems
engineering across the life cycle



**Industrial Base Engineering Team
(IBET)**

Mission:

Provide industrial engineering support
for the U.S. Industrial Base Operations
mission and the Diminishing
Manufacturing Sources and Material
Shortages (DMSMS) initiative. Provide
industrial engineering expertise and
experience to investigate, manage, and
resolve industrial base issues related to
production and sustainment of military
equipment



**Lawrence Technological University
(LTU) Doctorate of Engineering in
Manufacturing Systems (DEMS)**

Mission:

Solve appropriate dissertation problems that arise from the manufacturing facility which when solved will have relevance to advancing the 'state of the art' in manufacturing. The result may be a new manufacturing related device, process, system, or software for which high-level scholarship, engineering expertise, and ingenuity are required to find the solutions

Garett Patria

Mission:

Formulate a research topic that leverages my passion, unique skills, and current opportunities and resources

Preliminary research was conducted between 2010 and 2012 to gather actual results (e.g. documented systems attributes and U.S. Army efforts consuming tangible resources) that exemplify and expand on the priorities of the three aforementioned mission statements. In summary, a storyboard of the expanded priorities was maintained to map out the relationships between interconnected themes. An actual photograph of the storyboard is shown in Figure 128.

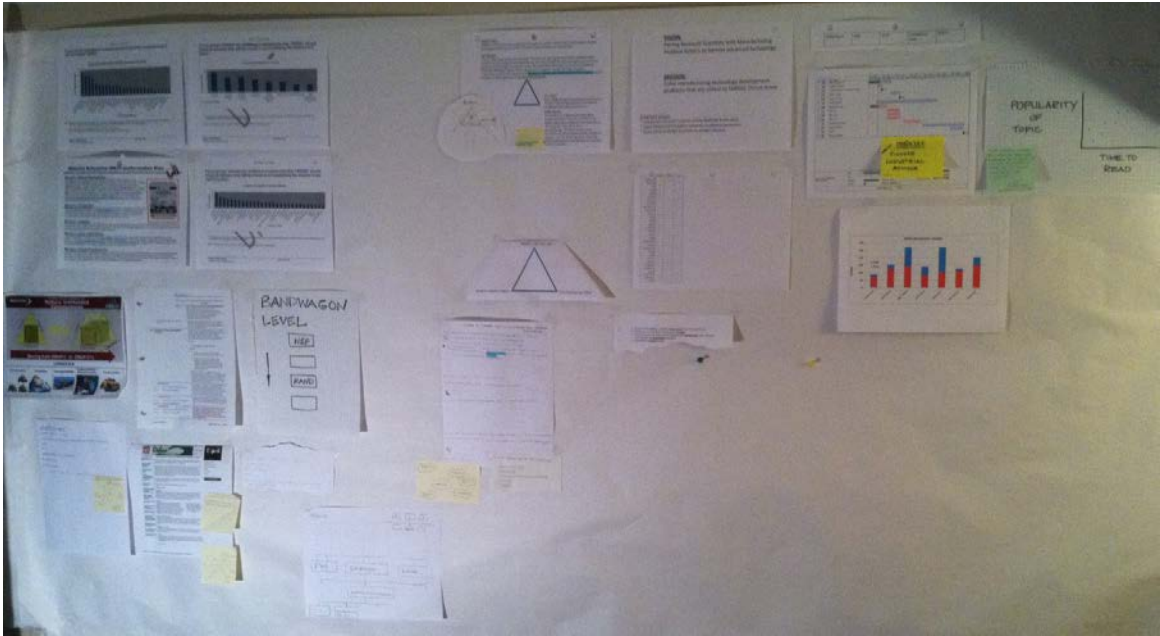


Figure 128. Storyboard used for DEMS proposal synthesis

A digital representation of the storyboard was re-created to effectively communicate the findings of the synthesis to the DEMS Advisement Committee (see Figure 129).

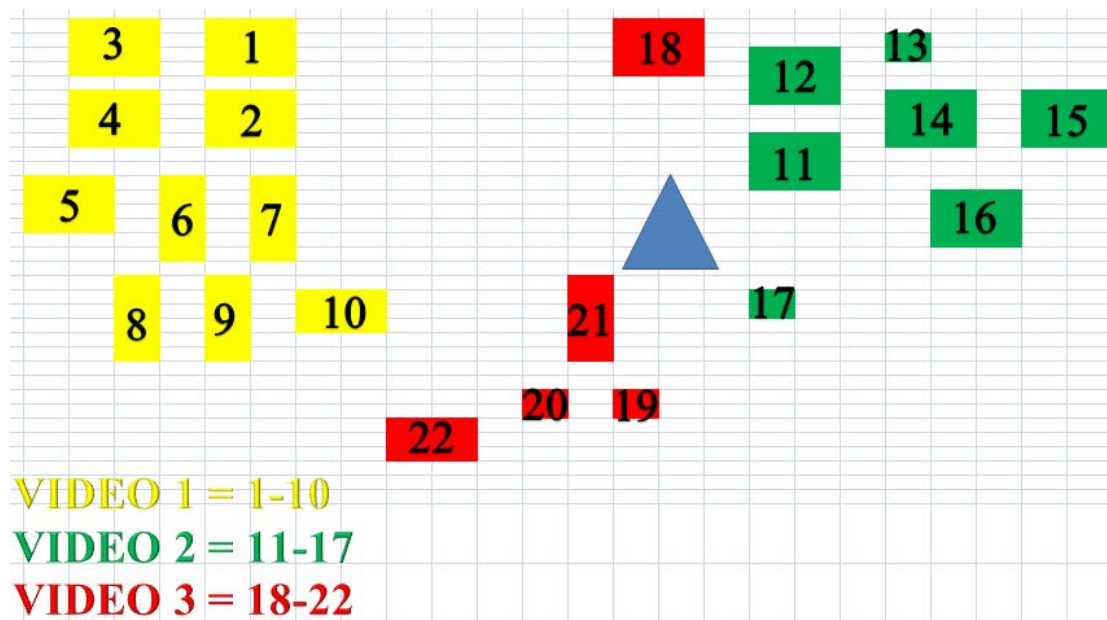


Figure 129. Digital representation of storyboard of Figure 128

A concise list outlining each numbered element of the storyboard is shown below:

Yellow Section or “Industry” Domain:

1. The top three TARDEC competencies needed within the next five years spanning from CY2010 to CY2015 were found to be: Visionary, Strategic Thinking, and Systemic Thinking [23]
2. The top three TARDEC competencies needed within the six months spanning from Jun 2010 to Dec 2010 were found to be: Proactive, Communication, and Relationship Building [23]
3. The top three CY2010 contributors to TARDEC success were found to be: Customer Focus, Technical Proficiency, and Problem Solving [23]
4. The second goal of the 2009 Department of the Army (DA) Materiel Enterprise Transformation Plan (METP) is to ensure a viable Industrial Base [182]
5. The TARDEC Director’s call to reduce unintended consequences through a paradigm shift from a Space, Weight, Power, and Cooling (SWaP+C) mind-set to a Space, Weight, Power, Cooling, and Logistics (SWaP+C+L) mind-set, where Logistics represents a third dimension, introducing depth to the old SWaP+C 2D model. Logistics encompasses the Commonality, Durability, Transportability, Supportability/Maintainability, and Producibility disciplines [18]
6. The Office of Management and Budget (OMB) nomenclature and funding distinctions explaining Basic Research (i.e. 6.1), Applied Research (i.e. 6.2) and Advanced Technology Development (6.3), which are transcribed below [183]:

Basic Research:

Systematic study directed toward greater knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications toward processes or products in mind

Applied Research:

Systematic study to gain knowledge or understanding necessary to determine the means by which a recognized and specific need may be met

Advanced Technology Development:

Includes all efforts that have moved into the development and integration of hardware for field experiments and tests

7. A hierarchical depiction of the different levels of research visibility (e.g. National Science Foundation (NSF) vs. International Council on Systems Engineering (INCOSE)) and organizational support that should be considered when conducting research – some research topics are higher-profile than others and may involve prominent sponsorship and buy-in from elevated levels of leadership
8. A preliminary list of hot topics observed within TARDEC – the beginning stages of a Pugh Analysis on DEMS dissertation proposal titles
9. An Acquisition, Logistics, and Technology (AL&T) Online article announcing the AL&T 2010 M&S Award – this storyboard element shows the unique opportunities associated with particular areas of research

10. A list explaining the considerations for choosing to conduct DA research, as opposed to private research not affiliated with the DA nor any of its requirements and restrictions (part of the aforementioned Pugh Analysis)

Green Section or “Academic” Domain:

11. A commonality matrix identifying overlapping key words between the missions and entities of Figure 127 – this matrix was considered when constructing the title of this dissertation proposal
12. The initial vision, mission, and strategic goals to generate and formally document a DEMS dissertation proposal [184]
13. The initial matrix of deadlines required to transform the DEMS dissertation strategic objectives into goals [185]
14. The initial Gantt Chart used to track DEMS goals and progress
15. A Concept Diagram depicting the relationship of prevalent dissertation topics as a function of literature search workload (time) – a consideration pertaining to Lloyd Alexander’s theory that suggests we learn more by looking for the answer to a question and not finding it than we do from learning the answer
16. A characterization of a historical sample of DEMS dissertations depicting data content as a function of total length (as measured in pages)
17. A synopsis of potential divergence between research areas, mission alignment, and perceived deadlines

Red Section or “Student” Domain:

18. DEMS call to “create new knowledge” linked with my mission at TARDEC
19. Traits and behaviors that make me a doctoral candidate
20. Subjects I want to explore in the future
21. A list of results-to-effort considerations
22. Organizational structures showing how manufacturing systems falls under the Logistics realm (in terms of Acquisition, Logistics, and Technology); but, in terms of the Systems, Planning, Research, Development, and Engineering (SPRDE) career field, manufacturing systems is considered an SE discipline (TARDEC hired me under the SE discipline)

A narrated, three-part video explaining each section was also created in 2011 to remotely brief targeted DEMS academic and industrial advisors on the development of this research topic (see Figure 130).



Figure 130. Video explanation of research motivation

In terms of how the Department of the Army (DA) is formally planning for the future and what technologies TARDEC should be working on, ARCIC provided insight, during a brief to TARDEC on 25 Oct 2012, emphasizing the 1) emergence of M&S applications

and 2) experimentation opportunities. ARCIC feels TARDEC should integrate more developed models into everyday practice, in order to sustain the organization of the future [1].

APPENDIX B

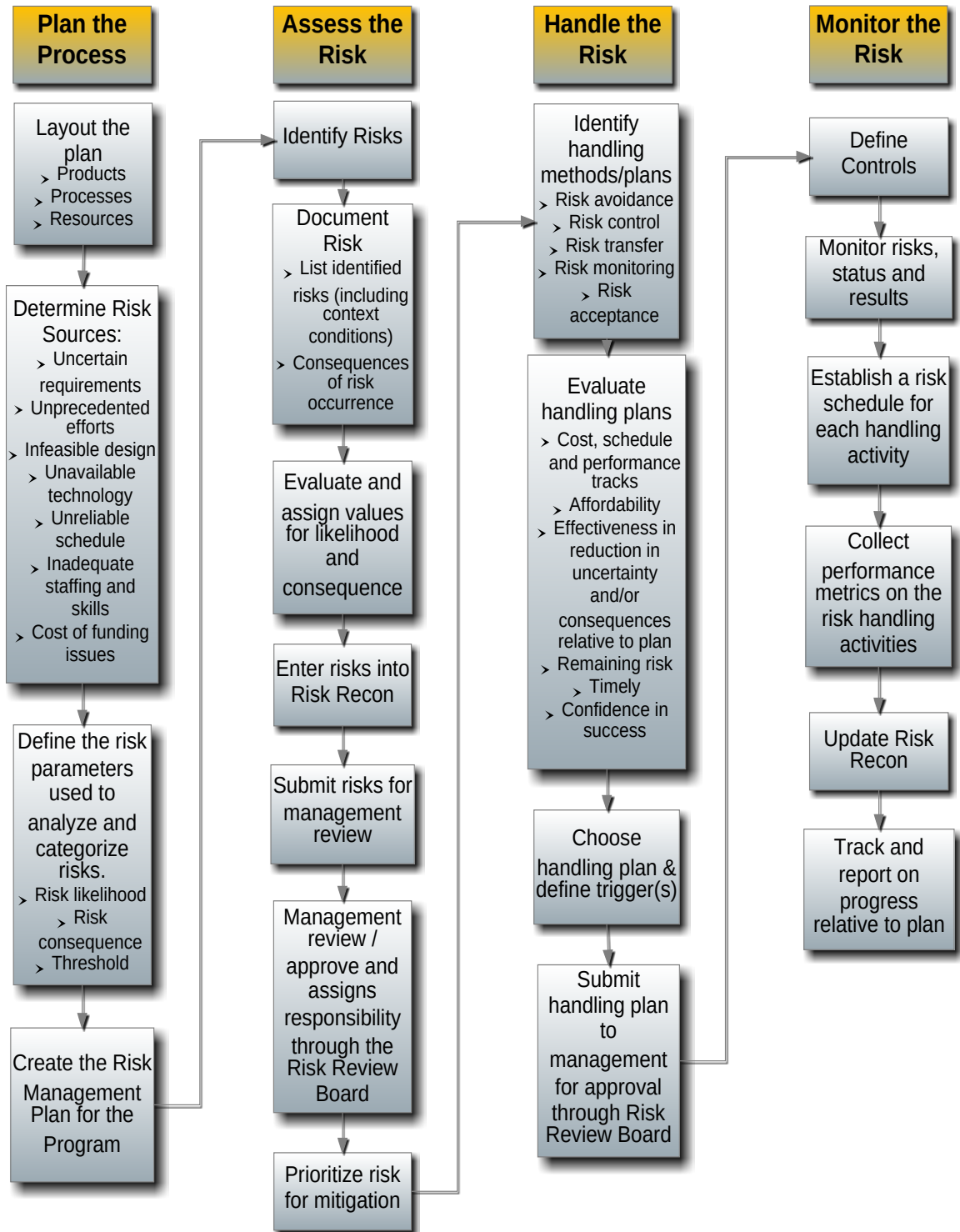


Figure 131. TARDEC Risk Management Process

APPENDIX C

Table 9. Abrams SERA vs. 339 Reason Codes Correlation Matrix

[illegible]

APPENDIX D

Binary Logistic Regression: 339: 1 versus txtCageCodeWt, txtWtTDPUnavail, txtWtWOLastYr, txtWtWOLastYrTop10Pcnt, txtWtCWITop10Pcnt

* WARNING * When the data are in the Response/Frequency format, the Residuals versus fits plot is unavailable.

Method

Link function Logit
Rows used 9670

Response Information

Variable	Value	Count
339: 1	1	244 (Event)
	0	9426
Total		9670

Deviance Table

Source	DF	Seq Dev	Contribution	Adj Dev	Adj Mean	Chi-Square	P-Value
Regression	5	150.44	6.61%	150.44	30.0879	150.44	0.000
txtCageCodeWt	1	14.92	0.66%	28.12	28.1162	28.12	0.000
txtWtTDPUnavail	1	8.44	0.37%	13.02	13.0194	13.02	0.000
txtWtWOLastYr	1	67.33	2.96%	26.35	26.3532	26.35	0.000
txtWtWOLastYrTop10Pcnt	1	52.98	2.33%	53.36	53.3550	53.36	0.000
txtWtCWITop10Pcnt	1	6.77	0.30%	6.77	6.7669	6.77	0.009
Error	9664	2127.00	93.39%	2127.00	0.2201		
Total	9669	2277.44	100.00%				

Model Summary

Deviance	Deviance	
R-Sq	R-Sq(adj)	AIC
6.61%	6.39%	2139.00

Coefficients

Term	Coef	SE Coef	95% CI	Z-Value	P-Value	VIF
Constant	-4.425	0.121	(-4.662, -4.188)	-36.59	0.000	
txtCageCodeWt	1.805	0.283	(1.250, 2.360)	6.38	0.000	1.10
txtWtTDPUnavail	0.546	0.146	(0.260, 0.833)	3.73	0.000	1.03
txtWtWOLastYr	0.804	0.154	(0.502, 1.106)	5.22	0.000	1.36
txtWtWOLastYrTop10Pcnt	1.455	0.185	(1.092, 1.818)	7.85	0.000	1.25
txtWtCWITop10Pcnt	0.706	0.250	(0.216, 1.196)	2.83	0.005	1.02

Odds Ratios for Continuous Predictors

	Odds Ratio	95% CI
txtCageCodeWt	6.0794	(3.4904, 10.5890)
txtWtTDPUnavail	1.7271	(1.2964, 2.3008)
txtWtWOLastYr	2.2354	(1.6528, 3.0233)
txtWtWOLastYrTop10Pcnt	4.2838	(2.9796, 6.1589)
txtWtCWITop10Pcnt	2.0258	(1.2415, 3.3055)

Regression Equation

P(1) = $\exp(Y') / (1 + \exp(Y'))$

$Y' = -4.425 + 1.805 \text{ txtCageCodeWt} + 0.546 \text{ txtWtTDPUnavail} + 0.804 \text{ txtWtWOLastYr} + 1.455 \text{ txtWtWOLastYrTop10Pcnt} + 0.706 \text{ txtWtCWITop10Pcnt}$

Goodness-of-Fit Tests

Test	DF	Chi-Square	P-Value
Deviance	9664	2127.00	1.000
Pearson	9664	9817.49	0.135
Hosmer-Lemeshow	3	3.35	0.340

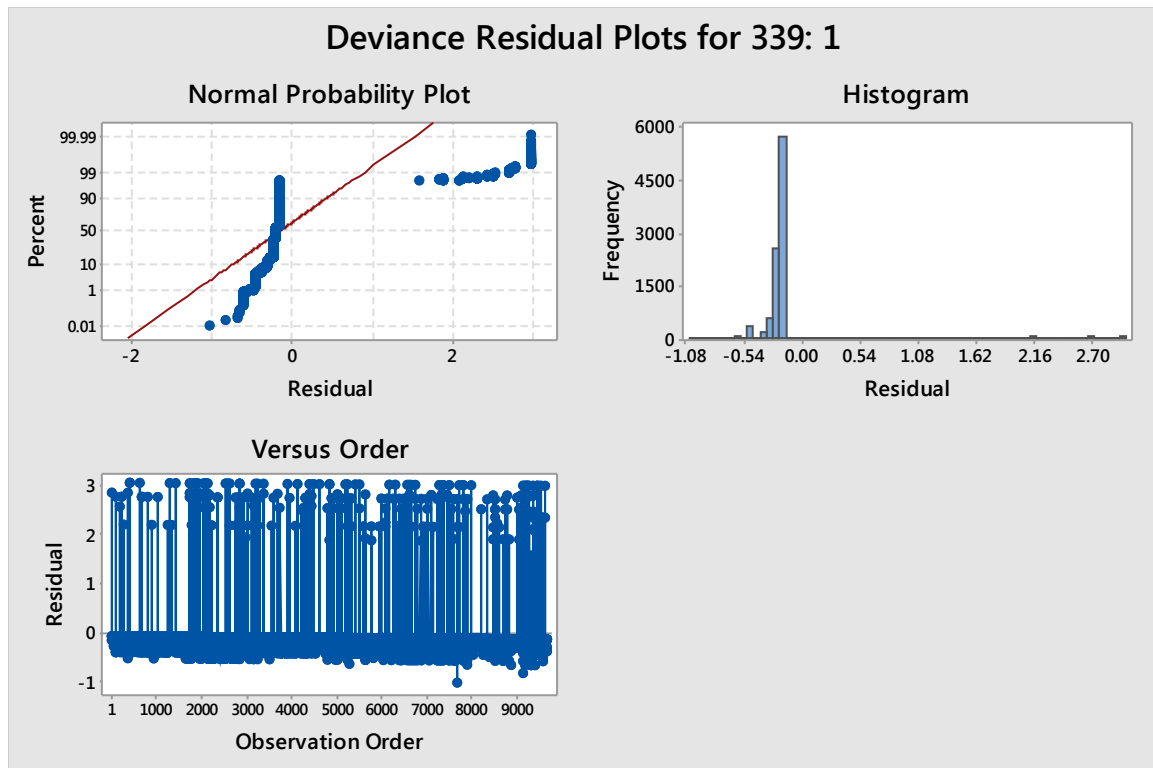


Figure 132. Deviance Residual Plots for LTV 339 versus LTV SERA Flags Regression

APPENDIX E

AAC Rates of Change Observations

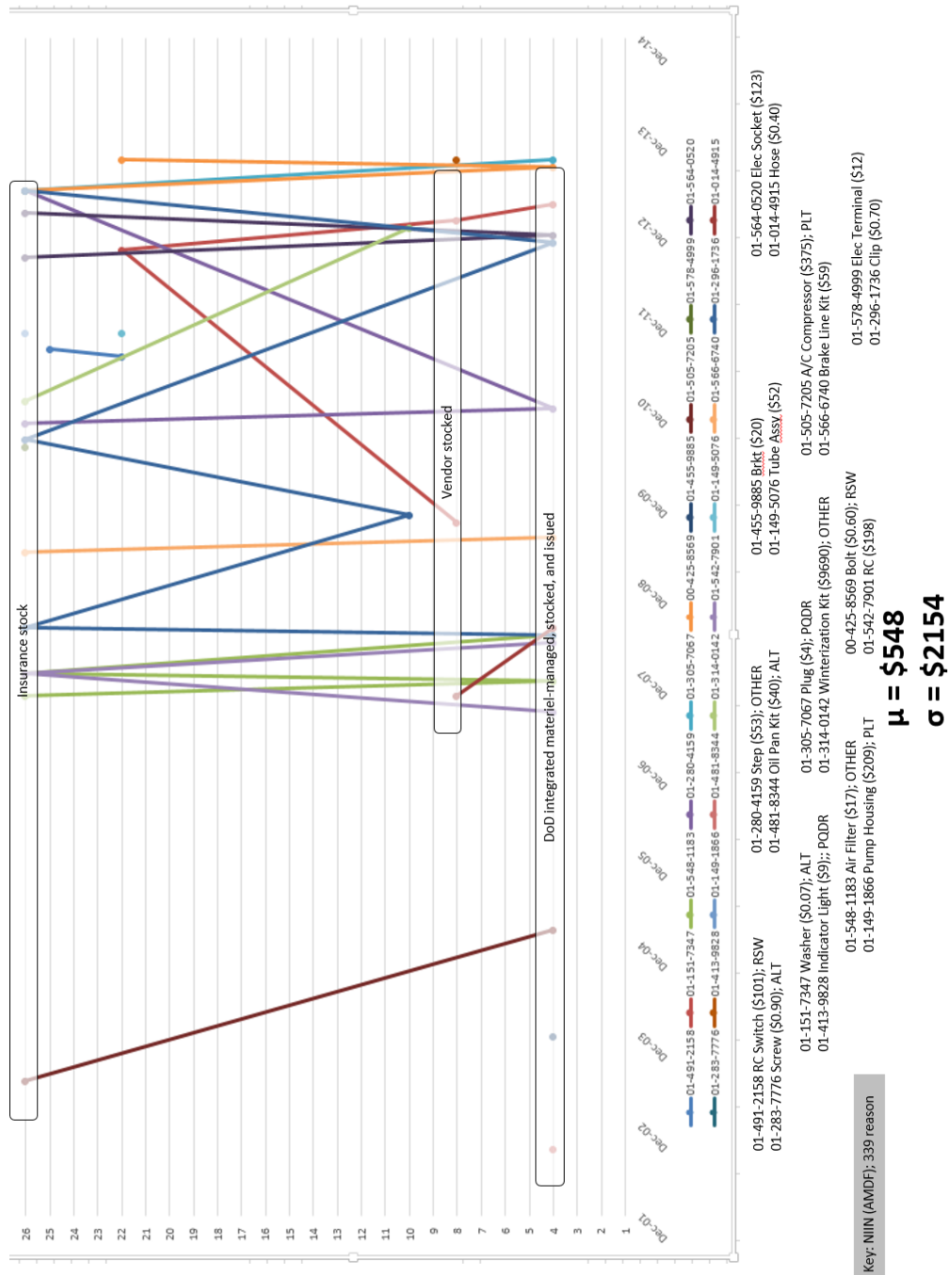


Figure 133. AAC state change for 339 NIINs in the LTV SERA

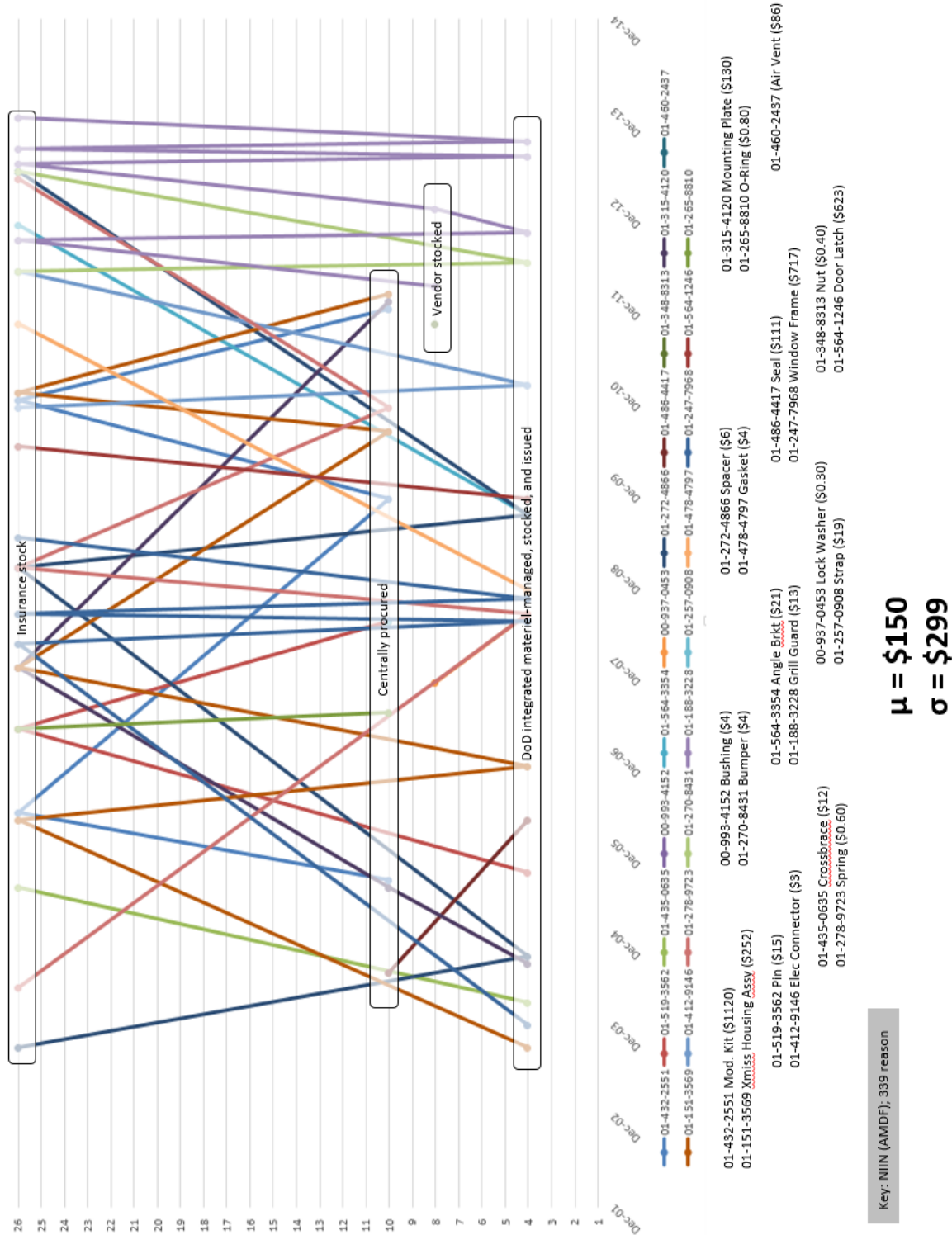


Figure 134. AAC state change for non-339 NIINs in the LTV SERA

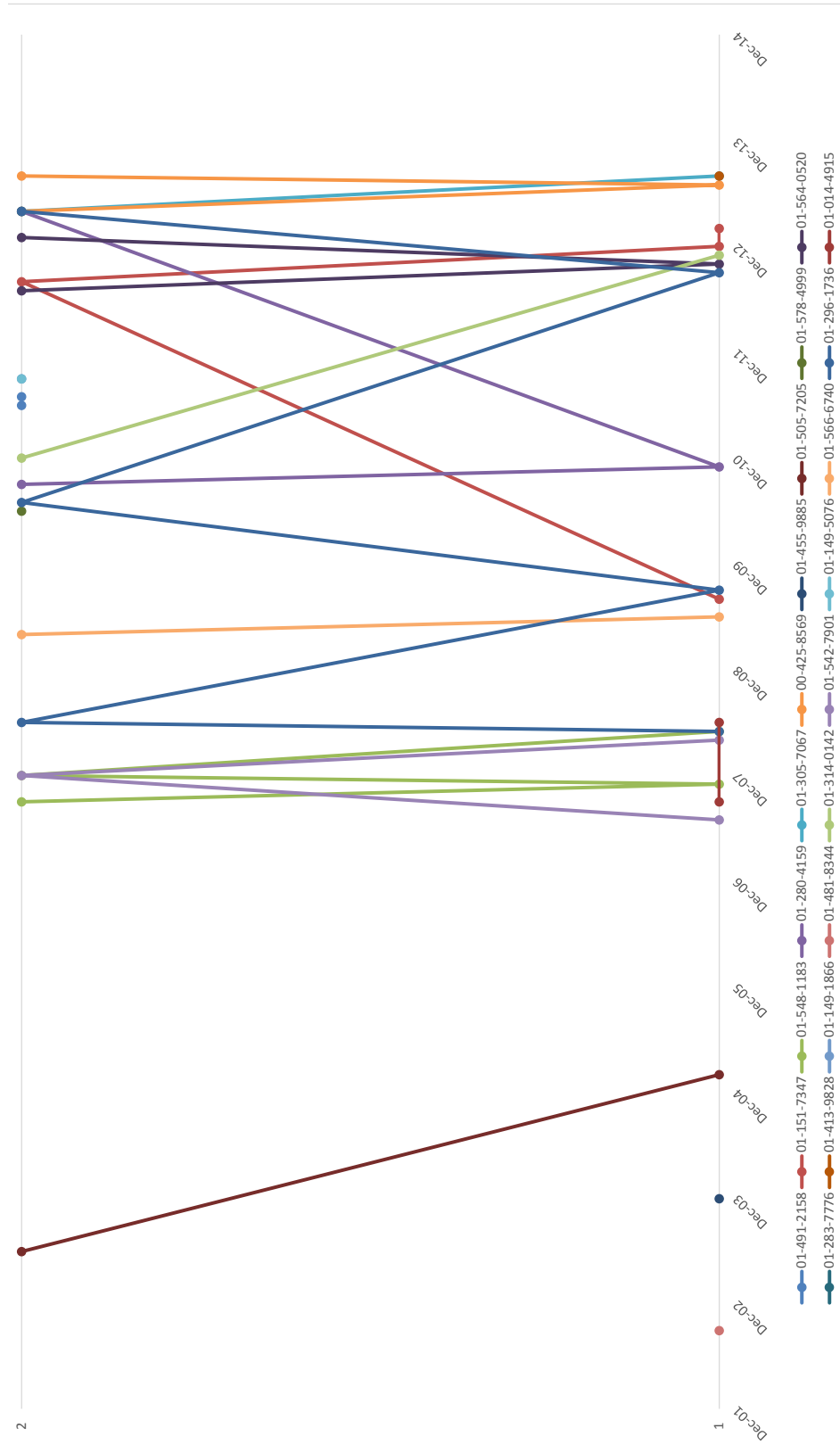


Figure 135. AAC state cluster change for 339 NIINs in the LTV SERA

APPENDIX F

Attempts at 339 Resolution Time Distribution Characterization

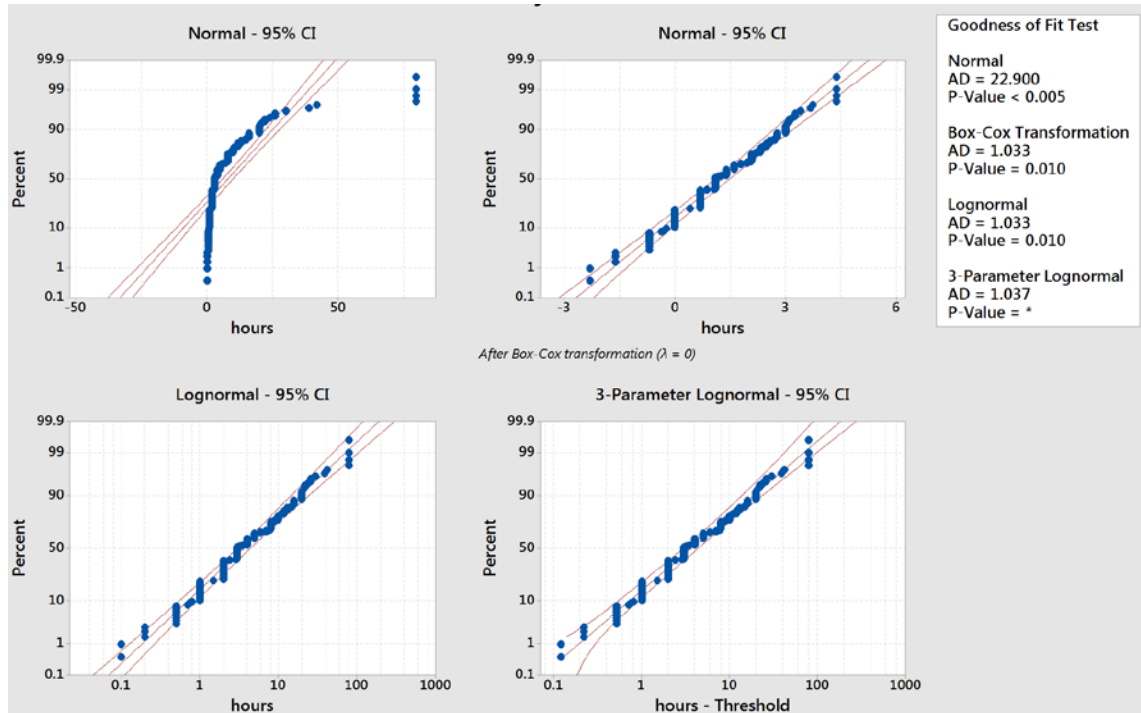


Figure 137. LTV 339 hours - normal and lognormal fit tests

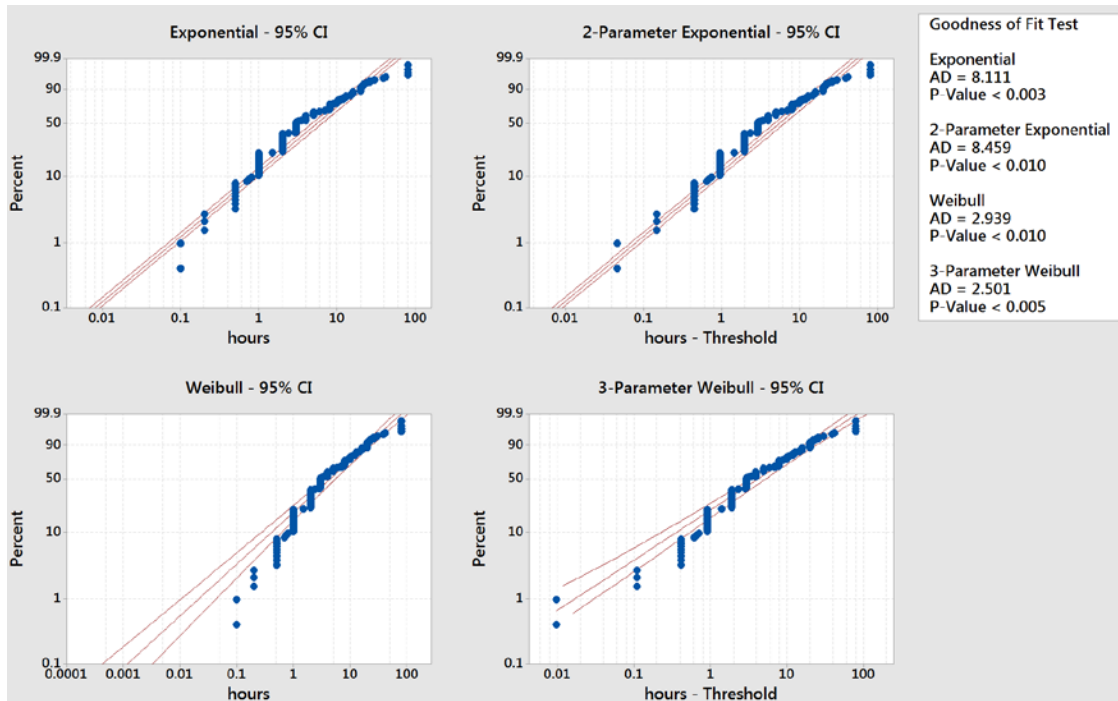


Figure 138. LTV 339 hours - exponential and Weibull fit tests

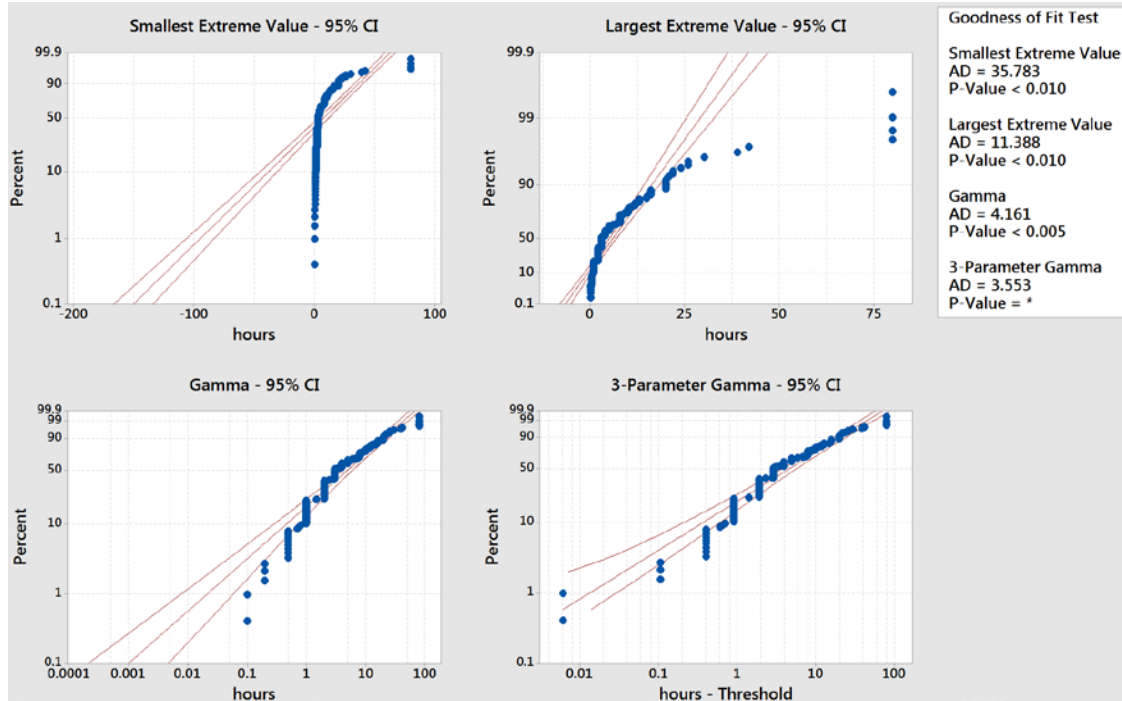


Figure 139. LTV 339 hours – extreme value and gamma fit tests

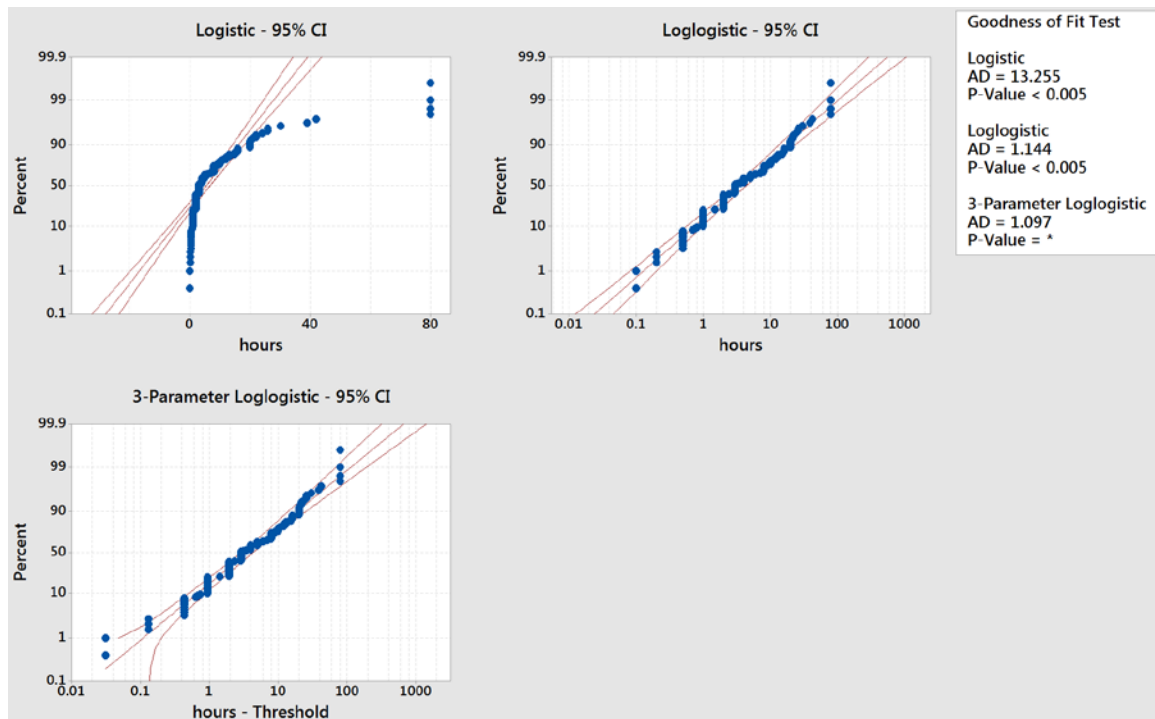
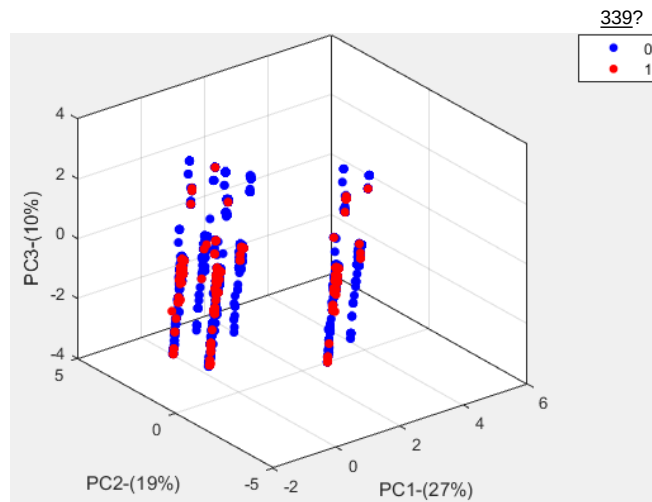
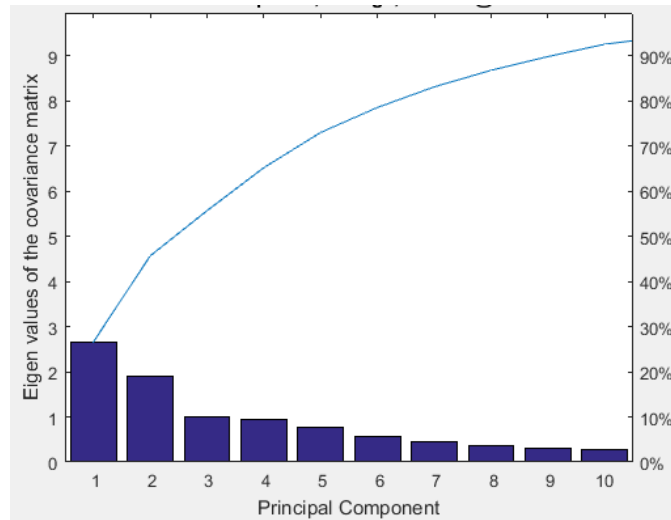
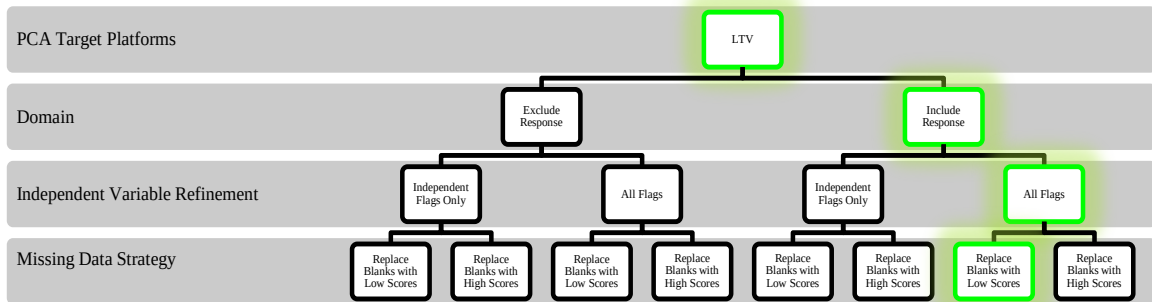
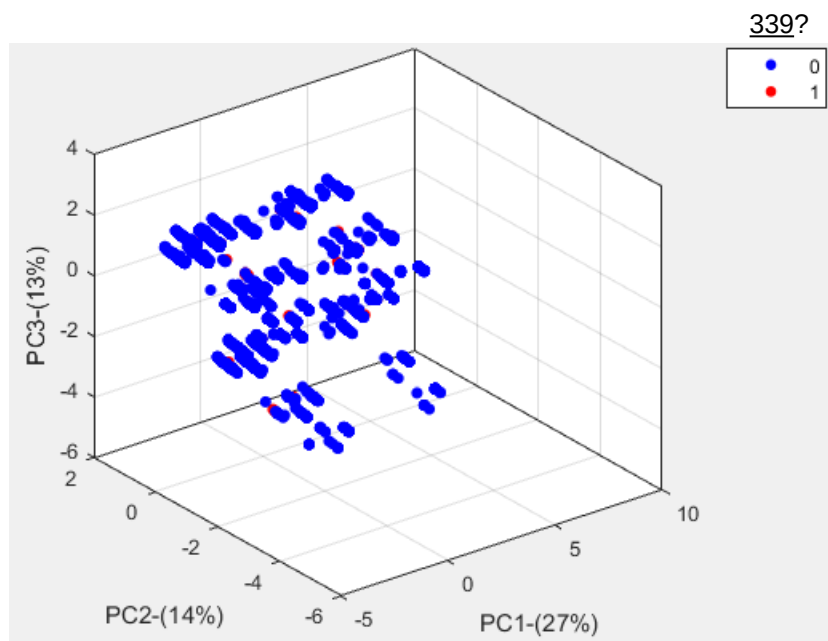
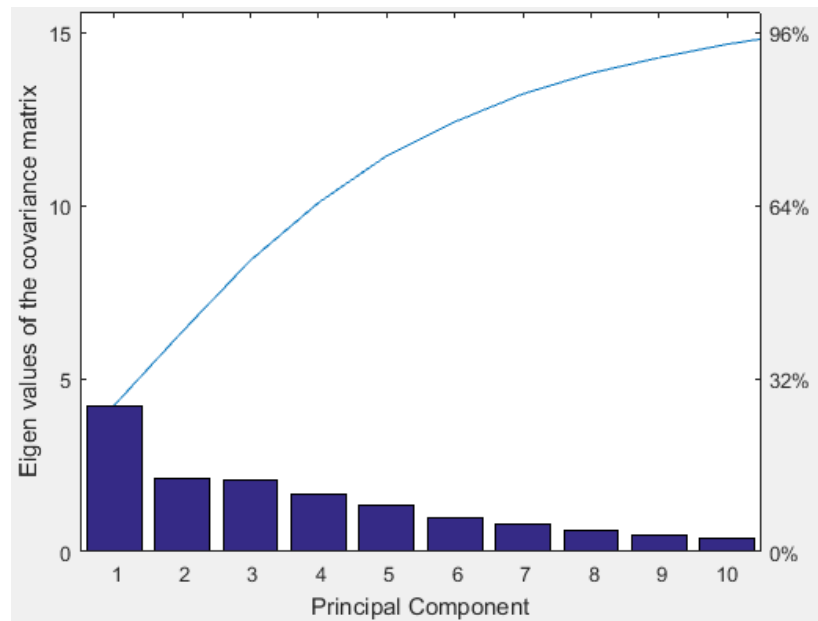
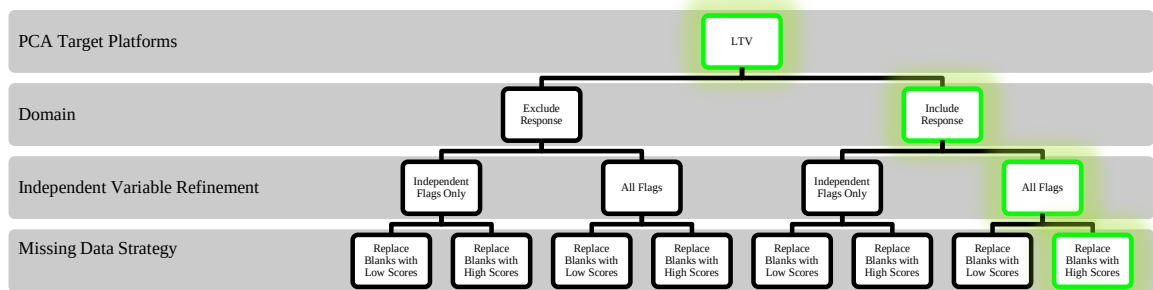


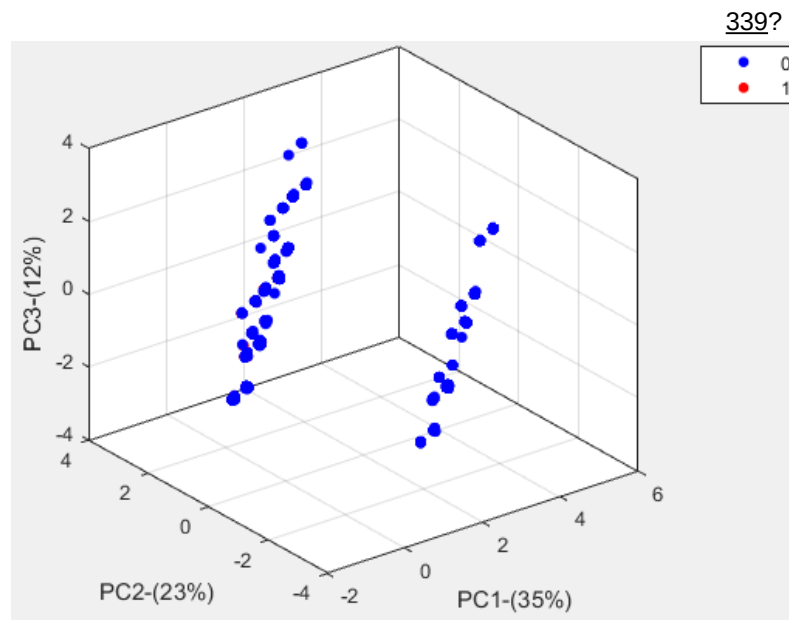
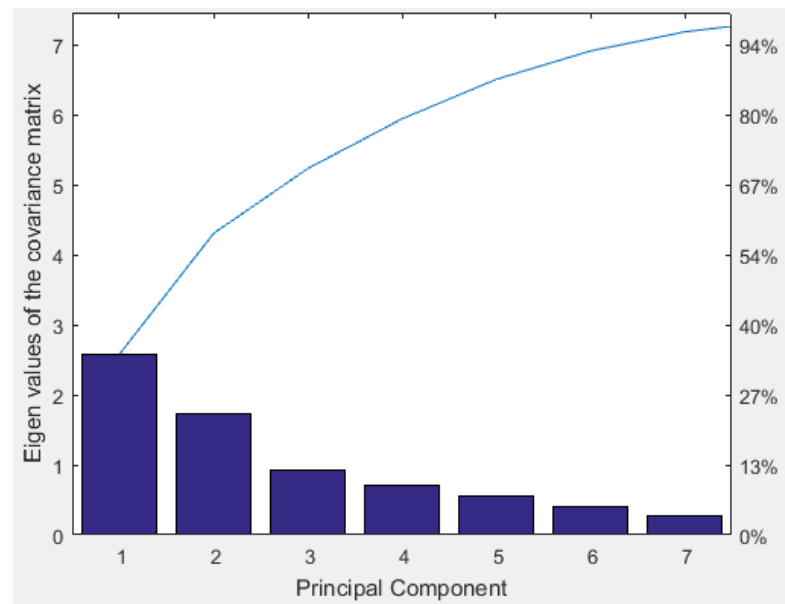
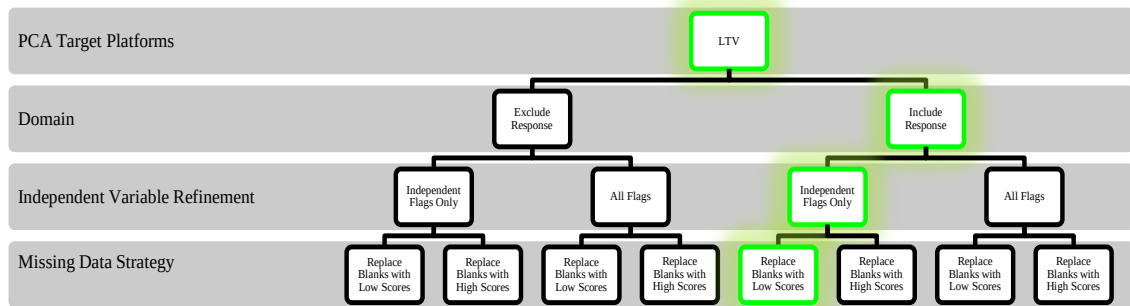
Figure 140. LTV 339 hours – logistic and loglogistic fit tests

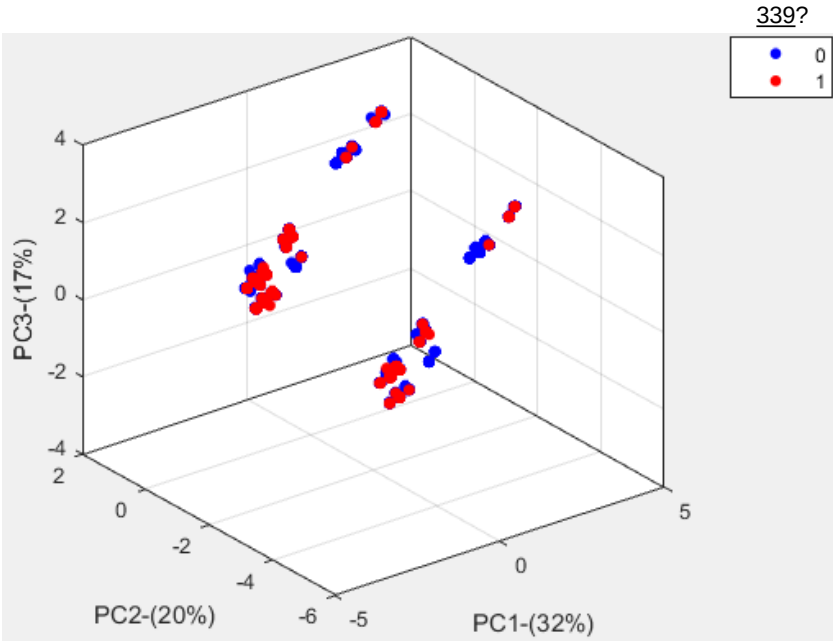
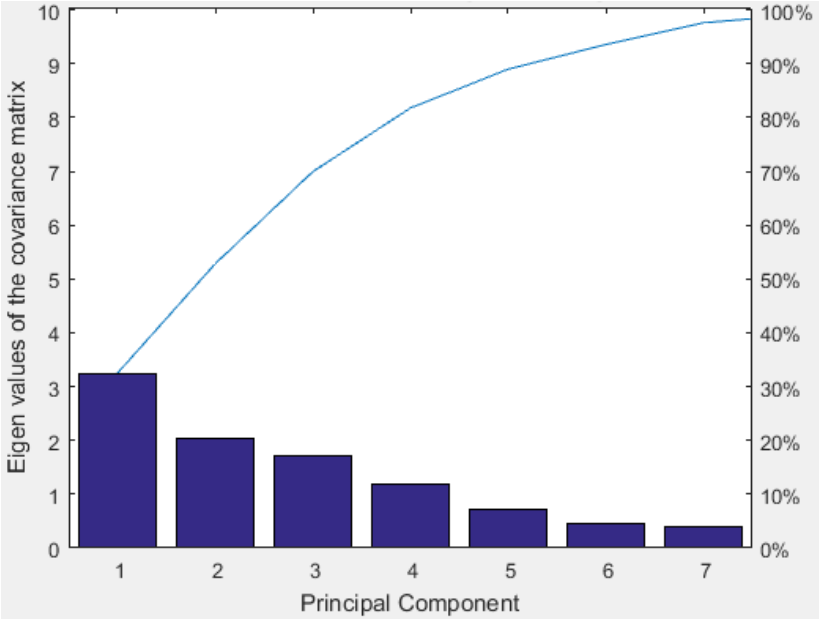
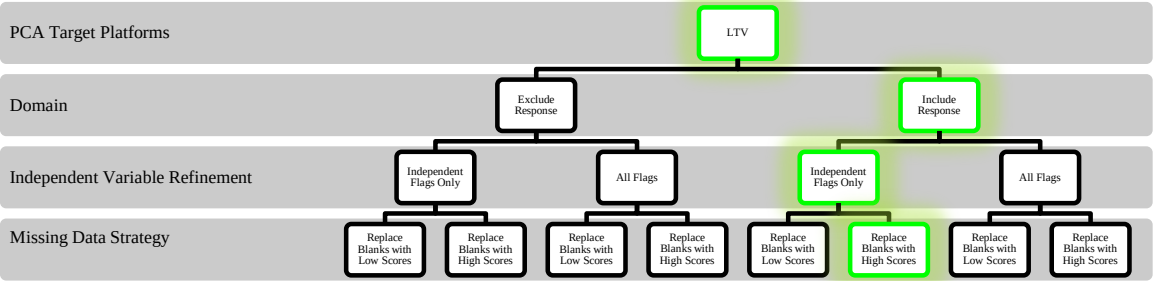
APPENDIX G

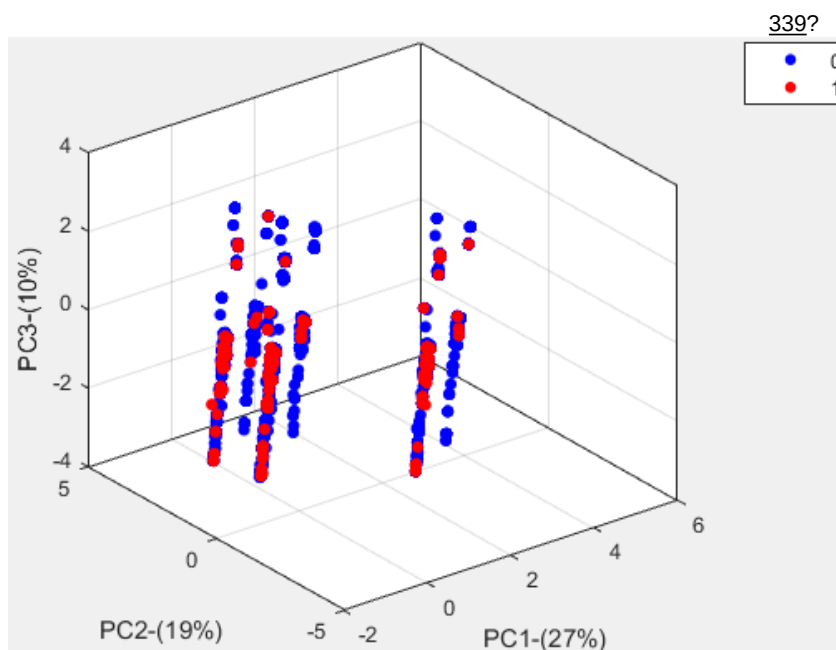
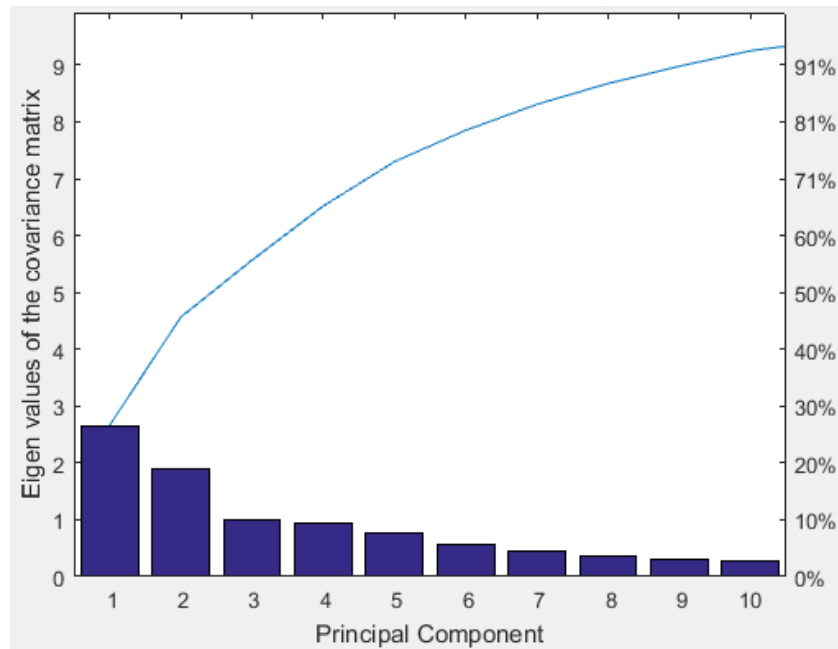
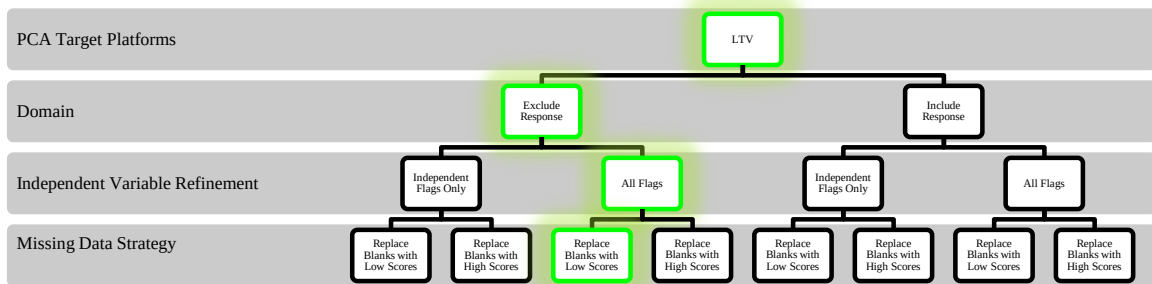
PCA Sensitivity Results: LTV

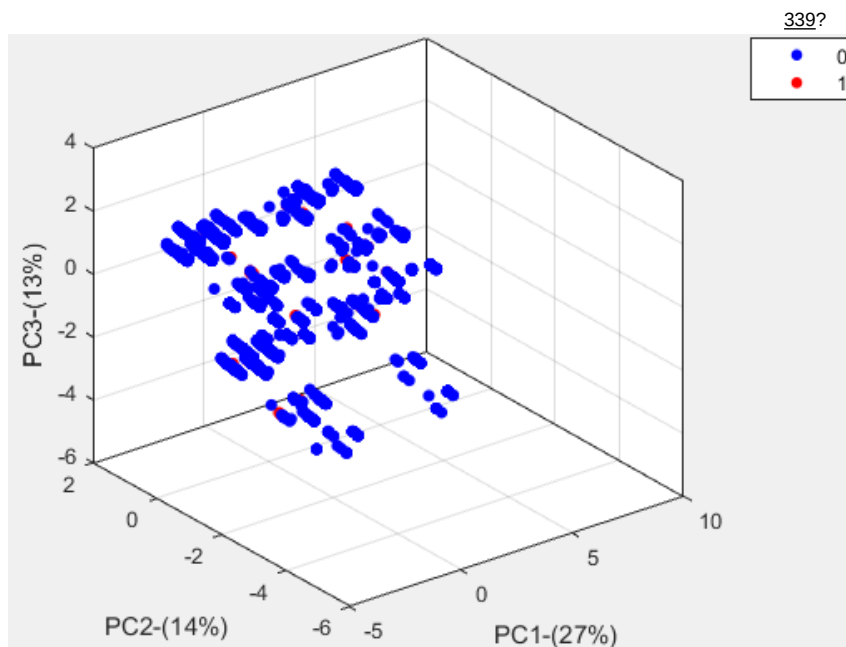
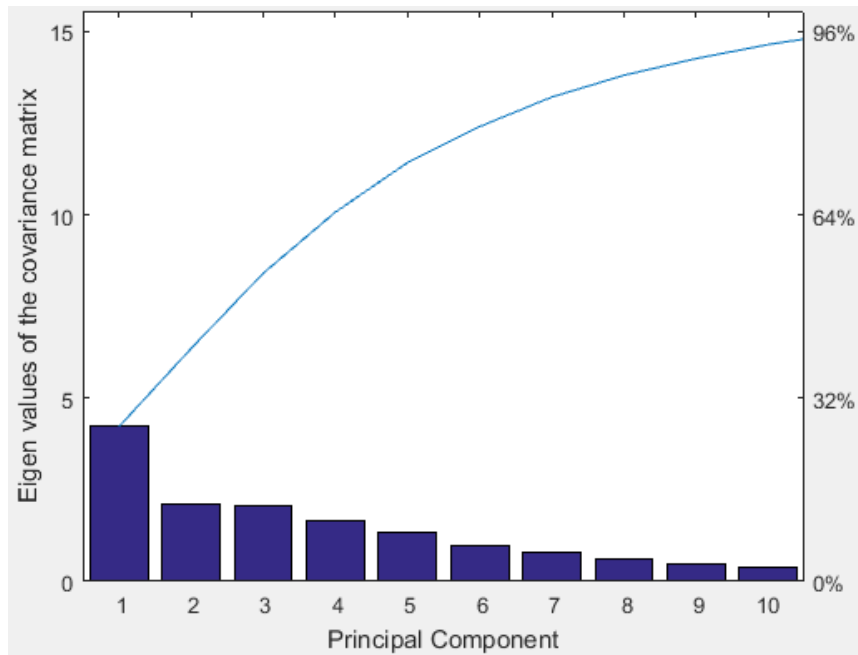
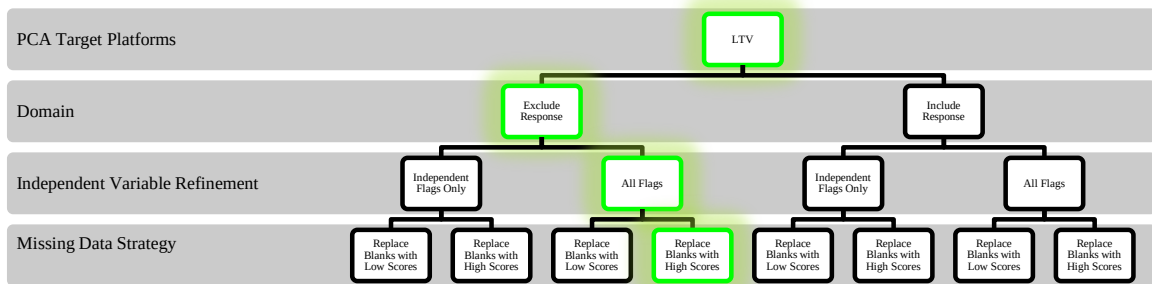


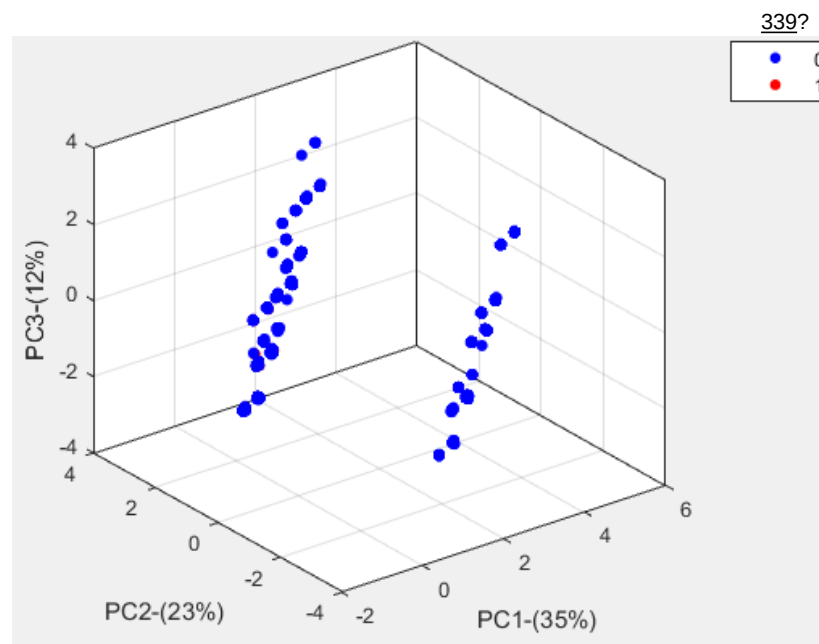
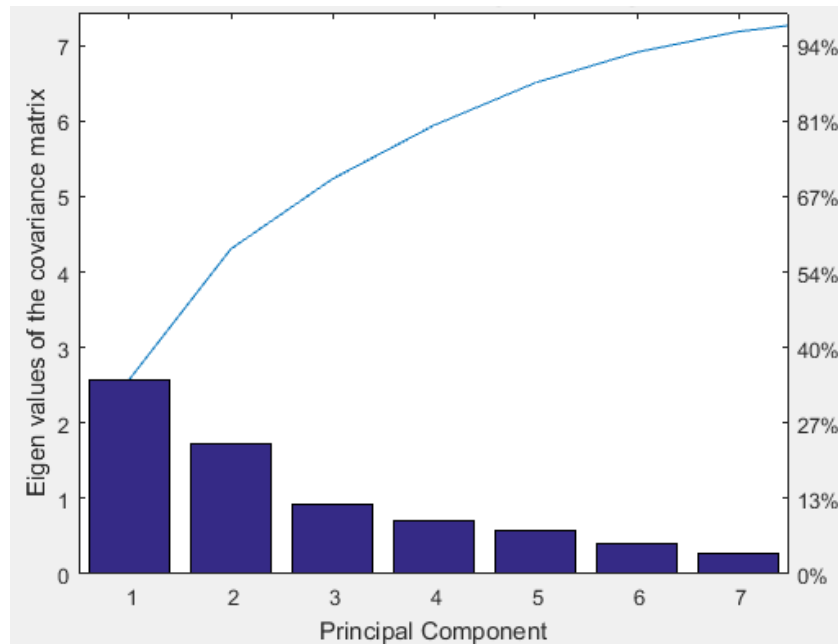
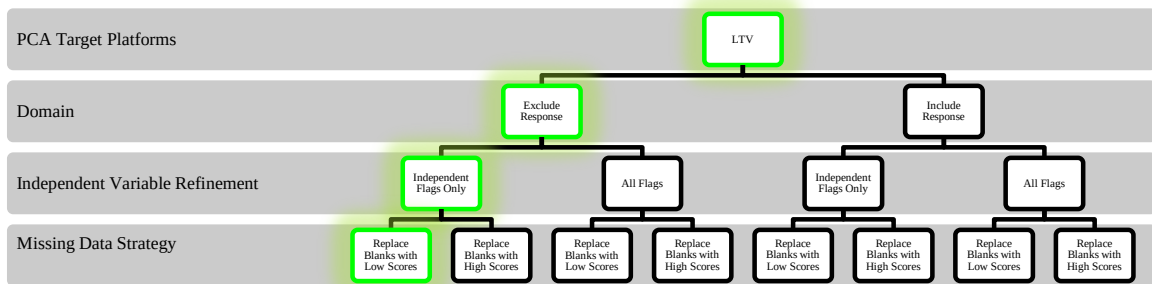


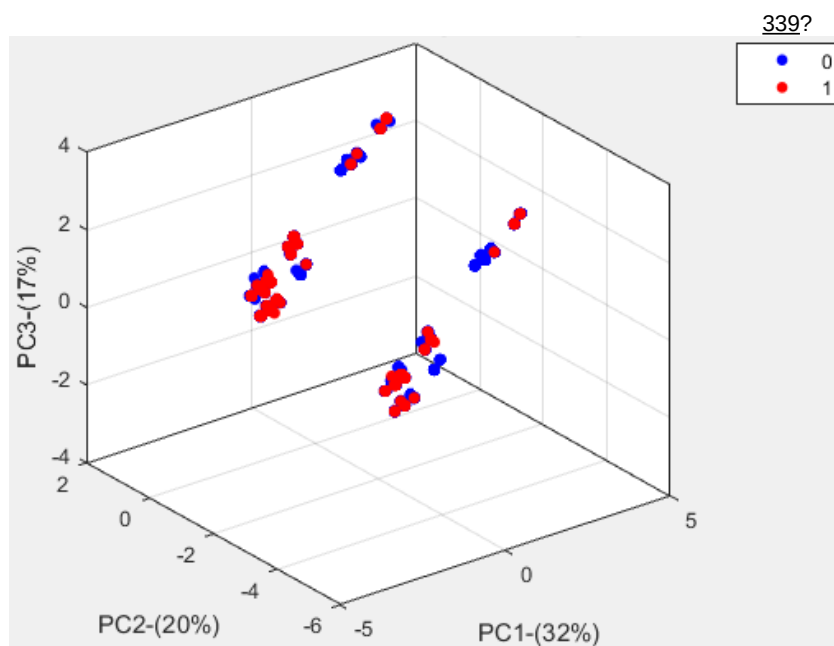
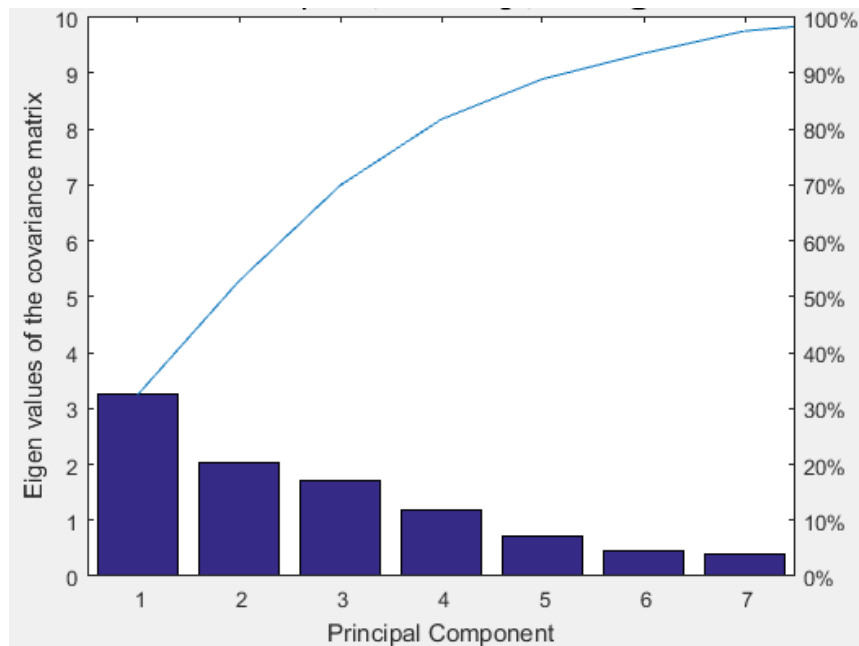
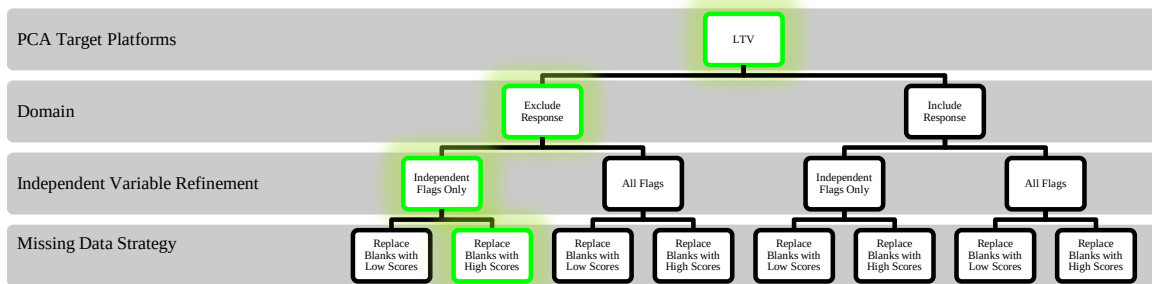






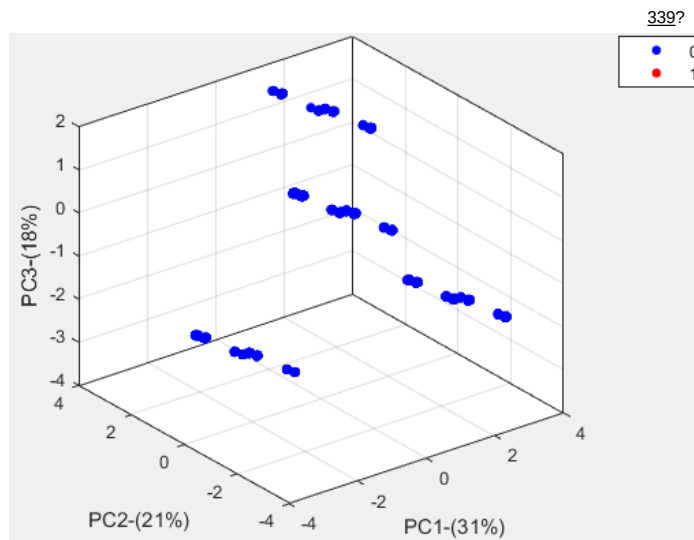
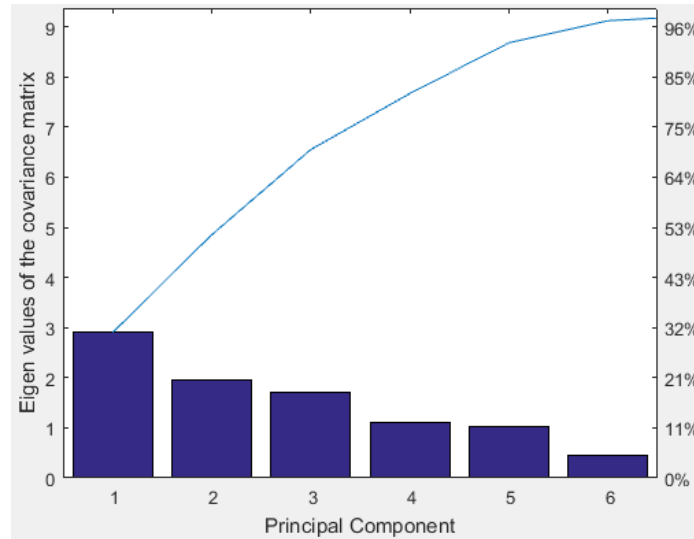
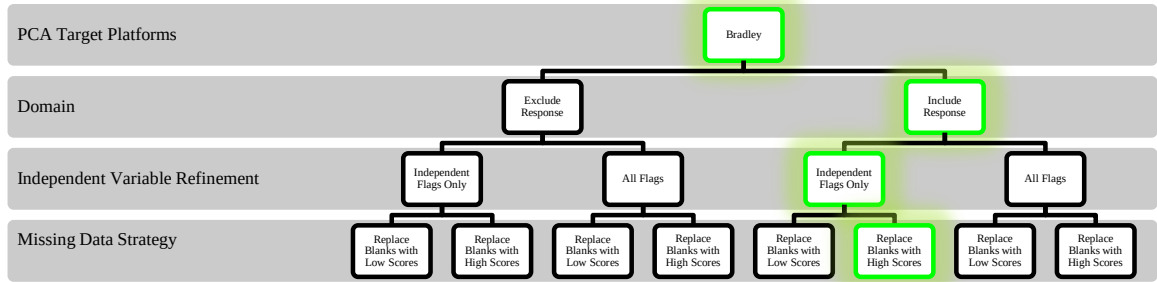


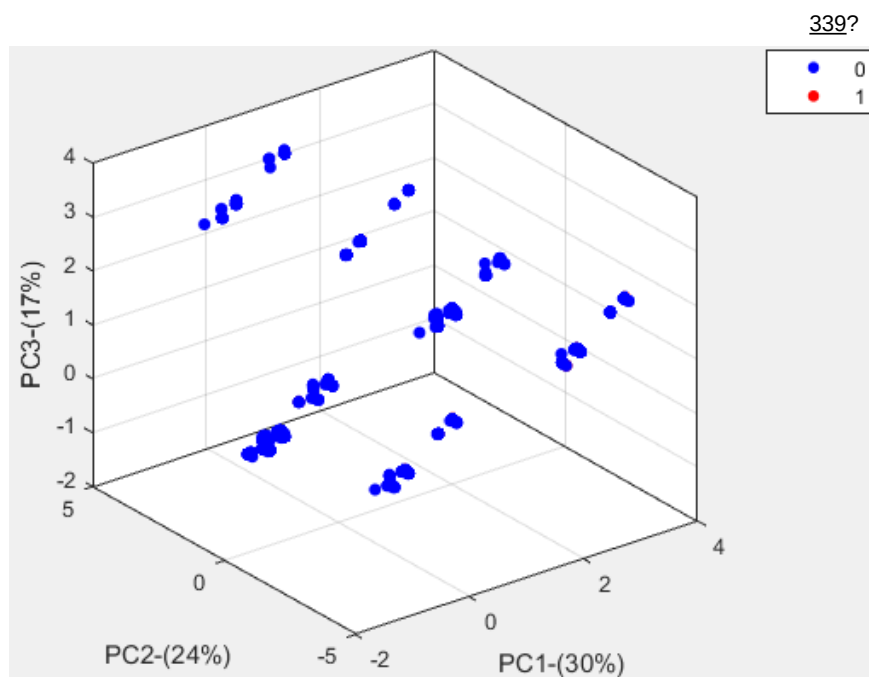
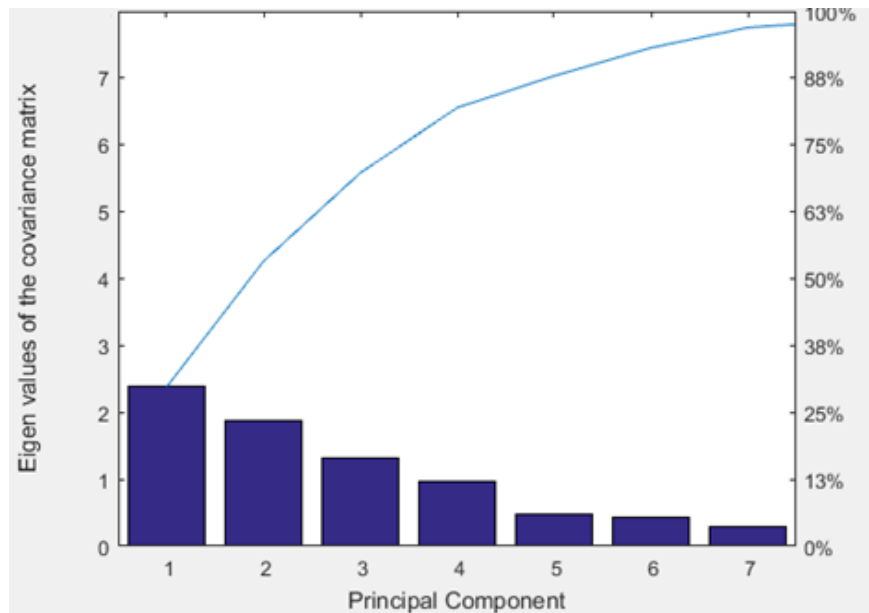
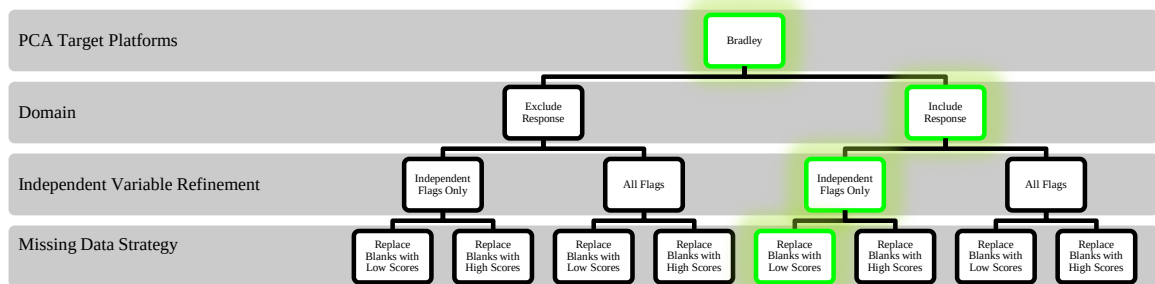


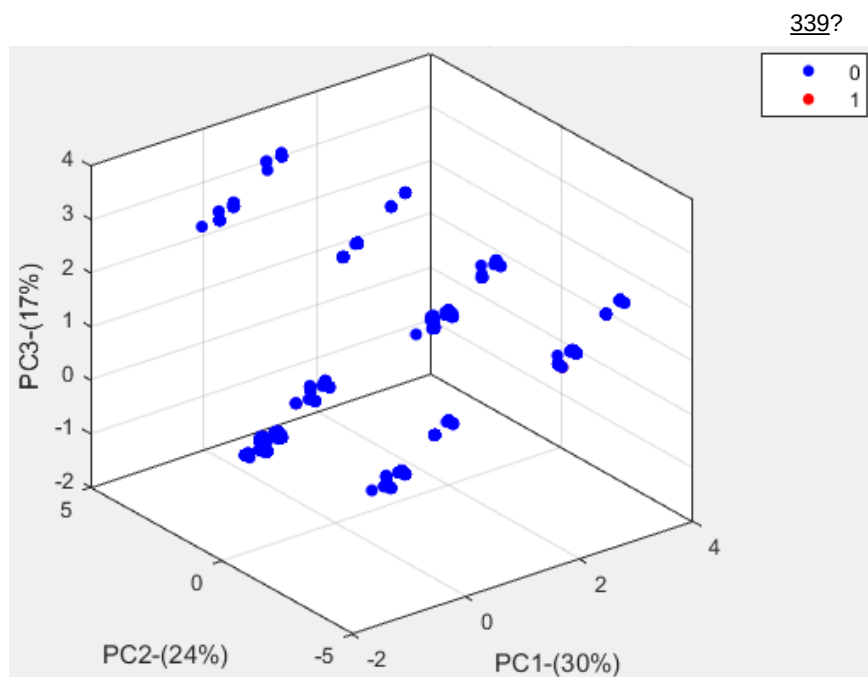
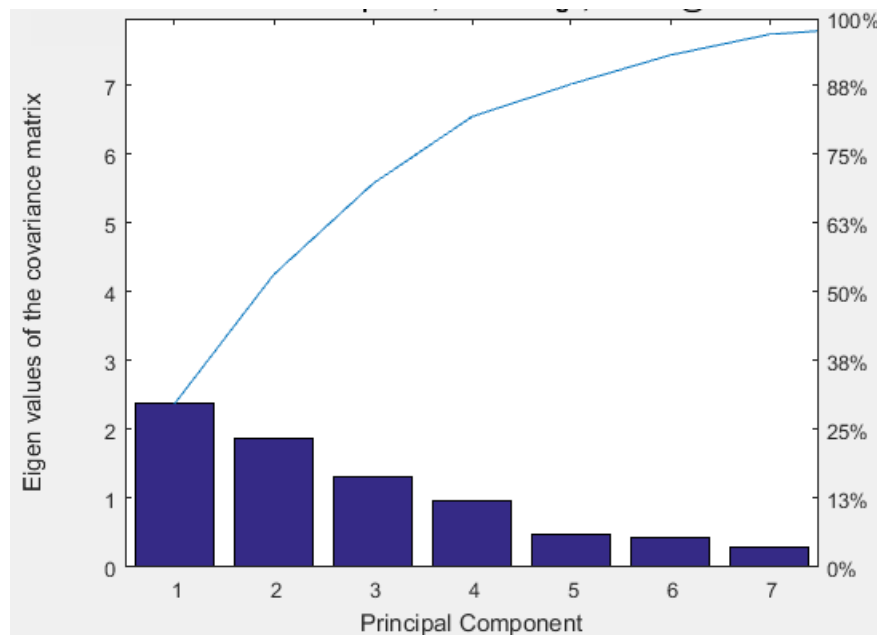
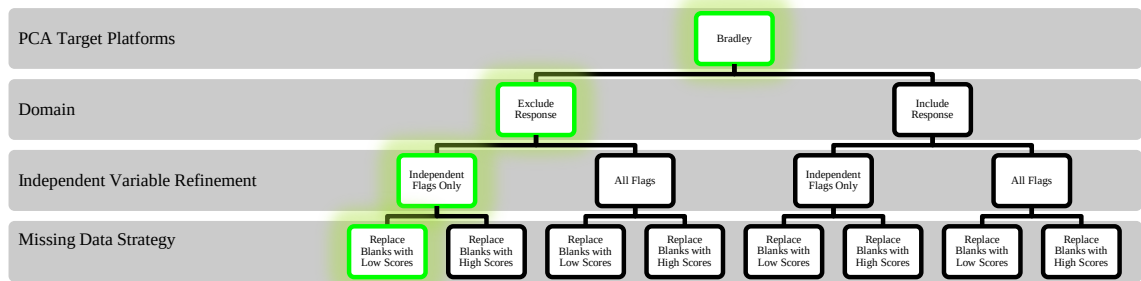


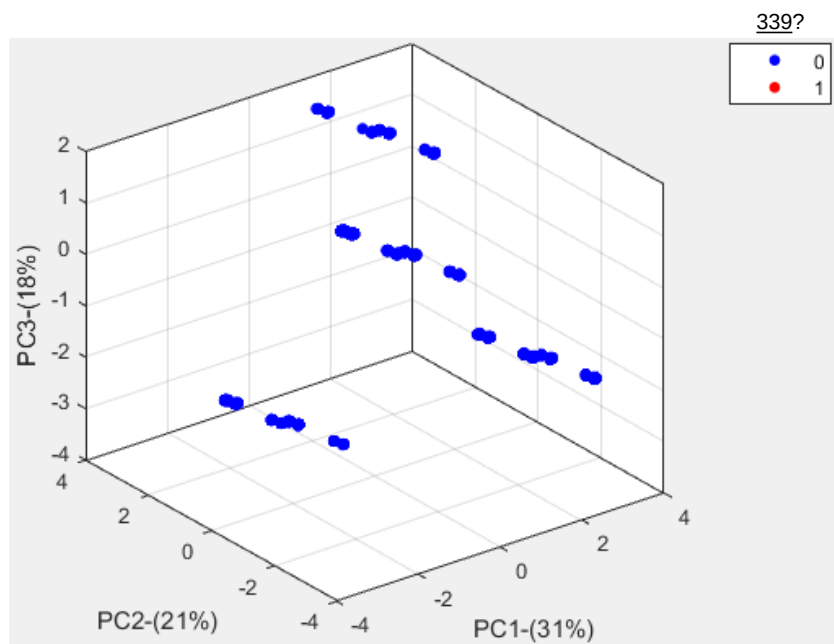
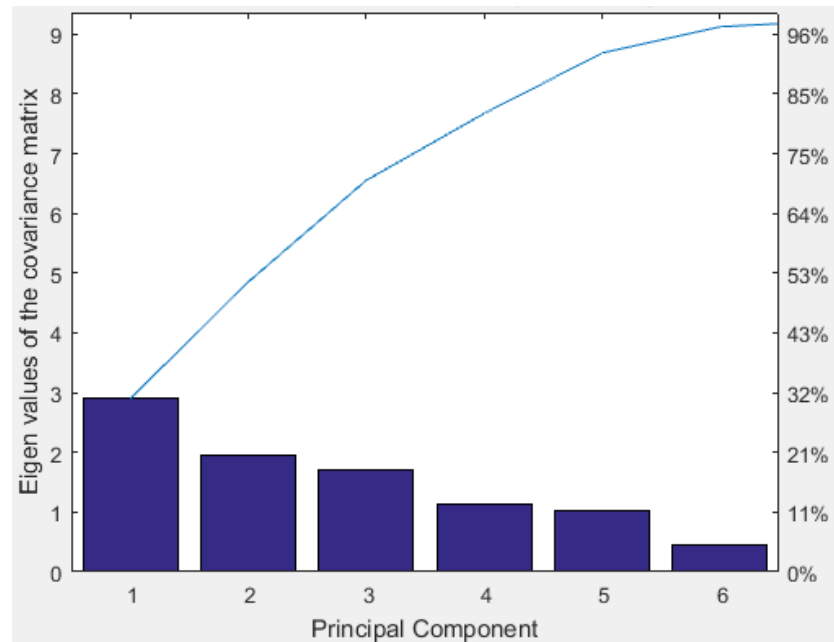
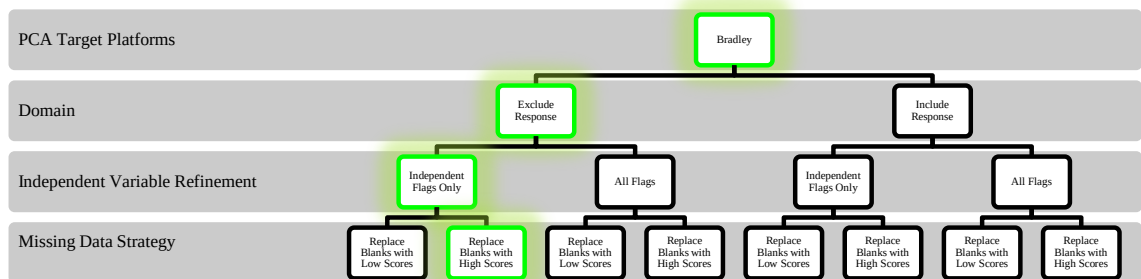
APPENDIX H

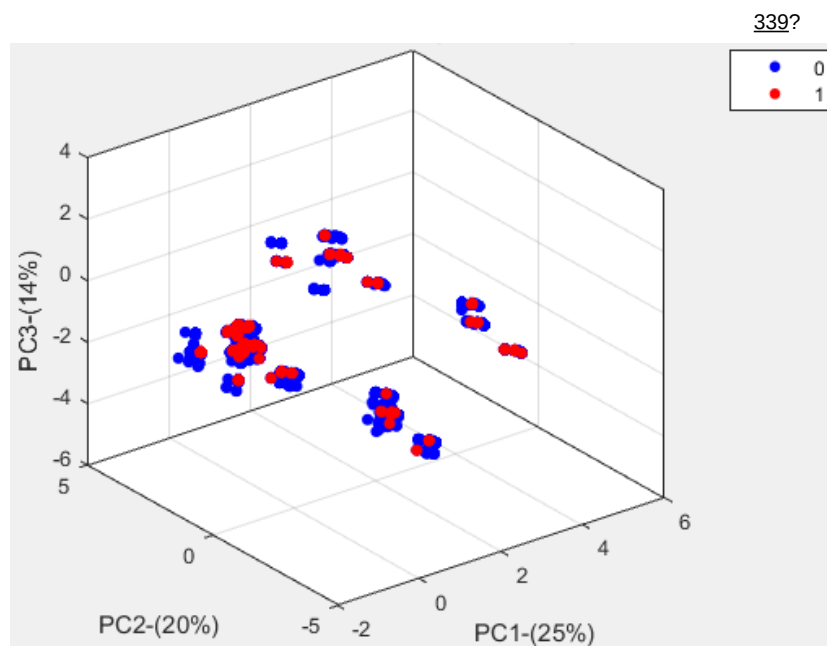
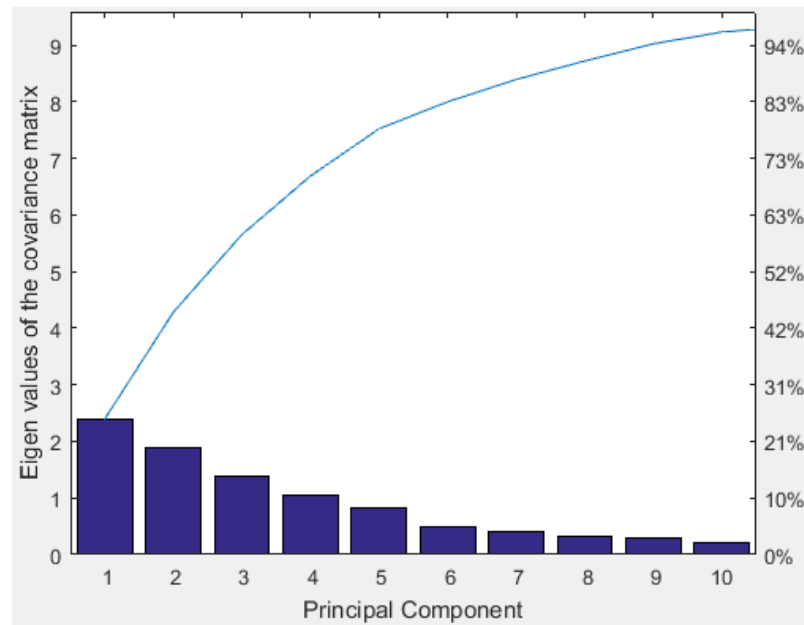
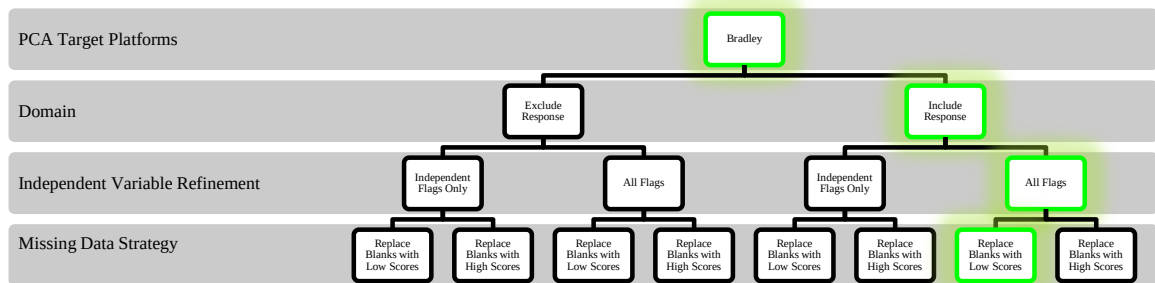
PCA Sensitivity Results: Bradley

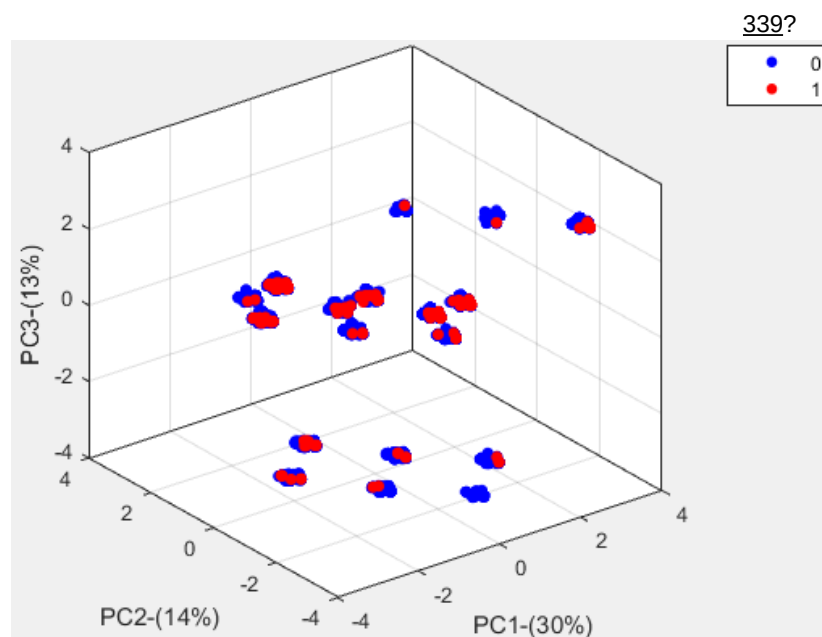
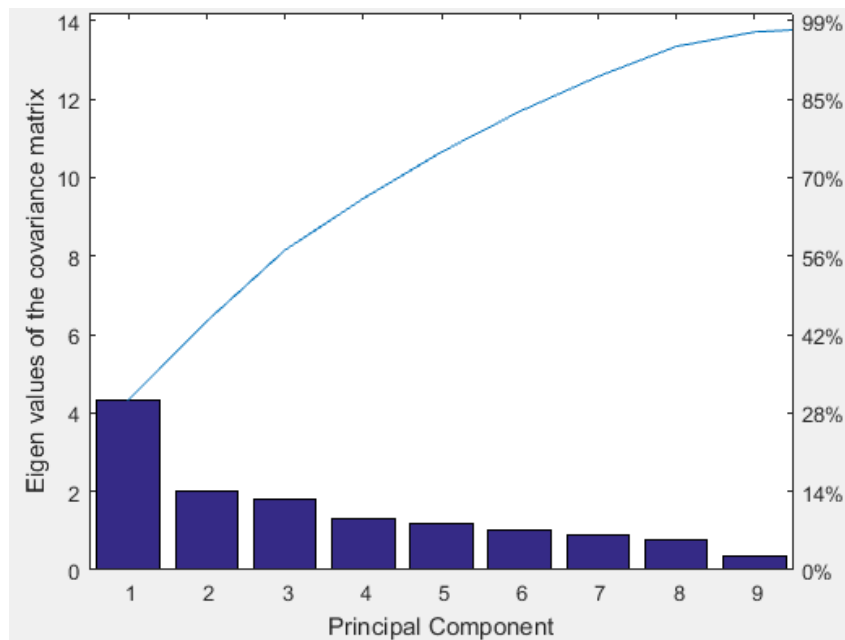
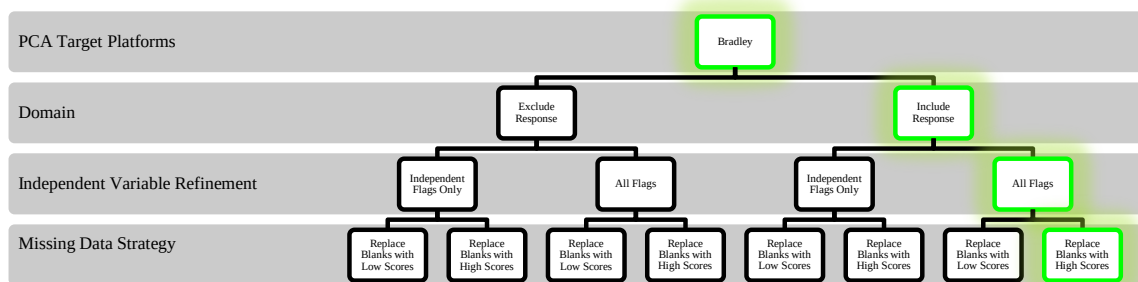


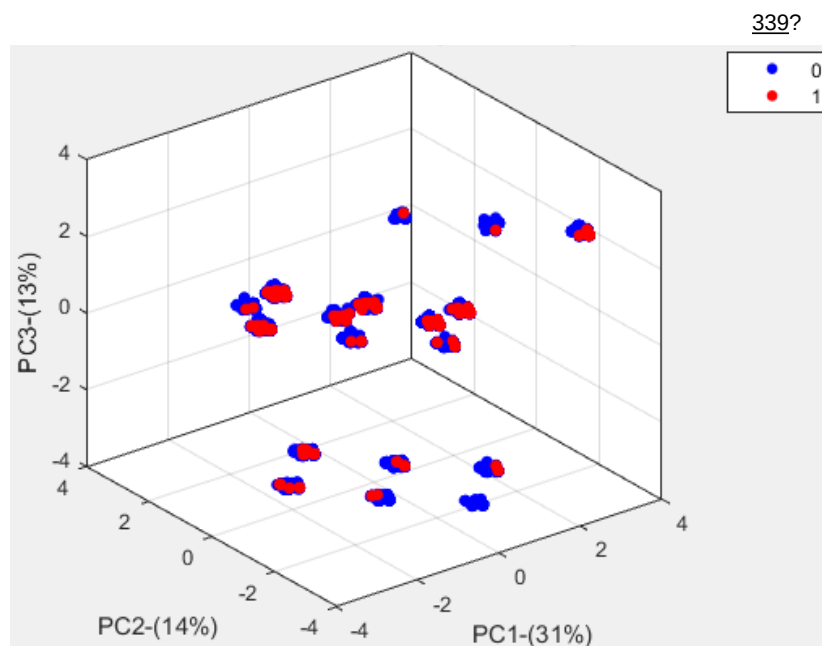
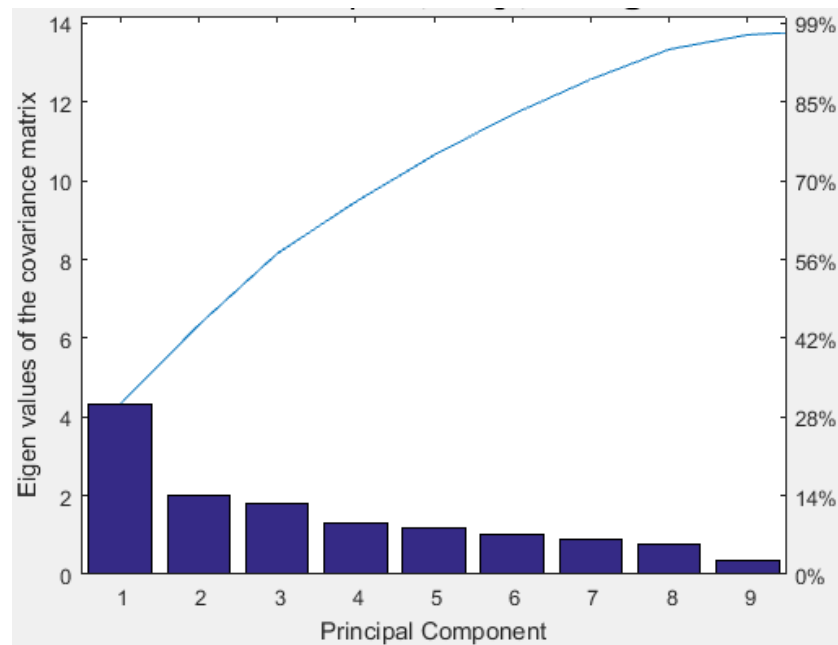
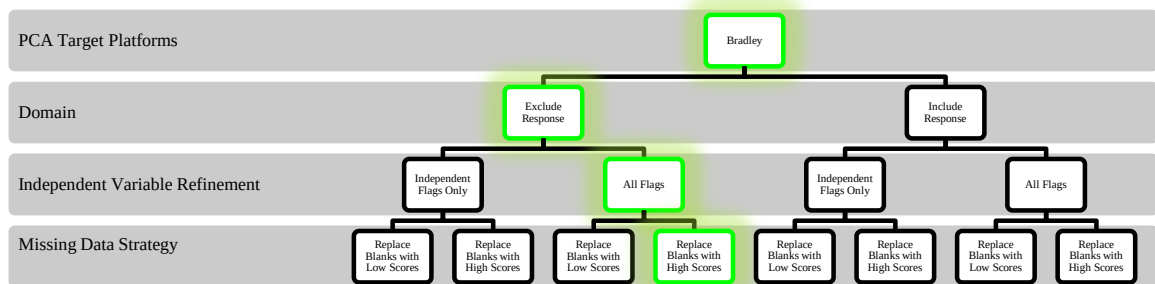


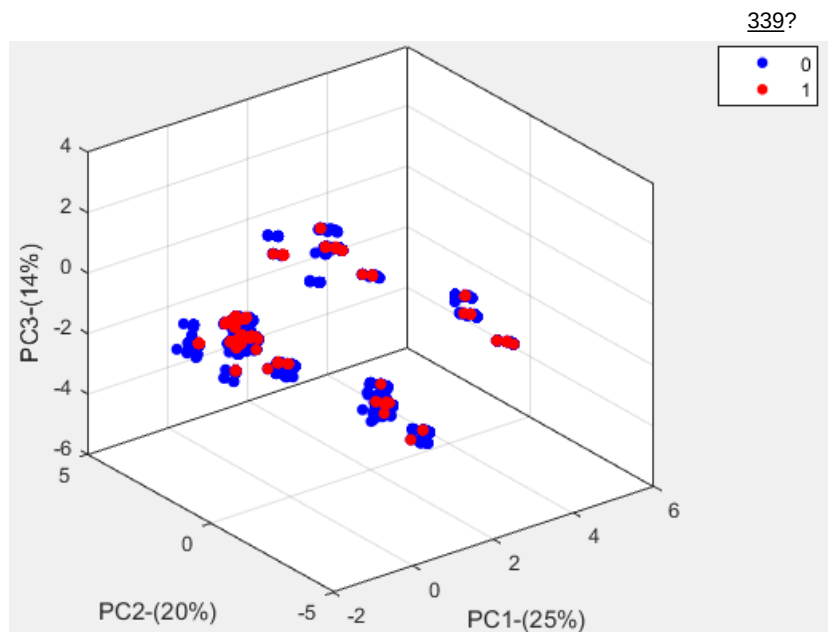
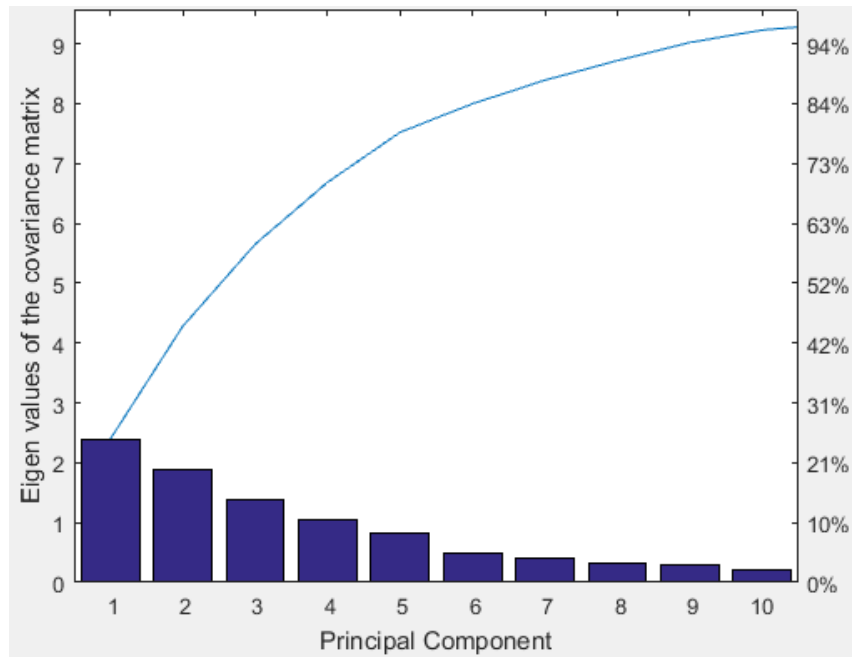
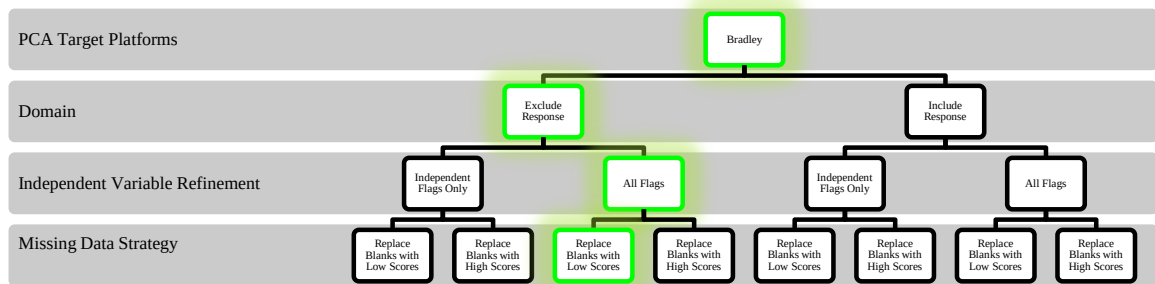






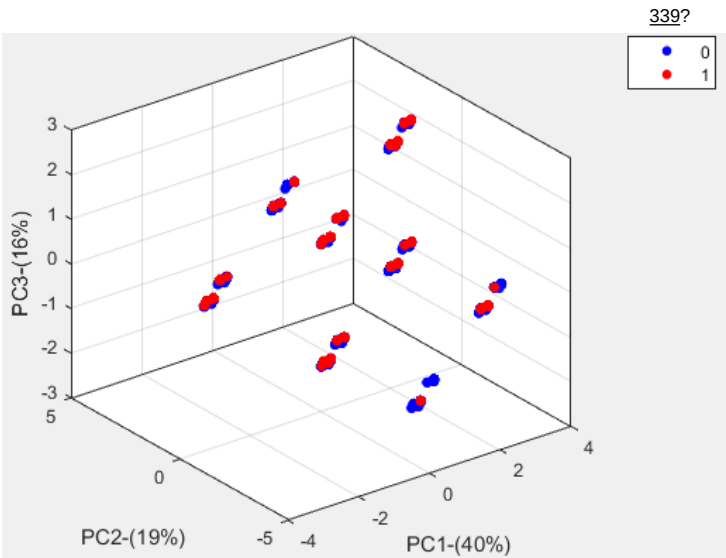
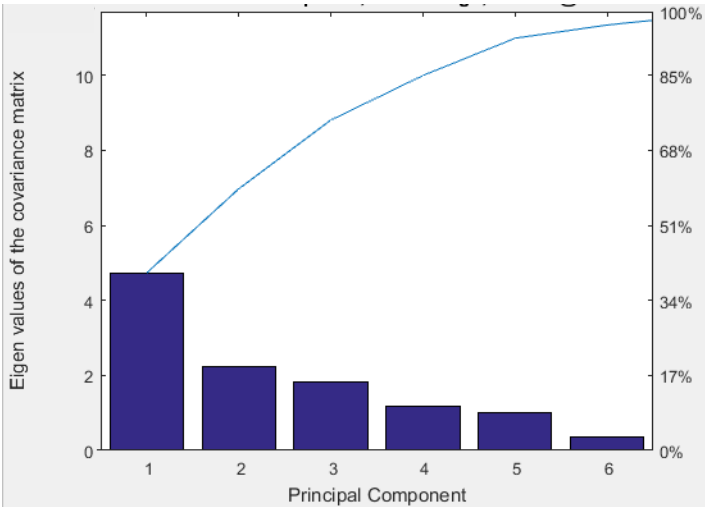
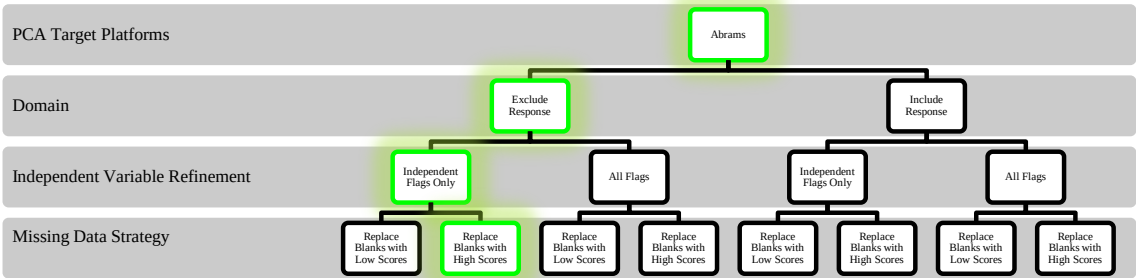


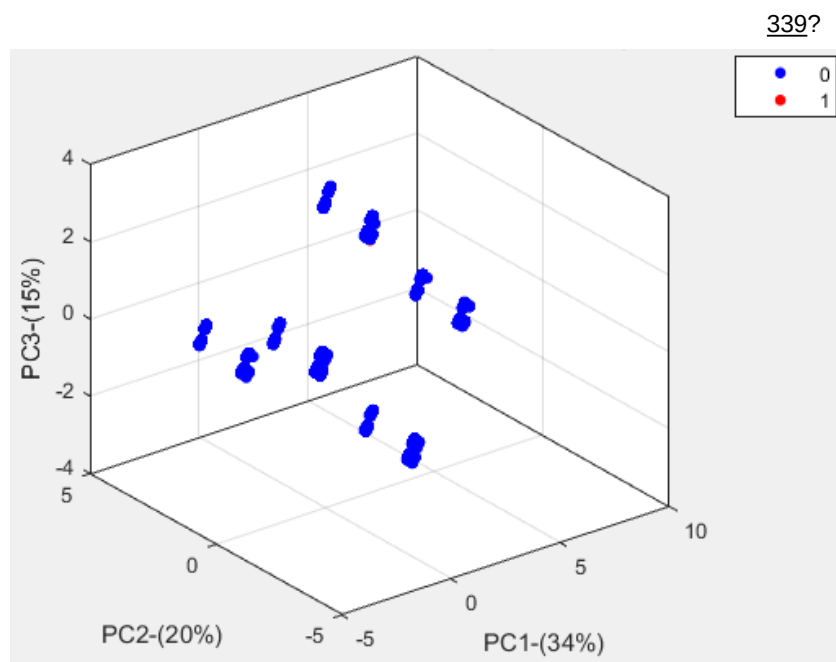
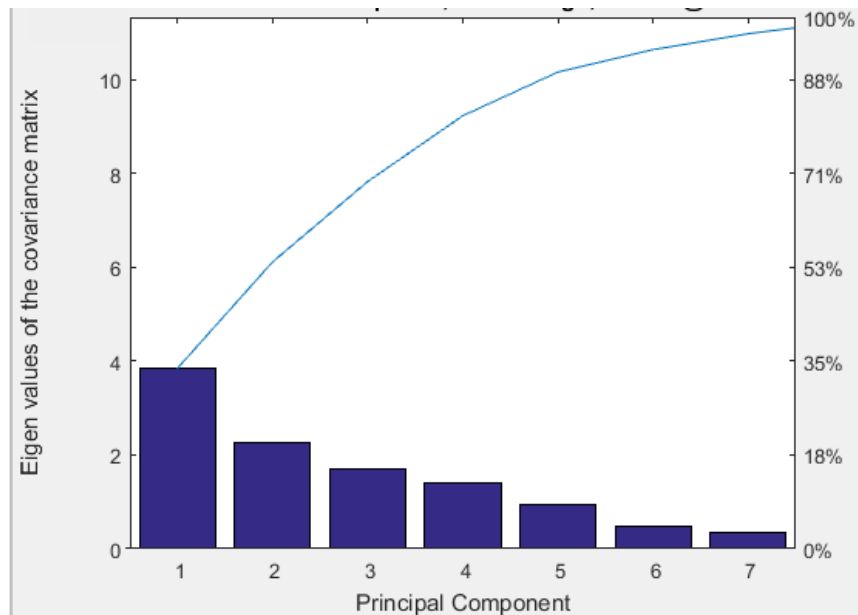
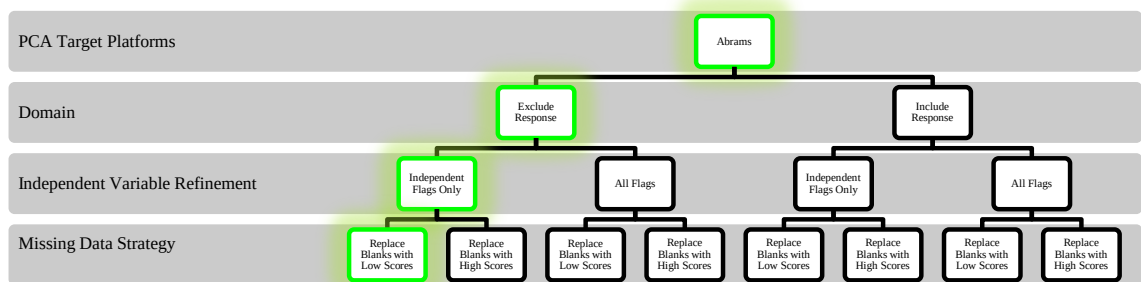


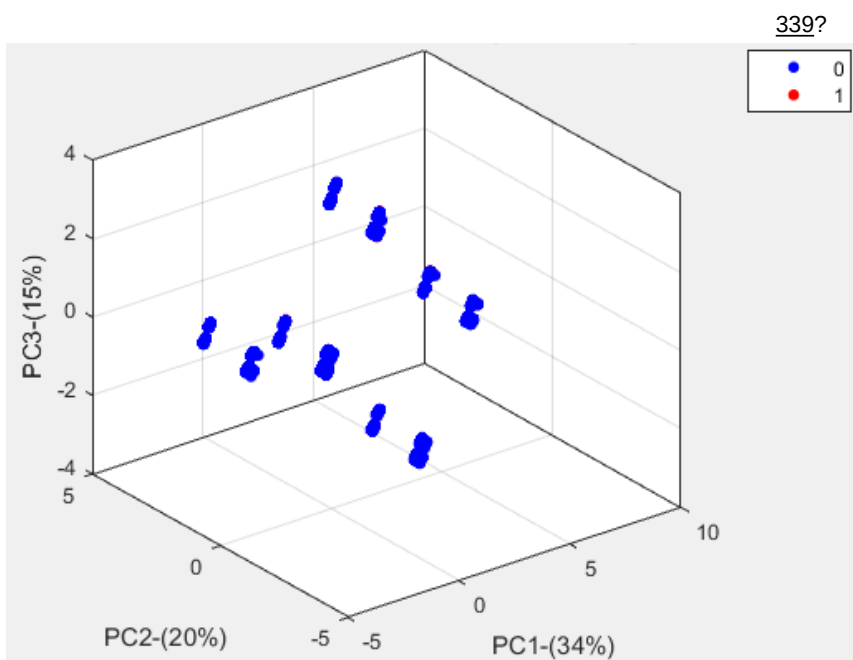
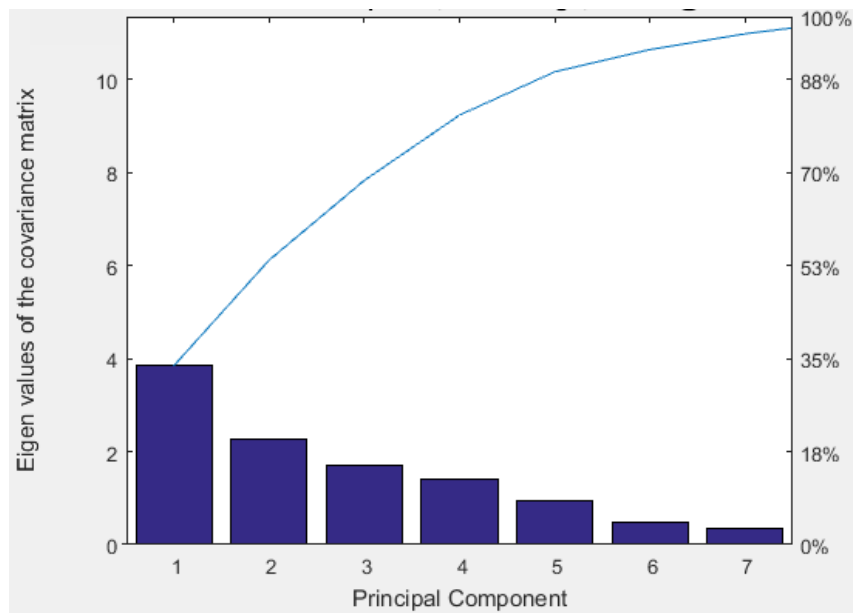
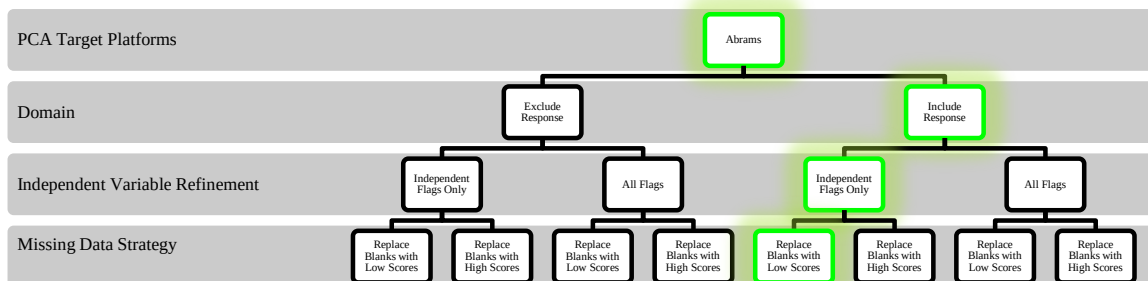


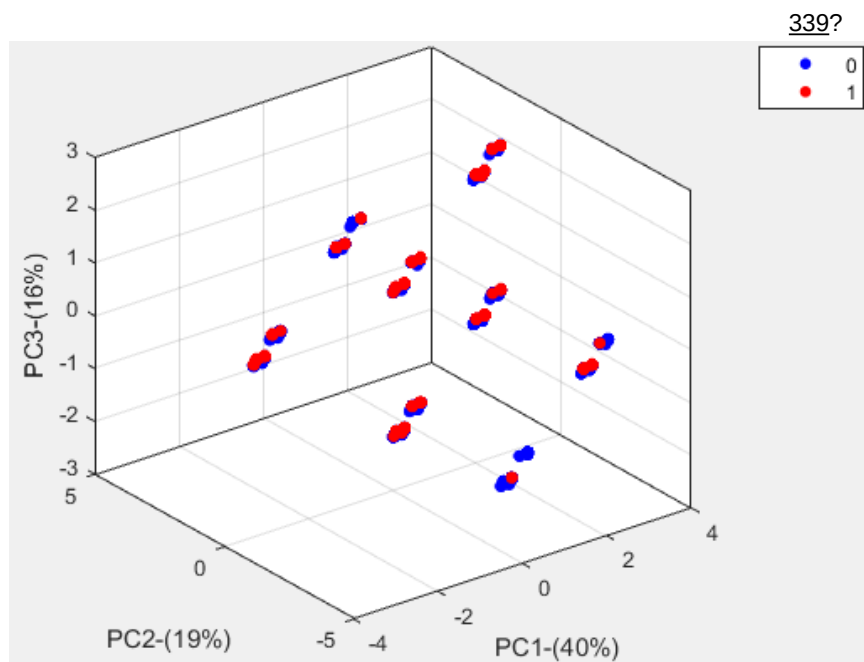
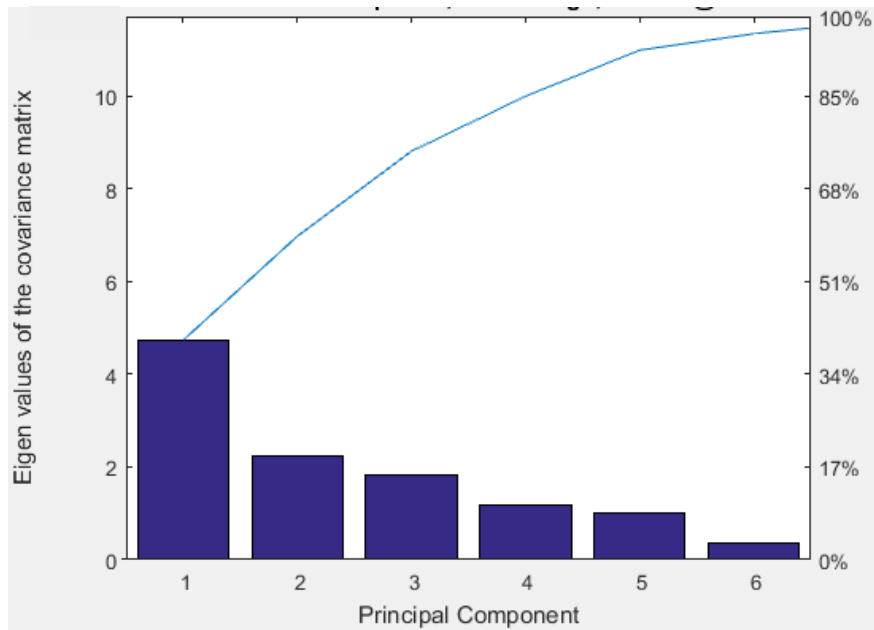
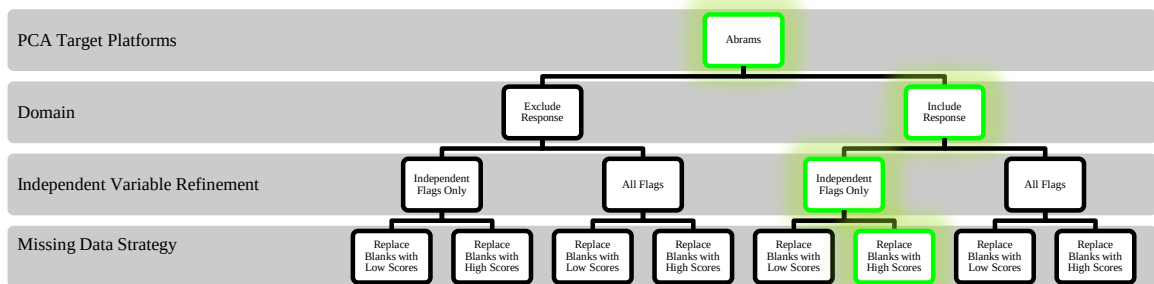
APPENDIX I

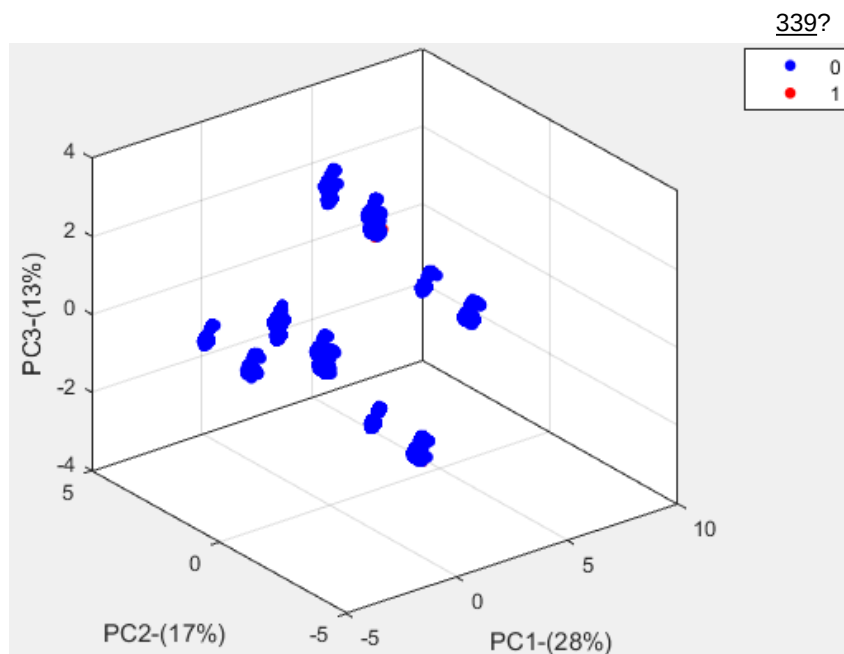
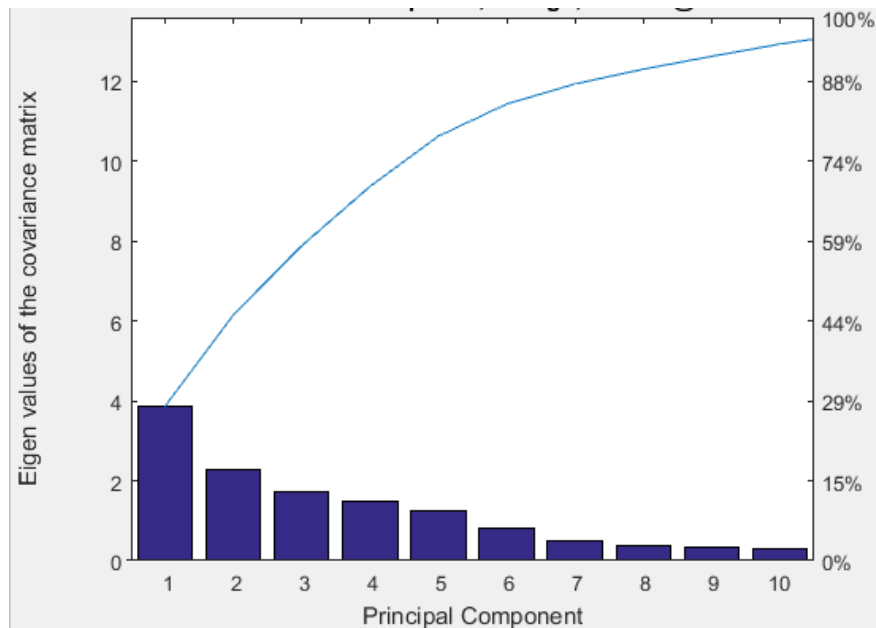
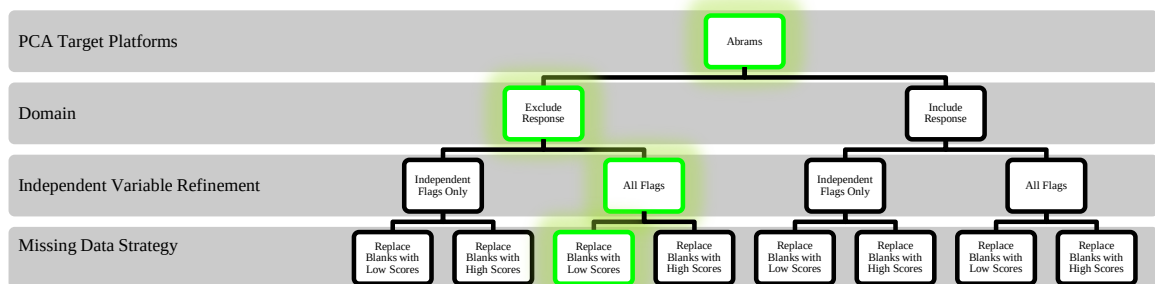
PCA Sensitivity Results: Abrams

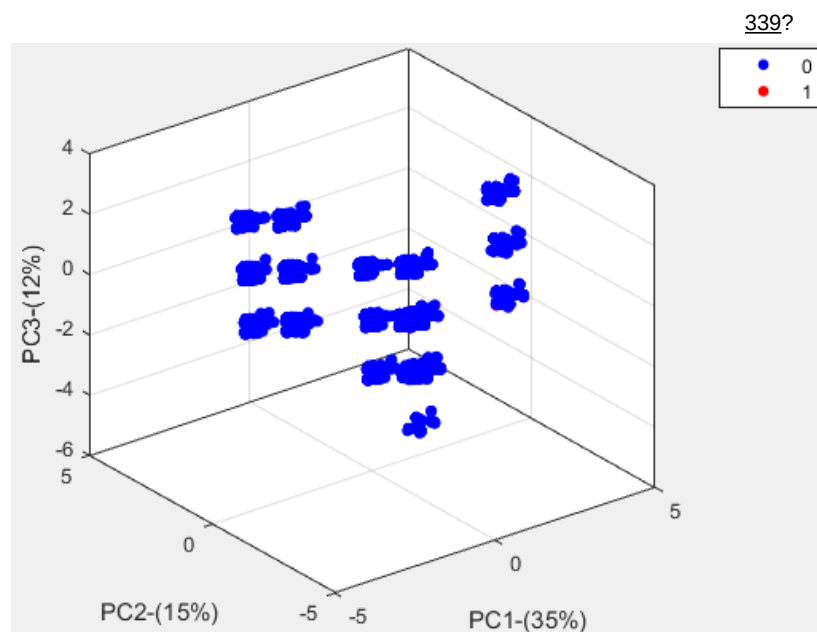
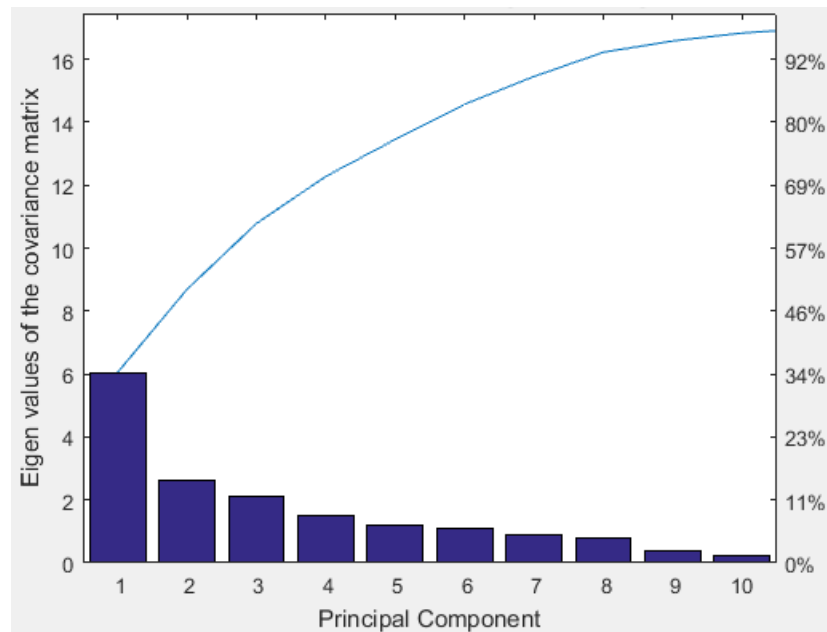
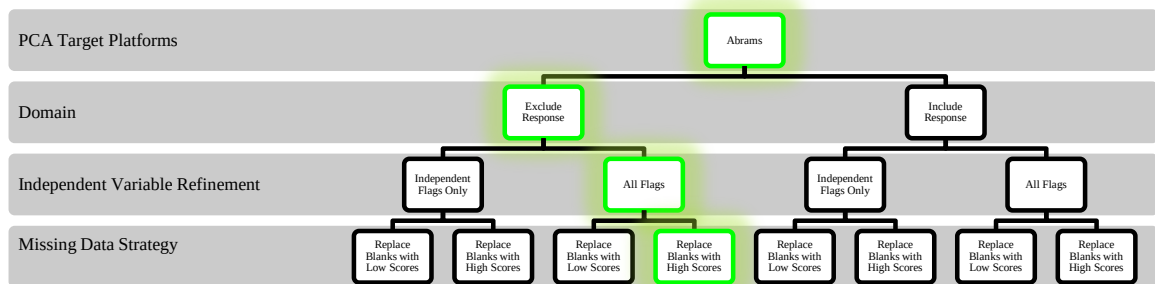


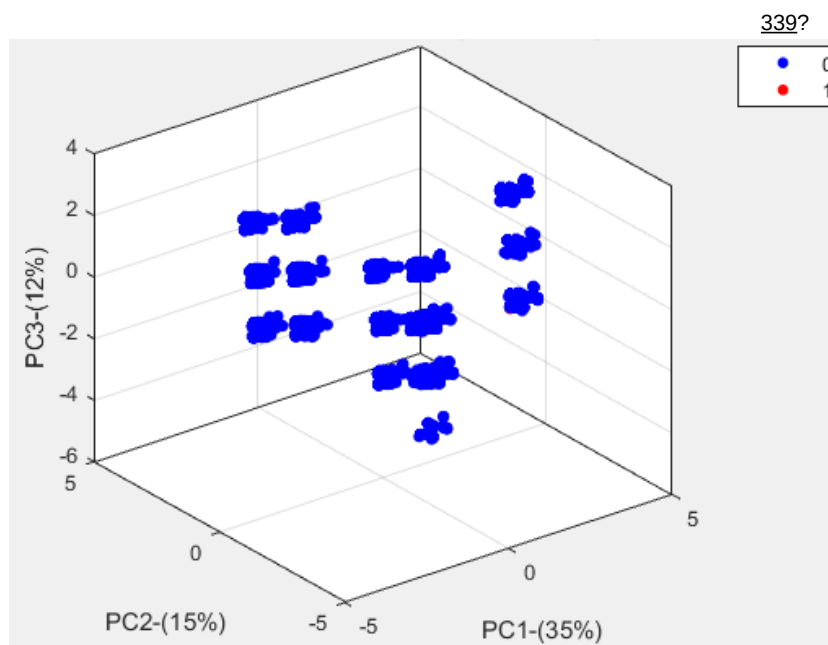
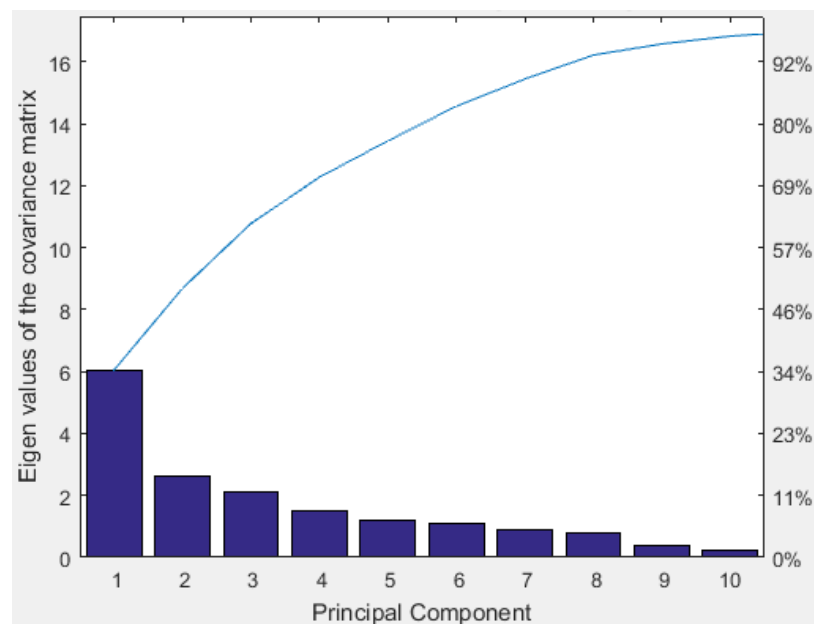
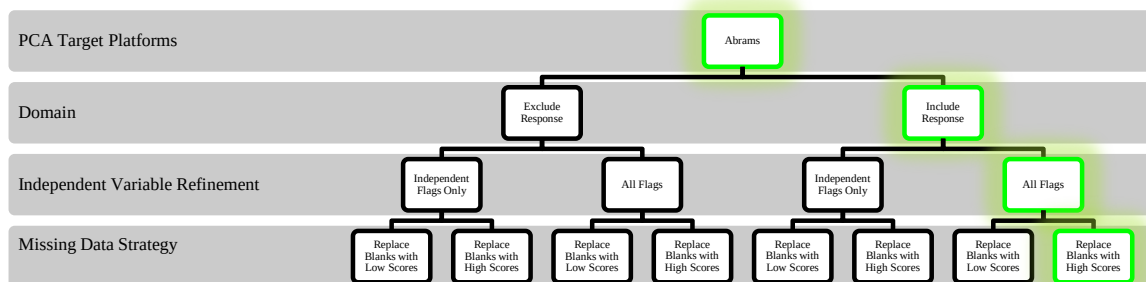


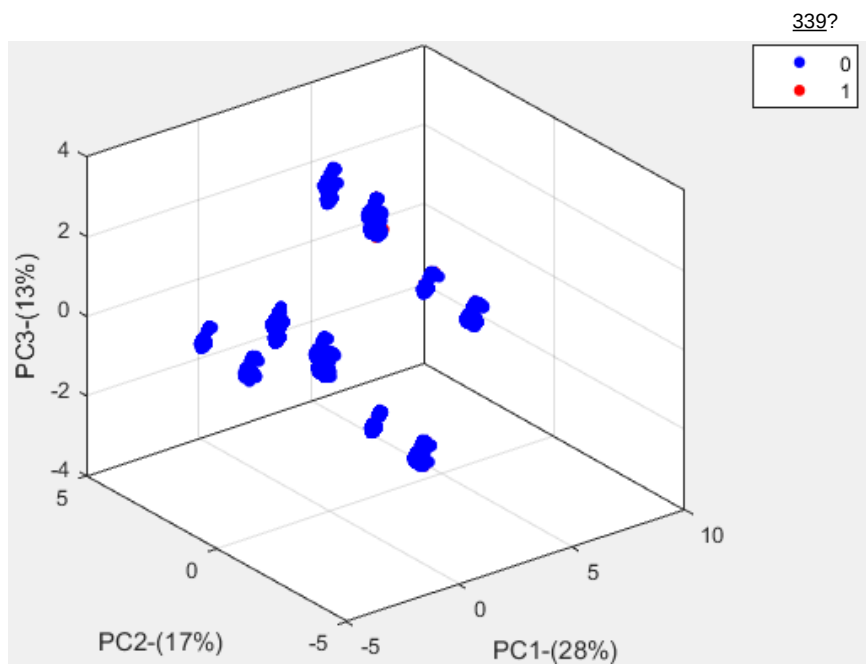
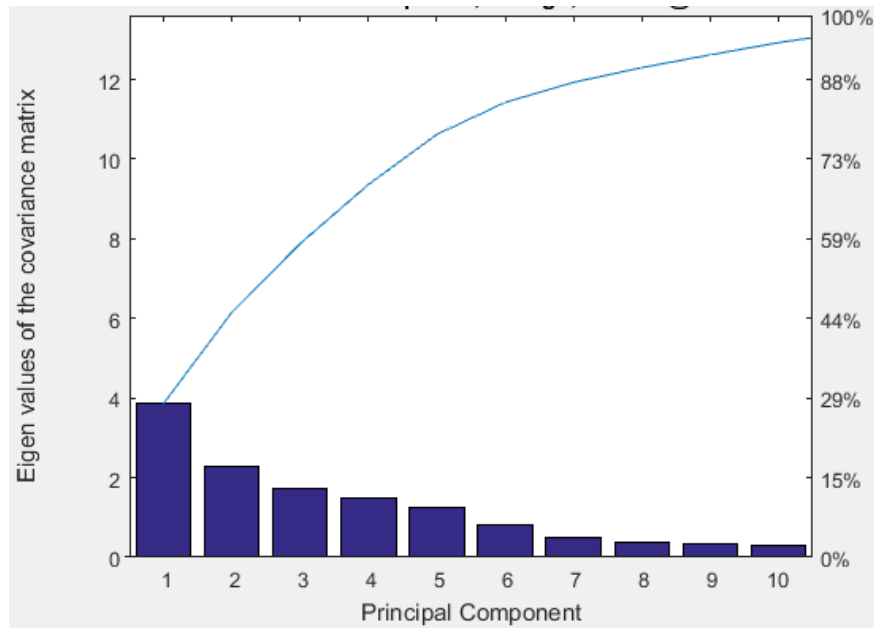
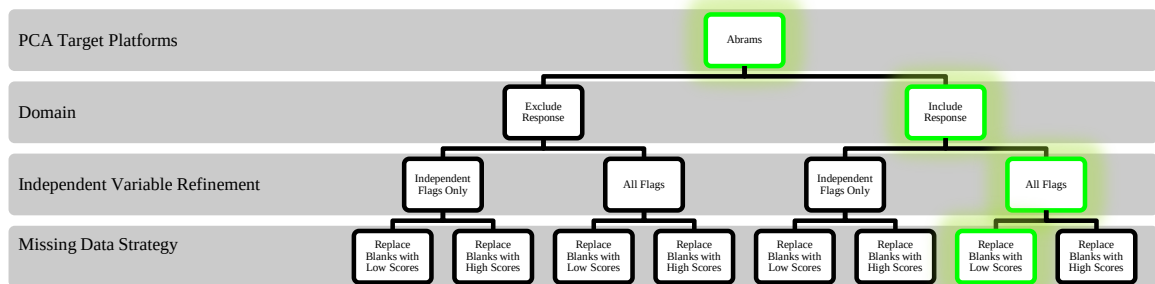












VITA

Garett Scott Patria is a Researcher on the U.S. Army Tank Automotive Research, Development, and Engineering Center's Diminishing Manufacturing Sources, Material Shortages, and Reverse Engineering (TARDEC DMRE) Team, formerly known as the Industrial Base Engineering Team (IBET). Mr. Patria researches and manages Diminishing Manufacturing Sources and Material Shortages (DMSMS) scenarios for platforms such as the Army Program Office for Mine-Resistant Ambush Protected Vehicles (APO MRAP). Mr. Patria has been researching industrial base modeling and simulation (M&S), since 2009. Mr. Patria recently helped establish a DoD-wide enterprise of ground vehicle and robotics systems researchers credited with enabling \$100M+ of R&D, while workloading the National Advanced Mobility Consortium (NAMC). Prior to joining the U.S. Army TARDEC in 2009, Mr. Patria led various teams between the stages of design and manufacturing, while at Chrysler and BAE Systems, where he enjoyed developing prototype mockups under various disciplines.