NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

OPERATIONAL RESILIENCY ASSESSMENT OF AN ARMY COMPANY TEAM

by

Army Operational Resiliency Team
Cohort SEA 22

December 2015

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
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1. AGENCY USE ONLY	**2. REPORT DATE** December 2015	**3. REPORT TYPE AND DATES COVERED** Capstone project report	
4. TITLE AND SUBTITLE OPERATIONAL RESILIENCY ASSESSMENT OF AN ARMY COMPANY TEAM			**5. FUNDING NUMBERS**
6. AUTHOR(S) Systems Engineering Cohort SEA 22/Army Operational Resiliency Team			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS systems engineering, resiliency, and multi-objective decision analysis			**15. NUMBER OF PAGES** 117
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89) Prescribed by ANSI Std. 239–18

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OPERATIONAL RESILIENCY ASSESSMENT OF AN ARMY COMPANY TEAM

Cohort SEA 22/Army Operational Resiliency Team

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING ANALYSIS

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MASTER OF SCIENCE IN SYSTEMS ENGINEERING

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from the

NAVAL POSTGRADUATE SCHOOL
December 2015

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ABSTRACT

This capstone report provides a practical example of how to assess the operational resiliency of an Army company team. In this research, operational resiliency is the ability of a company team to preserve its warfighting capability when operating in different operational scenarios comprised of distinct mission, enemy, and terrain requirements. This study evaluates three alternative configurations for their performance in three distinct scenarios (Mountain Attack, Urban Clear, and Desert Ambush) based on three measures of effectiveness (MOEs): force exchange ratio (FER), indirect-fire kill ratio (IDK), and intelligence time to detect 50% of enemy forces (INTEL). The systems engineering approach utilizes Model Based Systems Engineering (MBSE) techniques to produce nine agent-based simulation meta-models. The study performs a value-focused, multi-objective decision analysis of the three alternative configurations by developing MOE-specific value functions and scenario-specific swing-weight matrices. The results are compiled into an Operational Resiliency Decision Block that provides decision makers with a visual display tool to further analyze and assess performance. To ensure robustness of the results, the research analyzes the nine scenario-MOE weighted values for sensitivity.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	agent-based simulation
BFV	Bradley fighting vehicle
DOD	Department of Defense
DOE	Design of Experiments
FCS	U.S. Army Future Combat System
FER	force exchange ratio
GCV	ground combat vehicle
IDK	indirect-fire kill ratio
IED	improvised explosive device
ISR	intelligence, surveillance, and reconnaissance
KLE	key leader engagement
MANA-V	Map-Aware Non-Uniform Automata-Vector
MBSE	Model Based Systems Engineering
MCoE	U.S. Army Maneuver Center of Excellence
METT-TC	mission, enemy, terrain and weather, troops and support available, time, and civil considerations
MOE	measure-of-effectiveness
MOUT	military operations on urban terrain
MUM-T	manned/unmanned teaming
NPS	Naval Postgraduate School
OBJ	objective
OP	observation post
OR	operational resiliency
PI	percent of incapacitation
QRF	quick reaction force
RPG	rocket-propelled grenade
RPM	rounds per minute
SE	systems engineering
SoS	Systems of Systems
TRAC	U.S. Army Training and Doctrine Command Analysis Center

TTP	tactic, technique, and procedure
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
WFF	warfighting function

EXECUTIVE SUMMARY

The United States Army's Operating Concept mandates that the Army prepare to face an unknown enemy, in an unknown environment, with an unknown mission, and unknown partners (TRADOC 2014). With that in mind, operational commanders are charged with putting the right people against the right problems, even when the problems are complex and uncertain. This research develops and demonstrates a method for assessing a unit's performance across multiple potential scenarios through simulation. The analysis of the operational resiliency of an Army company team provides operational decision makers key insights into the effects of setting a resource requirement, namely a limited amount of men, weapons, and equipment—both organic and nonorganic.

In this project, operational resiliency is defined as "the ability of the system to absorb strain and preserve functioning despite the presence of adversity" (Sutcliffe and Vogus 2003, 96). Through adaptation, operational resiliency measures the ability of a company team to preserve its warfighting capability when operating in different operational scenarios comprised of distinct mission, enemy, and terrain requirements. Ultimately, the intended purpose of this project is to demonstrate a practical example of how to assess a company team's operational resiliency, with the intent to provide an operational decision maker and his/her staff with a valuable and useful analytical tool.

This study evaluates three alternative configurations (Configurations A, B, and C) of a combined-arms Army company team. Each combined-arms Army company team is composed of seven components: three ground maneuver assets, two air assets, one indirect fire support, and one headquarters command post. The three ground assets are the M1 Abrams main battle tank, the M2 Bradley fighting vehicle, and dismounted infantry squads. The two air assets are the AH-64 Apache attack helicopter and the RQ-7 Shadow unmanned aerial vehicle (UAV). The indirect fire support is the M777 155-millimeter howitzer artillery. Lastly, the headquarters element exists to provide command and control, and is simulated as the crucial communications link for generic situational awareness between the elements. The three configurations are leveraged from a recent capstone project (Basala et al. 2013) and selected specifically as being the three highest ranking alternatives developed in their study. Table 1 displays the three highest ranking alternatives as a result of their analysis.

Table 1. Army Company Team Unit Configurations

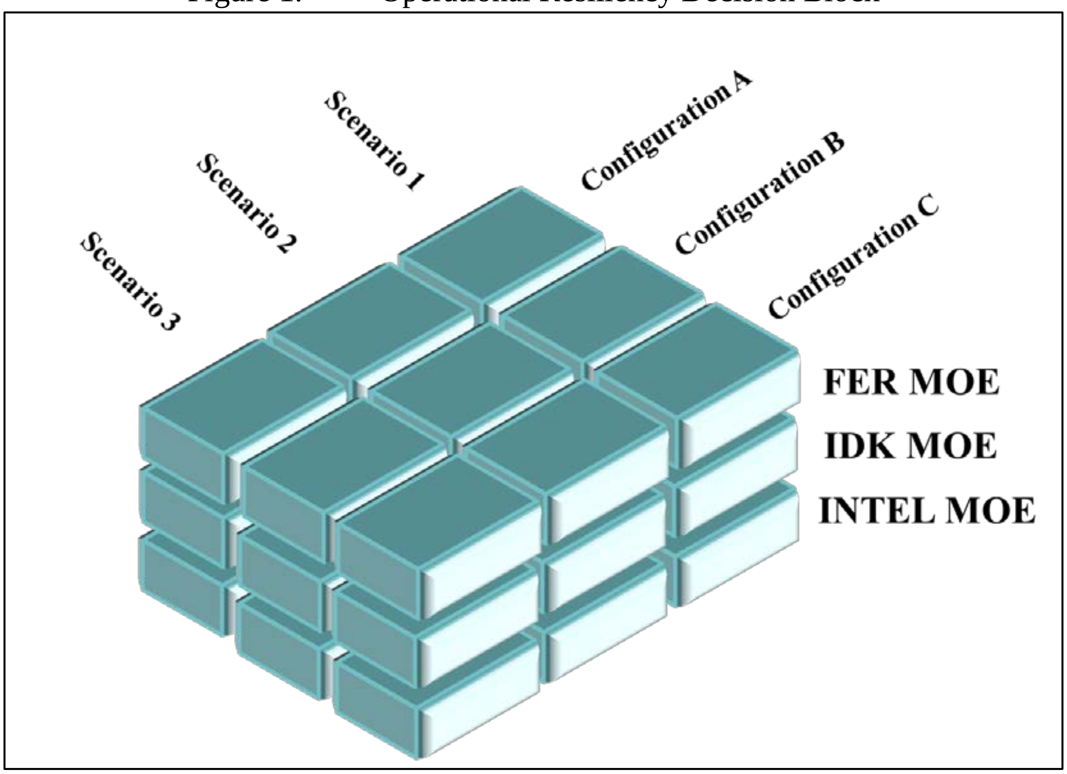
Configuration	Tanks	BFVs	Dismount Squads	155mm Artillery	AH-64 Apache	Shadow UAV	Headquarters
A	5	3	3	4	3	2	1
B	3	5	5	4	4	2	1
C	4	5	5	3	4	4	1

Each configuration is evaluated for their simulated performance in three distinct scenarios (Scenario 1—Mountain Attack, Scenario 2—Urban Clear, and Scenario 3—Desert Ambush) based on three measures-of-effectiveness (MOEs): force exchange ratio (FER), indirect-fire kill ratio (IDK), and intelligence time to detect 50% of enemy forces (INTEL). Each of the operational scenarios was developed based on selected factors from the Army mission variables of mission, enemy, terrain and weather, troops and support available, time available, and civilian considerations (METT-TC) (Department of the Army 2012a, 1-2). Specifically, each scenario was created with a distinct mission, enemy, and terrain using Map-Aware Non-Uniform Automata-Vector (MANA-V) agent-based-simulation software. This research developed three MOEs that are both representative of mission accomplishment in the scenarios and relevant to the study's objective. A single MOE was developed to measure a configuration's performance in each of three warfighting functions (movement and maneuver, intelligence, and fires) as they relate to mission accomplishment.

After conducting statistical analysis on the data from 500 iterations of each of the nine configuration-scenario simulations, the research performed a value-focused multi-objective decision analysis to evaluate the operational resiliency of the three alternative configurations. Specifically, the research employed methods developed by Gregory Parnell and Timothy Trainor (2009, 284) to assess "the trade-offs between objectives by evaluating the alternative's contribution to the value measures (a score converted to value by single-dimensional value functions) and the relative importance of each value measure (weight)." Accordingly, the research developed MOE-specific value functions and scenario-specific swing-weight matrices that combined to result in each configuration's Operational Resiliency Score (OR Score). Based on the selected value-function scales of zero to one, a configuration's OR Score could range from zero to three, with three representing the highest operational resiliency.

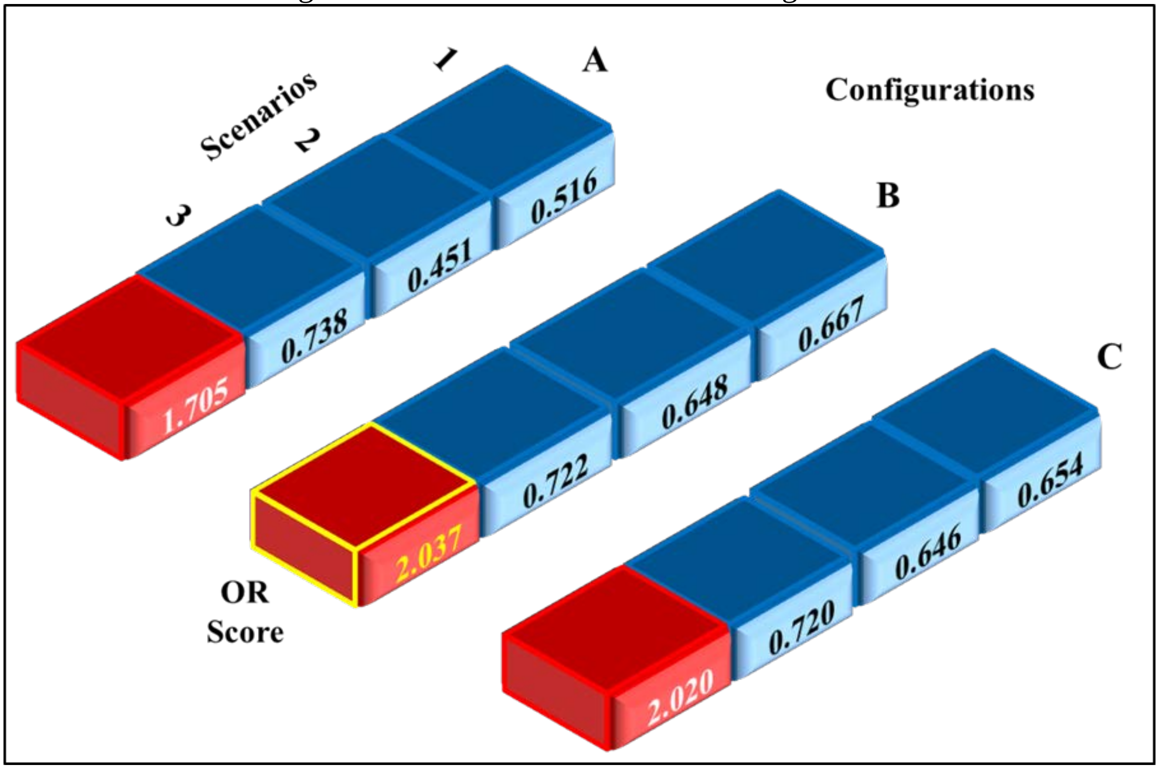
This research developed a visual representation of the process, data, and results called the Operational Resiliency Decision Block that provides a decision maker the opportunity to draw additional conclusions from the results. The block is three-dimensional with configurations along the length, scenarios along the width, and MOEs along the height. The block for this research is three-by-three-by-three, but the design allows it to be expanded in any direction to encompass additional configurations, scenarios, or MOEs as the process of obtaining the OR Score remains unchanged. Figure 1 presents the Operational Resiliency Decision Block.

Figure 1. Operational Resiliency Decision Block



The 27 weighted values of the OR Scores for each of the MOE-scenario-configuration combinations are calculated and placed in the block. The OR Score is then determined by first summing weighted values across the MOEs for each scenario-configuration combination and then across the scenarios. The three configurations' OR Scores are computed and highlighted in red in Figure 2.

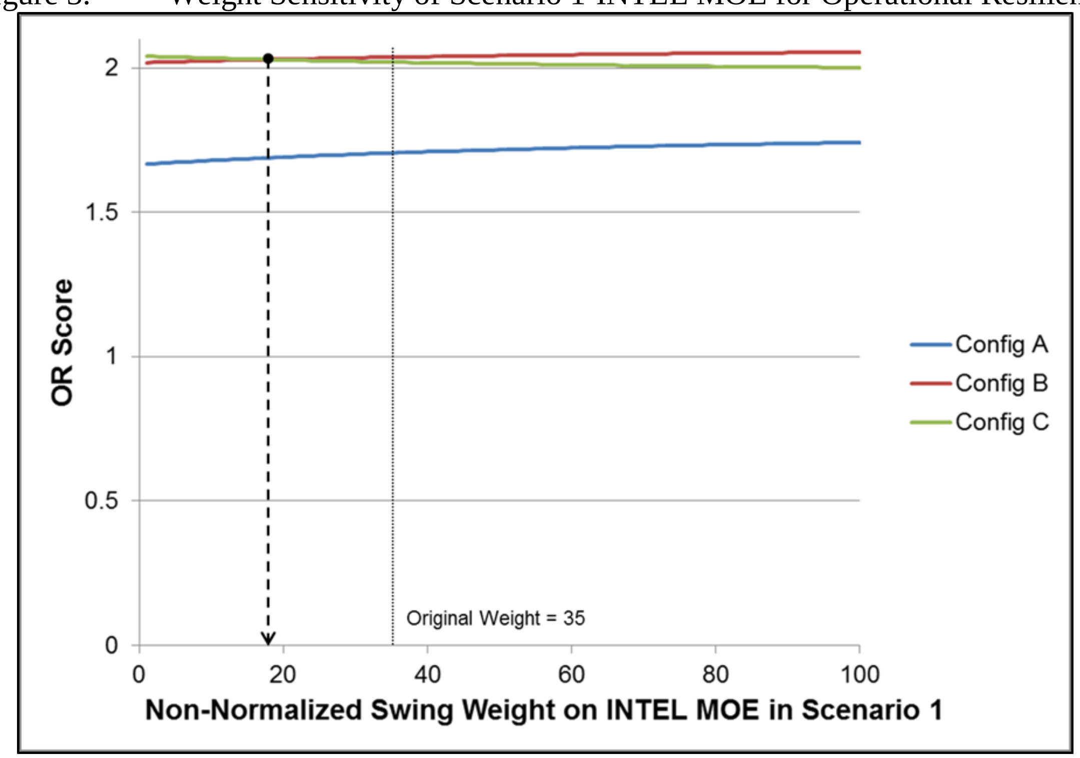
Figure 2. OR Score for each Configuration



In the end, this research found that Configuration B, with an OR Score of 2.037, is the most operationally resilient. Configuration C follows closely behind at 2.020 while Configuration A is the least operationally resilient with an OR Score of 1.705. While the two top-scoring configurations are nearly numerically equivalent, it is clear that Configuration A is dominated by the other two configurations, particularly in Scenarios 1 and 2. The difference in performance between Configuration A and Configurations B and C is most likely due to increased combat firepower from the higher number of maneuver troops (Bradleys and dismounts) and Apache support in the latter configurations. Note that this comprehensive look at the operational resiliency of each configuration produces a different conclusion than would be reached through examination of the scenarios in isolation. For example, although Configuration A is least operationally resilient, it actually performs better than the other two configurations in Scenario 3. The decision block affords the decision maker that ability to analyze performance across the scenarios.

To ensure robustness of the results, the research analyzed the nine scenario-MOE weighted values for sensitivity. The sensitivity analysis found that the most operationally-resilient configuration is only sensitive to the weight assessment of one of the nine scenario-MOE swing weight values—Scenario 1, INTEL. As seen in Figure 3, when the non-normalized swing-weight value for Scenario 1-INTEL MOE falls to 17 or below, Configuration C becomes the most operationally resilient.

Figure 3. Weight Sensitivity of Scenario 1-INTEL MOE for Operational Resiliency



Having developed a method to determine the operational resiliency of a company team that is reproducible and relevant, future work can be performed that employs the methods used in the study and refines and expands the scope of this study. Although this research leveraged configurations from another capstone project, future work could tailor the configurations to represent actual or planned task organizations of combined arms teams. This analysis could inform maneuver commanders' decisions regarding company-level force structures and training given the need to fight and win in an uncertain future. Additionally, the design of the Operational Resiliency Decision Block and the analytical method contained therein provides the ability to seamlessly incorporate an expansion of the decision space. Thus, one could easily expand the decision block to include additional unit configurations, operational scenarios, MOEs or any combination of the three, all based on the needs of the decision maker.

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ACKNOWLEDGMENTS

The team would like to thank our advisors, Dr. Eugene Paulo and Paul Beery, for their invaluable guidance, mentorship, and patience throughout the project. Additionally, the team would like to thank Mary McDonald for sharing her extensive knowledge and expertise in MANA-V modelling, as well as for assisting the team in simulation and data collection. The team would also like to recognize Professor Mark Stevens, Professor Jeffrey Kline, Professor Matthew Boensel, LTC Jeffrey House, and CPT Steve Gillespie for their collective input along the way that sharpened the focus of the work. Without the contributions of each and every one of these individuals, the team would not have been able to bring this project to completion. Lastly, the team would like thank our families and friends for all their support these last two years as we pursued master's degrees in systems engineering analysis and systems engineering.

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I. INTRODUCTION

A. OVERVIEW

The United States Army's Operating Concept calls for a force that can "Win in a Complex World." This mandates that the Army prepare to face an unknown enemy, in an unknown environment, with an unknown mission, and with unknown partners (TRADOC 2014). When designing, developing, and acquiring military systems, the Army assesses its projected operational needs relative to its current capabilities and turns an identified gap into a requirement or set of requirements. As such, it is extremely difficult to apply this requirement-development methodology to future combat systems due to the lack of ability to actually realize the system and the system's operational performance. One such solution is to apply Model-Based Systems Engineering (MBSE) to make early life-cycle-design decisions and requirements for systems of systems (SoS) that must operate in a dynamic, unknown future environment. INCOSE defines MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life-cycle phases" (BKCASE Editorial Board 2015). This research seeks to utilize MBSE, along with an agent-based simulation, to explore the operational resiliency of an Army company team.

Previous studies by Naval Postgraduate School (NPS) Systems Engineering (SE) cohorts have sought to analyze company team performance with regard to various capabilities—specifically, the survivability of ground combat vehicles and the effectiveness of intelligence, surveillance, and reconnaissance (ISR). These studies produced singular meta-models to analyze tradeoff effects between performance factors in a single scenario. This study expands on those earlier studies by applying similar techniques to a multi-scenario environment.

B. PROBLEM STATEMENT

This study aims to expound upon earlier research focused on developing a conceptual methodology utilizing MBSE techniques for determining the design trade-space of various SoS. Prior research focused on analyzing the impact of alterations to materiel and non-materiel parameters of a company team in a single scenario. This research seeks to develop a method to assess the operational resiliency of a company team by simulating various unit configurations against a variety of operational scenarios. This is expected to support development of future combat systems by demonstrating a new development methodology where the operational scenario is varied to assess the utility of new systems against a variety of potential threats in a variety of potential operating environments. As a result, the analysis seeks to develop a general methodology for analyzing the performance of military SoS through the development of multiple operational simulation models.

1. RESEARCH OBJECTIVES

This research project is governed by the following objectives:

- Develop multiple operational scenarios that can be utilized in future SoS synthesis models by leveraging and evolving existing models for dynamic application.
- Produce an analytic method for assessing operational performance of a company team across a range of scenarios.
- Determine a method for evaluating and displaying multi-dimensional data so that the results can be used and trusted.

2. BENEFITS OF THE STUDY

The intended purpose of this project is to provide a practical example of how to assess a company team's operational resiliency. This research and the outputs of this study provide several benefits. First, it demonstrates that the examination of multiple operational simulations early in the system life-cycle is a potentially valuable approach to assess the resiliency of future Army combat systems. Secondly, it works to help provide a proof-of-principle of the value of MBSE as an analytical method for the Army in the form of feeding our analysis into the "dashboard." Lastly, it provides a building block for doctoral research being done on a general methodology for developing a SoS synthesis model and how MBSE can be applied to make early life-cycle-design decisions and requirements for SoS.

C. ARMY COMPANY TEAM SOS

This research identifies the Army company team as a representative SoS to which the proposed methodology can be applied. It warrants brief discussion of the difference between a system and SoS in terms of Army units. Harney (2013, 2) defines a system as "[a]n integrated set of equipment, computer programs, facilities, human and logistic support resources, and procedures which are assembled to accomplish a single purpose or mission." For the purposes of this research, a system consists of an Army unit that is capable of accomplishing a mission given its integrated set of men, weapons, and equipment (such as a platoon of dismounted infantry). The Department of Defense (DOD) classifies SoS, as a "set or arrangement of systems that results from independent systems integrated into a larger system that delivers unique capabilities" (Department of Defense 2010, 310). Therefore, SoS are comprised of an arrangement of Army units that, when integrated, deliver a unique and improved capability.

It follows that this research designates an organic company as a system and a company team as a SoS. An organic company "is a unit consisting of two or more platoons, usually of the same type, with a headquarters and a limited capacity for self-support" (Department of the Army 2012d, 2-14). This represents the standard task organization of any company-sized formation throughout the Army. Depending on mission requirements, an organic company's task organization can be augmented with nonorganic assets that are themselves considered systems. Specifically, the addition of nonorganic combat multipliers such as tank platoons, field artillery batteries, or aviation support transforms the organic company into a company team (Department of the Army 2012d). The heart of the company team remains the organic company, while the nonorganic multipliers represent independent systems that when combined, deliver a unique capability set to an operational commander otherwise not present in his or her organic formation. Therefore, the Army company-team configurations used in this study (see Chapter III) qualify as representative SoS.

D. OPERATIONAL RESILIENCY

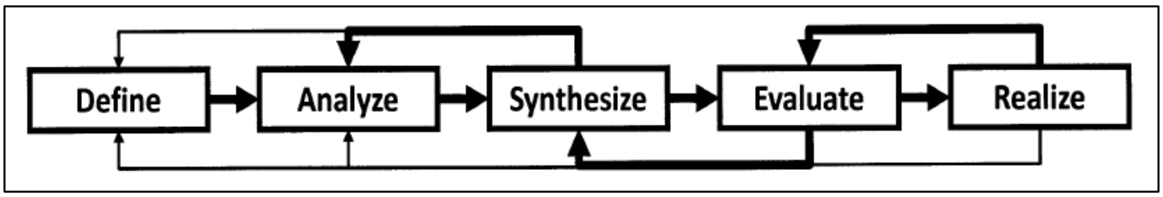
The interaction of systems as part of a larger SoS is of particular interest to both the Army operational and acquisition communities. The analysis of the operational resiliency of an Army company team would provide operational decision makers key insights into the effects of setting a resource requirement, namely a limited amount of men, weapons, and equipment—both organic and nonorganic. In this project, operational resiliency is defined as "the ability of the system to absorb strain and preserve functioning despite the presence of adversity" (Sutcliffe and Vogus 2003, 96). This definition of operational resiliency is composed of three main components—system, functionality, and adversity. In the case of this project, the system refers to the Army company team and all potential unit configurations. As will be detailed later, the unit configurations are leveraged from previous research on vehicle combat survivability (Basala et al. 2013). When considering the system's ability to preserve functionality, that functionality is based off the system's designed capabilities and operational activities it performs. For the purpose of the project, the functionality is traced directly from Army doctrine. Lastly, the presence of adversity is provided by the different simulation operational scenarios. These operational scenarios have distinct terrain, enemy, and mission requirements.

Qualitative metrics that enable the assessment of each unit configuration come in the form of the measures-of-effectiveness (MOE). The MOEs provide the framework to analyze each system's performance in each operational scenario, affording the context with which to evaluate its operational resiliency. The MOEs are tied directly to the functionality trying to be preserved and are addressed in Chapter III. The MOE raw values will then be analyzed through a value-focused thinking approach to evaluating the alternatives developed by Parnell (2007, 619). Specifically, the research will apply multiple objective decision analysis through the use of value curves and swing weights to ultimately assess the operational resiliency of each company team configuration. Further discussion of the multiple-objective-decision-analysis process can be found in Chapter VI.

E. SYSTEMS ENGINEERING PROCESS

The systems engineering (SE) process is used to develop and analyze how a variety of SoS, by adjusting unit configurations, performs across a wide spectrum of possible scenarios. The SE process model that this research primarily utilizes is outlined in Figure 1.

Figure 1. Systems Engineering Process Model



Source: Harney, Robert C. 2013. Systems Engineering & Integration. Vol. 6 of Combat Systems Engineering. Monterey: Naval Postgraduate School.

The first step of the SE process presented in Figure 1 is problem definition. As presented earlier, this research will test and analyze the operational resiliency of an Army company team. This includes determining the various stakeholders and potential users of the research results. Additionally, the generic company team architecture is defined and modeling strategy with software determined. Since this project is building off previous work, the unit configurations are also defined in this step.

In the second step, the operational scenarios are determined based on selected factors from the Army standard METT-TC (Mission, Enemy, Terrain and Weather, Troops and Support Available, Time, and Civil Considerations) analysis. Specifically, each scenario will be comprised of a distinct mission, enemy, and terrain. In addition, MOEs that will be used to evaluate each potential configuration are defined for each operational scenario.

In the third step, the majority of modeling and simulation is executed. The three scenarios are developed into their enemy-terrain models. Following that, the unit configurations are then added and schemes of maneuver created. Much of the modeling refinement effort will be focused on ensuring that the operational fire and maneuver are as close to real-world as possible. This synthesizing step is the most comprehensive and time-consuming, with the outputs being the raw value data results from each scenario.

The fourth and fifth steps are comprised of receiving the simulated raw value data, transforming it into the specified MOE, conducting performance comparison analysis, and displaying the results. Overall, this model emphasizes the explicitly iterative nature of the SE process and displays the immediate feedback between steps.

Within this process, the research will be employing MBSE. A formal, model-based approach, versus traditional document-based SE, includes the use of systems-architecting software, so is more efficient during iterations of the SE process. Particularly in comparing and evaluating different company teams, it is crucial to be able rapidly to redefine, analyze, and synthesize the unit configurations within the different operational scenarios. Ultimately, this method will lead the research to realize the most operationally effective and resilient system.

F. STAKEHOLDER ANALYSIS

Traditionally, capstone projects have specific stakeholders, but the goal is to have this research prompt more research that is of interest to the following organizations—the NPS Systems Engineering Department, the United States Army Maneuver Center of Excellence (MCoE), and the United States Army Training and Doctrine Command Analysis Center (TRAC). As mentioned earlier as a benefit, this work will help provide a proof-of-principle of the value of MBSE as an analytical method for the Army in the form of feeding analysis into the "dashboard." The dashboard and dashboard-related activities are being developed by the NPS Systems Engineering Department. This work furthers research in the department and will be useful for not only doctoral students working in this area, but also for future capstone projects in this area.

The second organization that this research may benefit is the MCoE. The MCoE ensures the maneuver force is prepared to fight and win in dynamic and unknown future engagements. The synthesis of current and emerging technology and doctrine may provide MCoE with a means of measuring operational resilience in a SoS. Particularly, the MCoE could utilize this method when faced with task organizing units against an unknown enemy with the desire to analyze the operational performance of a few configurations to aid in selecting the most operationally resilient option to field.

The mission of U.S. Army TRADOC Analysis Center (TRAC) is, in part, developing models and simulations for capability development and studying the integrated battlefield. TRAC is interested in the Army's emerging aviation concept of manned/unmanned teaming (MUM-T) (Whittle 2015). This research may provide insight to the impact of integrating MUM-T capabilities on the battlefield as part of a SoS. This project produces meta-models based on agent-based simulation results that could be utilized for future analysis in a plug-and-play simulation environment. This type of modelling would most likely be employed for rapid analysis and response in a low fidelity simulation.

G. MODELING STRATEGY

As noted in Siebers, Macal, Garnett, Buxton, and Pidd (2010, 206), "Good modelling practice dictates that you should identify the research question, first, and then ask what methods would be most applicable in solving it, second." Therefore, before jumping directly into the chosen modeling strategy, it is important to first examine the goal of the project with respect to modeling and simulation. Although the ultimate objective is to determine which company team displays the most operational resiliency, this section seeks to identify how to accomplish this with modeling and simulation.

Based on the definition for operational resiliency in the context of this report, the strategy must model the ability of a system to absorb strain and preserve functioning despite the presence of adversity provided by various operational scenarios. As such, an appropriate modeling strategy must be able to model the Army combat system individual and collective entities and their abilities to shoot, move, and communicate. Paramount to the successful strategy is the modeling of interactions between friendly and enemy forces as well as between friendly and friendly forces. Additionally, the modeled system must be capable of functioning through the adversity of a changing operational scenario.

Based on those standards and the guidance presented in Siebers et al. (2010), agent-based modeling and simulation is the appropriate solution. Agent-based simulation

(ABS) models are “individual based” with a focus on “modelling the entities and interactions between them” (207). ABS has the capability to model the behaviors of individuals and capture dynamic relationships between agents. Specifically, it allows for a bottom-up modelling approach by building the individuals to make up the system. Moreover, ABS can account for the spatial and geo-spatial aspects of the forces moving across various terrains. This last part is crucial to effectively modelling a land-based combat environment and different weapon system and sensor capabilities (207).

To conduct the ABS for this project, this research selected Map-Aware Non-Uniform Automata-Vector (MANA-V) software. Major Tobias Treml (2013) gives a detailed explanation for reasons for using MANA-V in his thesis, which this research summarizes. First, MANA-V employs low resolution yet highly transparent simulation models that can be run multiple times quickly and that produce necessary data. Secondly, MANA-V allows the user to input and modify necessary combat aspects of each agent such as movement speed, weapons lethality, and sensor range; these aspects govern the behavior of agents, allowing them to individually act and react. Thirdly, Treml highlights MANA-V’s easy-to-use graphical user interface characterized by a beneficial rapid learning curve.

II. LITERATURE REVIEW

This thesis uses the findings of recent capstone projects in systems engineering by examining how various company-level force structures react in various scenarios.

A. A REVOLUTIONARY APPROACH FOR THE DEVELOPMENT OF FUTURE GROUND COMBAT SYSTEM SPECIFICATIONS

The failure and subsequent cancellation of the acquisition of the U.S. Army's Future Combat System (FCS) project left questions for the acquisition of future systems. Major Tobias Treml (2013), an officer in the German Army, sought to create a method for providing decision makers with information to reduce cost and schedule impacts while maximizing overall system performance.

Treml synthesized existing combat systems with potential future systems. These future systems were created by altering a baseline configuration of some system with design specifications that included ranges for parameters set by subject matter experts, real-world experiences, and field studies. Treml developed scenarios using the agent-based combat simulation tool Map Aware Non-Uniform Automata-V (MANA-V) to determine the factors that had the most significant impact on SoS performance.

The result of Treml's research showed that survivability of ground combat vehicles operating as part of a SoS is a result of various factors of the interaction of agents in the scenario. Moreover, the method he suggests can feasibly be used as part of the up-front analysis of future land-based systems. Treml concludes that active defense measure is the most influential factor to the MOEs that combine for survivability. Additionally, a combat vehicle's ability to employ concealment and detect enemy positions proved to be influential as well. Of most interest is the singular meta-model developed by Treml that can be utilized in future work. This project expands on Treml's general methodology by creating several meta-models that allow for the examination of various unit configurations in various scenarios to determine an alternative's operational resiliency in an effort to aid the decision maker.

B. VEHICLE SURVIVABILITY TEAM

An SE capstone project (Basala et al. 2013) investigated using MBSE techniques for determining the trade-space of a ground combat vehicle (GCV) as part of a SoS. This research sought to find methods of improving the overall survivability of combat vehicles beyond the addition of armor. This research determined those factors that most influenced survivability and developed a trade-space between survivability, lethality, and mobility.

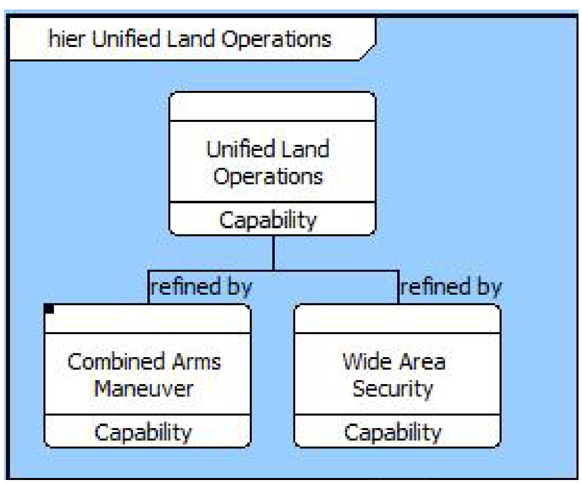
This research began with the previously discussed model created by Treml. It was determined that, given the specific scenario and force composition, four factors including armor thickness, weapon range, armor penetration, and unmanned aerial vehicle detection range had the greatest impact on unit survivability. It was further concluded that altering the force structure increased overall unit performance. That project combined the simulation results with cost and MOE analysis and determined that the most cost-effective method of increasing survivability of the unit was through improvements to unmanned aerial vehicle sensors.

III. COMPANY TEAM ARCHITECTURE AND MOE

A. OPERATIONAL ARCHITECTURE

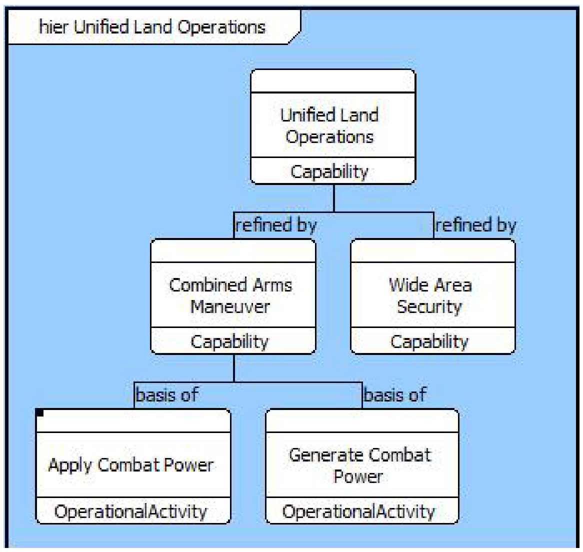
As this project serves to analyze existing company team configurations and not to design new ones, it is important to understand the architectural framework of the unit. The primary focus of the Army's operational concept is the ability to conduct unified land operations (Department of the Army 2012a, 1-1). In terms of what is required to conduct unified land operations, commanders must demonstrate the two core competencies of combined arms maneuver and wide area security (2-1), as shown in Figure 2. Combined arms maneuver encompasses the majority of traditional operations involving seizing, retaining, and exploiting the initiative through offensive and defensive operations (2-2). Wide area security is primarily focused with retaining the initiative and preventing a secure situation from deteriorating through stability operations (2-2). In this project, offensive operations are selected as the focus, and therefore will continue refining the combined arms maneuver capability.

Figure 2. Army Company Team Capability



A unit capable of successfully executing combined arms maneuver requires the ability to generate and apply combat power (Department of the Army 2012a, 3–1), with traceability from unified land operations shown in Figure 3. These are separate operational activities in that generating combat power focuses on the buildup and replenishment of combat power whereas applying combat power involves units engaged with enemy in combat (3-2). These two activities are the basis for combined arms maneuver and provide the link to the functional framework of the company team. Combat power is defined as "the total means of destructive, constructive, and information capabilities that a military unit or formation can apply at a given time" (3-1).

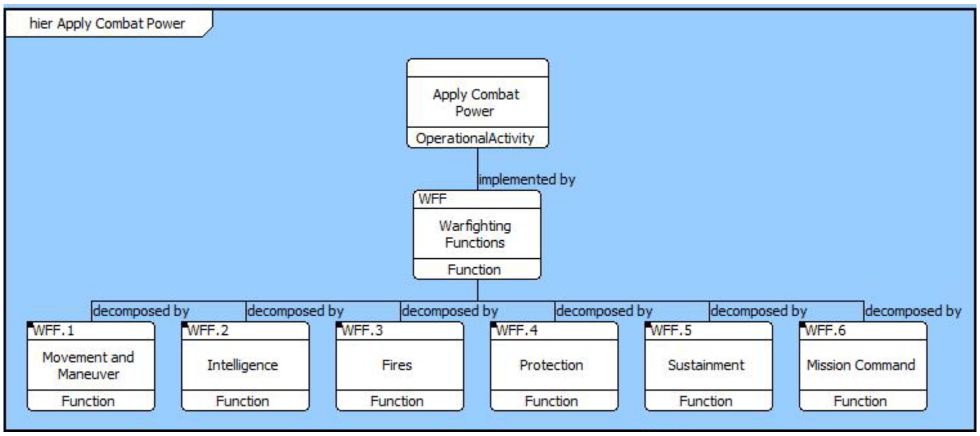
Figure 3. Army Company Team Traceability to Operational Activity



B. FUNCTIONAL ARCHITECTURE

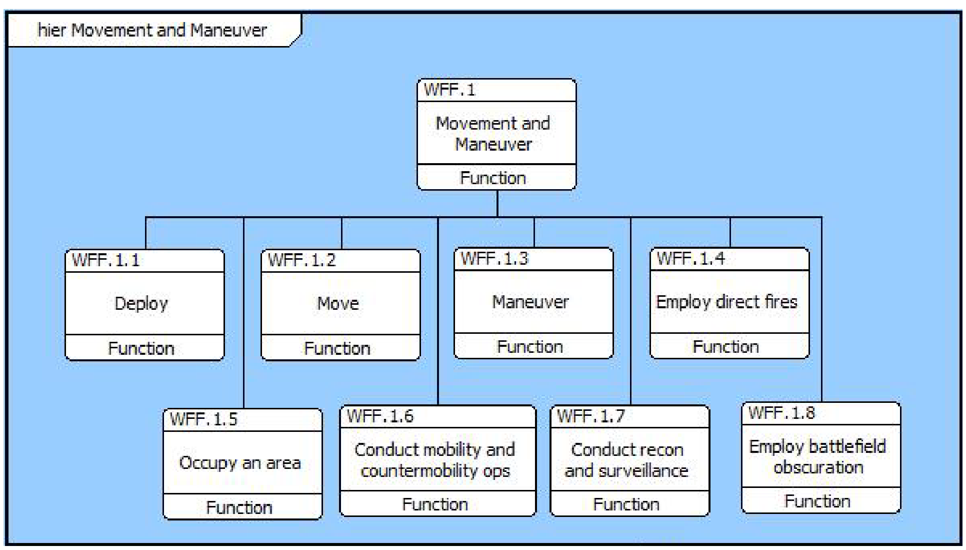
Further decomposing each of the operational activities shown in Figure 3, commanders apply combat power through what are called the warfighting functions. The six warfighting functions are movement and maneuver, intelligence, fires, protection, sustainment, and mission command (Department of the Army 2012a, 3-1), as shown in Figure 4. Commanders use the six functions to "help them exercise command and to help them and their staffs exercise control" (3-2). More specifically, a warfighting function is "a group of tasks and systems (people, organizations, information, and processes) united by a common purpose that commanders use to accomplish missions" (3-2).

Figure 4. Army Company Team Traceability to Functions



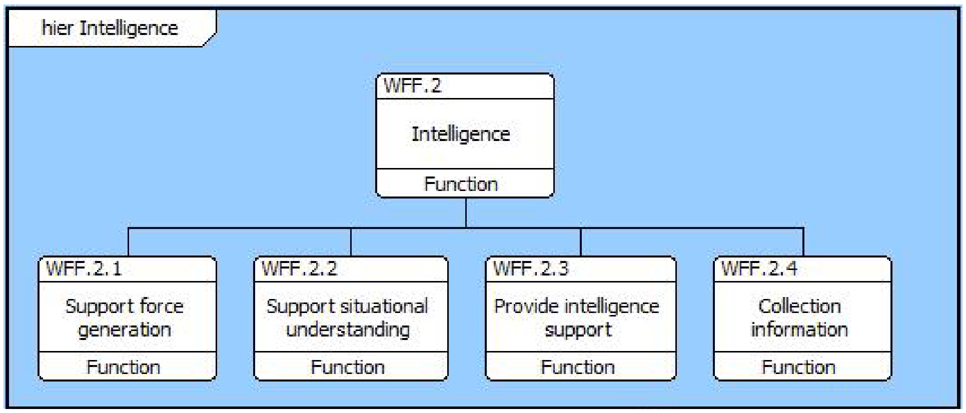
The movement and maneuver warfighting function is defined as "the related tasks and systems that move and employ forces to achieve a position of advantage over the enemy and other threats" (Department of the Army 2012a, 3-3) and is further decomposed into the eight sub-functions shown in Figure 5.

Figure 5. Movement and Maneuver Functional Decomposition



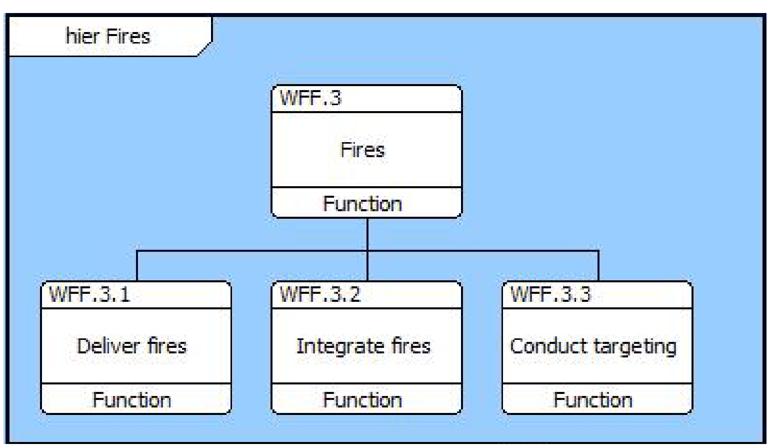
The intelligence warfighting function is defined as “the related tasks and systems that facilitate understanding the enemy, terrain, and civil considerations” (Department of the Army 2012a, 3-4) and is further decomposed into the four sub-functions shown in Figure 6.

Figure 6. Intelligence Functional Decomposition



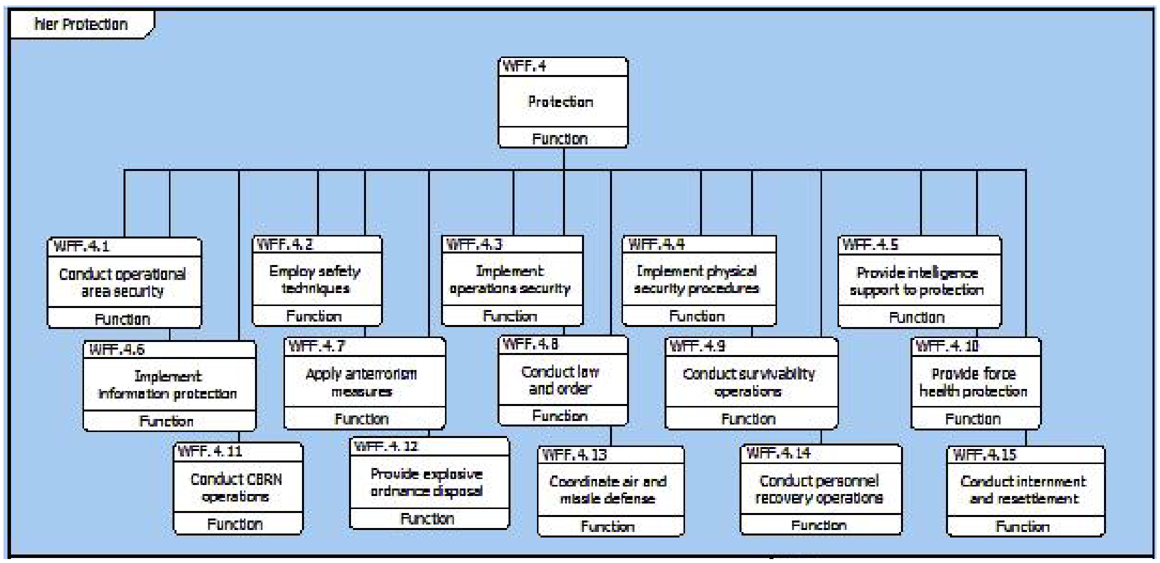
The fires warfighting function is defined as “related tasks and systems that provide collective and coordinated use of Army indirect fires, air and missile defense, and joint fires through the targeting process” (Department of the Army 2012a, 3-4) and is further decomposed into the three sub-functions shown in Figure 7.

Figure 7. Fires Functional Decomposition



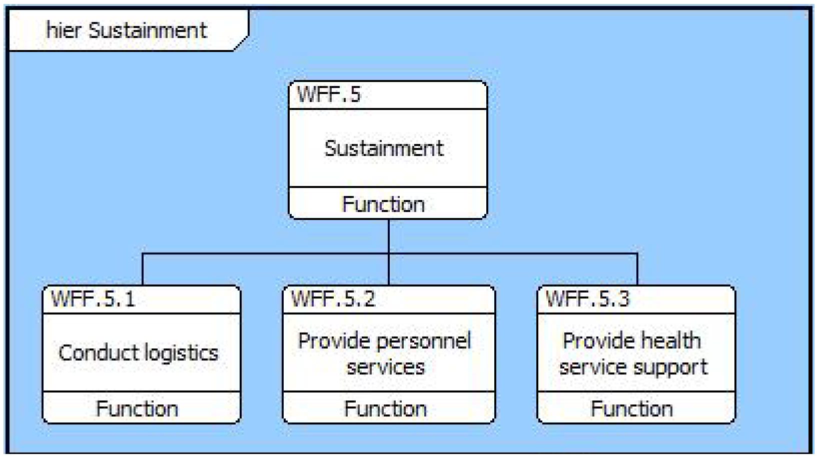
The protection warfighting function is defined as "related tasks and systems that preserve the force so the commander can apply maximum combat power to accomplish the mission" (Department of the Army 2012a, 3-5) and is further decomposed into the 15 sub-functions shown in Figure 8.

Figure 8. Protection Functional Decomposition



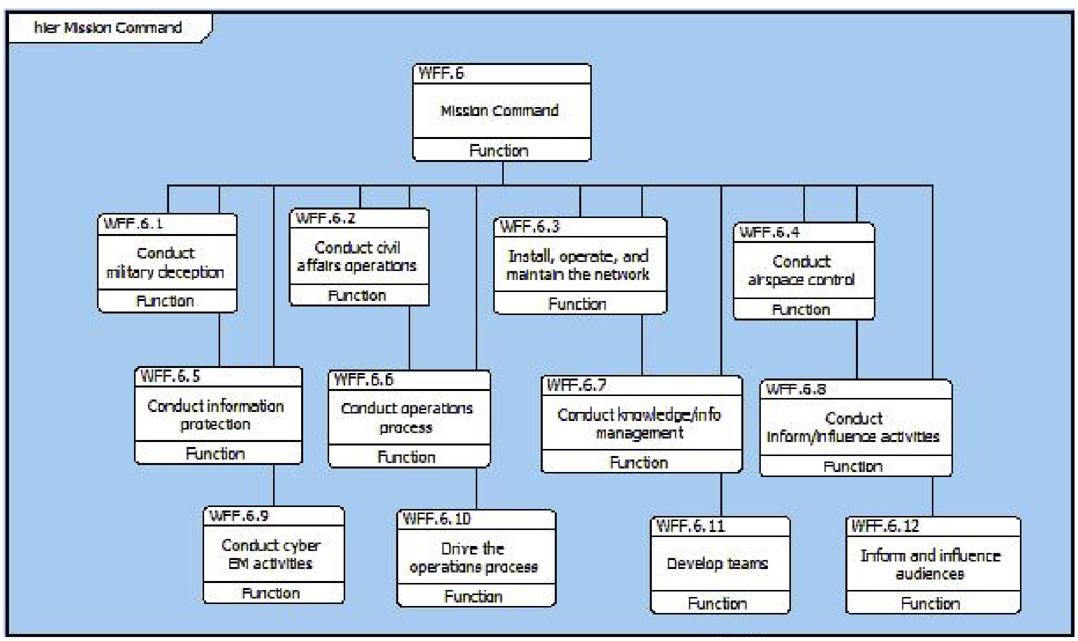
The sustainment warfighting function is defined as "related tasks and systems that provide support and services to ensure freedom of action, extend operational reach, and prolong endurance" (Department of the Army 2012a, 3-4) and is further decomposed into the three sub-functions shown in Figure 9.

Figure 9. Sustainment Functional Decomposition



The mission command warfighting function is defined as "related tasks and systems that develop and integrate those activities enabling a commander to balance the art of command and the science of control in order to integrate the other warfighting functions" (Department of the Army 2012a, 3-2) and is further decomposed into the 12 sub-functions shown in Figure 10.

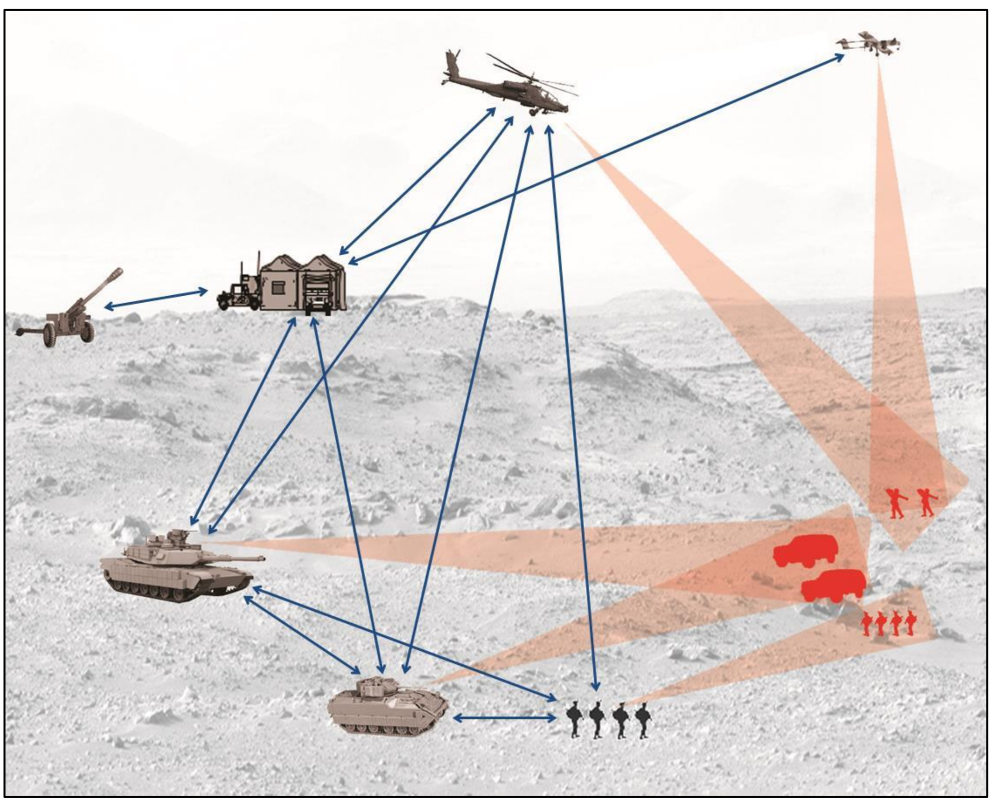
Figure 10. Mission Command Functional Decomposition



C. PHYSICAL ARCHITECTURE

As mentioned previously, this research leveraged an Army company team structure based on a combined arms organization that was used in two earlier capstone projects by Treml and the Vehicle Survivability Team. The combined arms Army company team is composed of seven components, three ground maneuver assets, two air assets, one indirect fire support, and one headquarters command post. The three ground assets are the M1 Abrams main battle tank, the M2 Bradley fighting vehicle, and dismounted infantry squads. The two air assets are the AH-64 Apache attack helicopter and the RQ-7 Shadow unmanned aerial vehicle (UAV). The indirect fire support is the M777 155-millimeter howitzer artillery. Lastly, the headquarters element exists to provide command and control, but will primarily be simulated as the crucial communications link for generic situational awareness between the elements. These seven components are shown in Figure 11.

Figure 11. Army Company Team OV-1



In the above figure (Figure 11), the red cones indicate sensor capability of the elements and the blue bi-directional arrows indicate direct communication. Only five of the elements have the ability to actually sense or see the enemy with varying capability. For example, the dismount infantry squads would only be able to detect enemy personnel out to a maximum range of 800 meters. On the other end of the detection spectrum, the Apache attack helicopter is capable of identifying an enemy vehicle out to nearly 8,000 meters. The various sensor capabilities of each element utilized in the project can be found in Appendix A.

As for communications, a combined arms company team employs advanced technology which allows shared situational understanding of friendly and enemy positions on the battlefield. Significantly, the seven elements do not possess the ability to directly communicate with each other. The headquarters command post has direct communication with two of the three ground elements, both air assets, and the indirect fire support assets. Conversely, the UAV can only relay imagery directly to its controller located in the headquarters command post. All enemy information identified by the UAV would therefore have to be collected and passed to the other elements through other command post operators. As a result, the communication of that information incurs a time delay penalty in processing time.

Although not specifically depicted in the OV-1 diagram, only five of the seven elements can engage the enemy with fire, with the two impotent elements being the UAV and the headquarters command post. The Apache attack helicopter, Abrams tank, Bradley fighting vehicle, and dismount infantry squads all have the ability to engage the enemy with direct fire assets. For example, the Abrams tank employs a 120 millimeter main gun and a .50 caliber machine gun with which to engage and destroy enemy targets. The M777 artillery piece is the only element to employ indirect fire capability with a maximum range of 14 kilometers and kill radius of 125 meters. The capabilities of the various weapons can be found in Appendix A.

D. UNIT CONFIGURATIONS

This research assesses operational resiliency of three different unit configurations. Three Army company teams facilitate the multiple-objective-decision-analysis techniques utilized to assess operational resiliency and are appropriate in scope in terms of simulation-modelling requirements for a team of this size. The three unit configurations are leveraged from the Vehicle Survivability Team's capstone project (Basala et al. 2013) and selected specifically as being the three highest ranking alternatives developed in their study. In that project, a design of experiments resulted in 22 unique unit configurations. Furthermore, each of the 22 configurations maintained a single headquarters command post element, but varied the remaining elements from two to six for the ground assets and from one to four for the air and indirect fire assets. Table 1 displays the three highest ranking alternatives as a result of their analysis.

Table 1. Army Company Team Unit Configurations

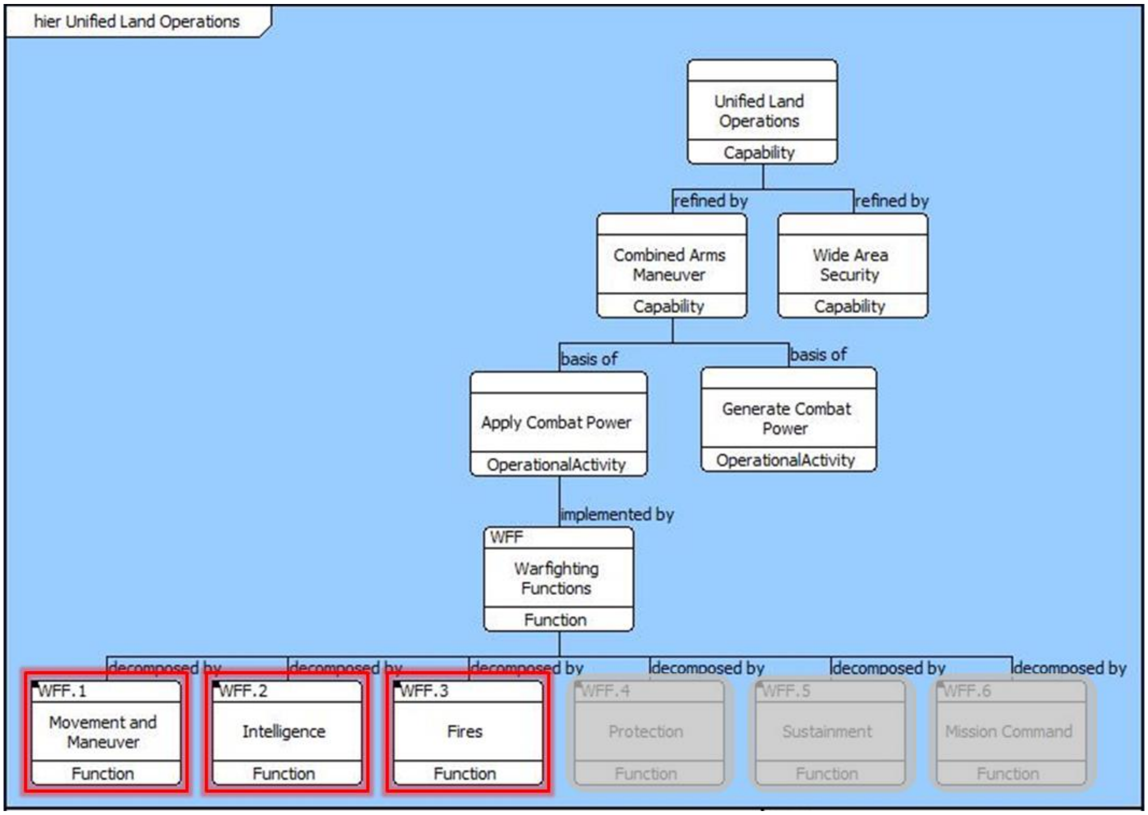
Configuration	Tanks	BFVs	Dismount Squads	155mm Artillery	AH-64 Apache	Shadow UAV	Headquarters
A	5	3	3	4	3	2	1
B	3	5	5	4	4	2	1
C	4	5	5	3	4	4	1

E. MEASURES-OF-EFFECTIVENESS

According to Harney, measures of effectives "must be measurable...quantifiable...and relevant (it must directly measure to what degree the real objective being studied is achieved)" (Harney 2013, 184). Additionally, they "are used to evaluate the performance of the unit in accomplishing the mission" (184). Using this definition to guide the research, each MOE must satisfy two requirements. They must evaluate the performance of the unit in accomplishing the mission, and directly measure to what degree the real objective is achieved. In each operational scenario, the Army company team performs an offensive mission designed to defeat an enemy. Mission accomplishment is therefore directly linked to identifying, engaging, and destroying enemy personnel. As such, MOEs must satisfy that first requirement of evaluating performance of the unit's ability to accomplish the mission and defeating the enemy.

Each MOE must also satisfy the requirement of being relevant to the real objective of the study. The real objective is to assess the operational resiliency of each company team configuration, with their ability to preserve functionality being the key point of performance. The functionality of the team stems from the six warfighting functions as mentioned earlier. This research focused on three of the six warfighting functions as applicable to the project. These three warfighting functions—movement and maneuver, intelligence, fires—comprise the functionality desired by the Army company team operating in the offense and can be modeled through the simulation technique selected. By definition, the sustainment and protection warfighting functions are relevant to force preservation and support activities, which are not associated with the direct offensive combat missions being modeled and simulated. Additionally, mission command was scoped out of the study to reduce the number of operational decisions made by the authors and to ensure that any recommendations are focused on the configuration of the company team, rather than altered operational decisions. Figure 12 shows the traceable functional architecture with selected functionality outlined in red.

Figure 12. Army Company Team Functionality for MOE Development

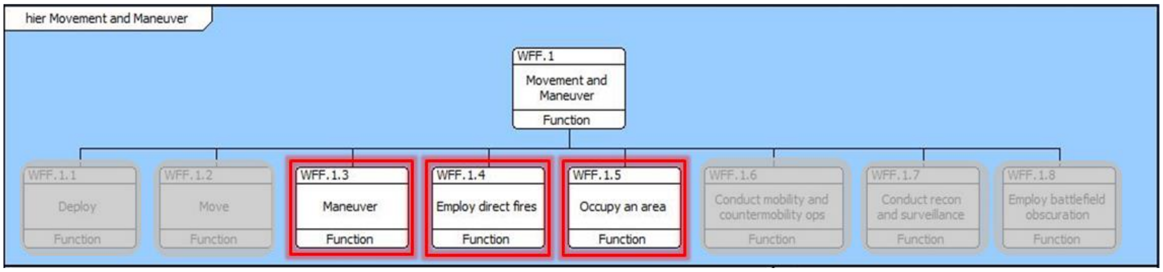


This research developed three MOEs that satisfy both aforementioned requirements of being representative of mission accomplishment and relevant to the study's objective. A single MOE was developed to measure the performance of each of the three functions as they relate to mission accomplishment. Doing this allows the assessor to capture the representative data and ultimately utilize it in the decision criteria for selecting the most operationally resilient unit configuration.

1. MOE 1—Force Exchange Ratio (FER)

In analyzing the movement and maneuver warfighting functionality being modeled, three of the seven sub-functions are directly modeled and simulated in the MANA-V software. These three are maneuver, employ direct fires, and occupy an area and are shown in Figure 13.

Figure 13. Movement and Maneuver MOE Sub-functions



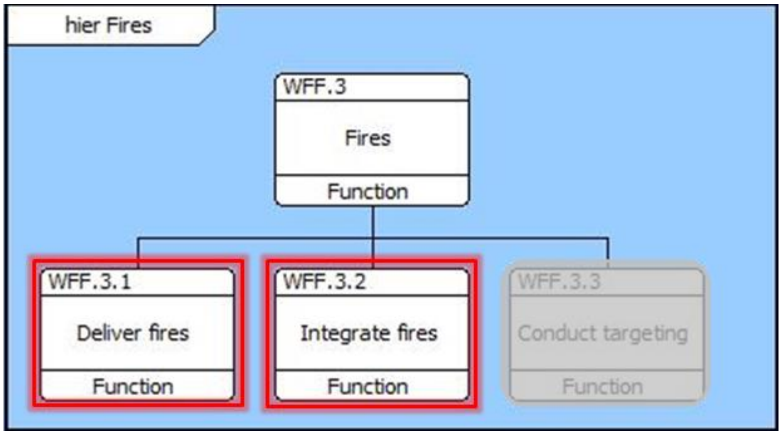
The MOE selected that captures the movement and maneuver functionality related to mission accomplishment is force exchange ratio (FER). FER is the ratio of two casualty ratios and is shown Equation (1.1). The values of FER can range from 0 (in the case of only friendly casualties) to very large (in the case of only enemy casualties). This ratio of casualty ratios is useful in measuring a unit's ability to move and maneuver because of the inherent impact the number of forces remaining has on a combat unit.

$$FER = \frac{\dfrac{\#\text{of friendly forces remaining}}{\#\text{of friendly forces total}}}{\dfrac{\#\text{of enemy forces remaining}}{\#\text{of enemy forces total}}} \qquad (0.1)$$

2. MOE 2—Indirect Fire Kill Ratio (IDK)

In analyzing the fires warfighting functionality being modeled, two of the three sub-functions are directly modeled and simulated in the MANA-V software. These are the company team's ability to deliver and integrate fires, and are shown in Figure 14.

Figure 14. Fires MOE Sub-functions



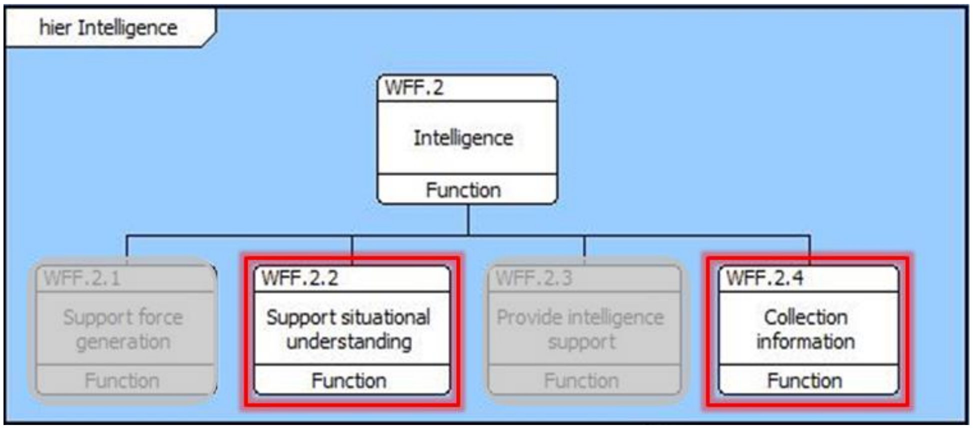
The MOE selected that captures the fires functionality related to mission accomplishment is indirect-fire kill ratio (IDK). IDK captures the effectiveness of the indirect fire support and is shown in Equation (1.2). For this MOE, a smaller IDK represents a more effective indirect fire capability, capturing a unit's ability to identify and engage targets with artillery fire.

$$IDK = \frac{\text{\# friendly artillery rounds fired}}{\text{\# enemy killed by artillery}} \quad (0.2)$$

3. MOE 3—Intelligence Time to Detect 50% of Enemy Forces (INTEL)

In analyzing the intelligence warfighting functionality being modeled, two of the four sub-functions are directly modeled and simulated in the MANA-V software. These are the company team's ability to collect information and support situational understanding, and are shown in Figure 15.

Figure 15. Intelligence MOE Sub-functions



The MOE selected that captures the intelligence functionality related to mission accomplishment is the intelligence time to detect 50% of enemy forces (INTEL). INTEL captures the unit's ability to detect and relay enemy position and is shown in Equation (1.3). INTEL is measured in seconds with a smaller value representing a unit's ability to more quickly collect and disseminate enemy positions on the battlefield. Enemy detection on the battlefield is of paramount importance to a commander's decision-making process in combat.

$$INTEL = \text{time of 50th percent enemy detection - time of first enemy detection} \quad (0.3)$$

IV. SCENARIO DEVELOPMENT AND IMPLEMENTATION

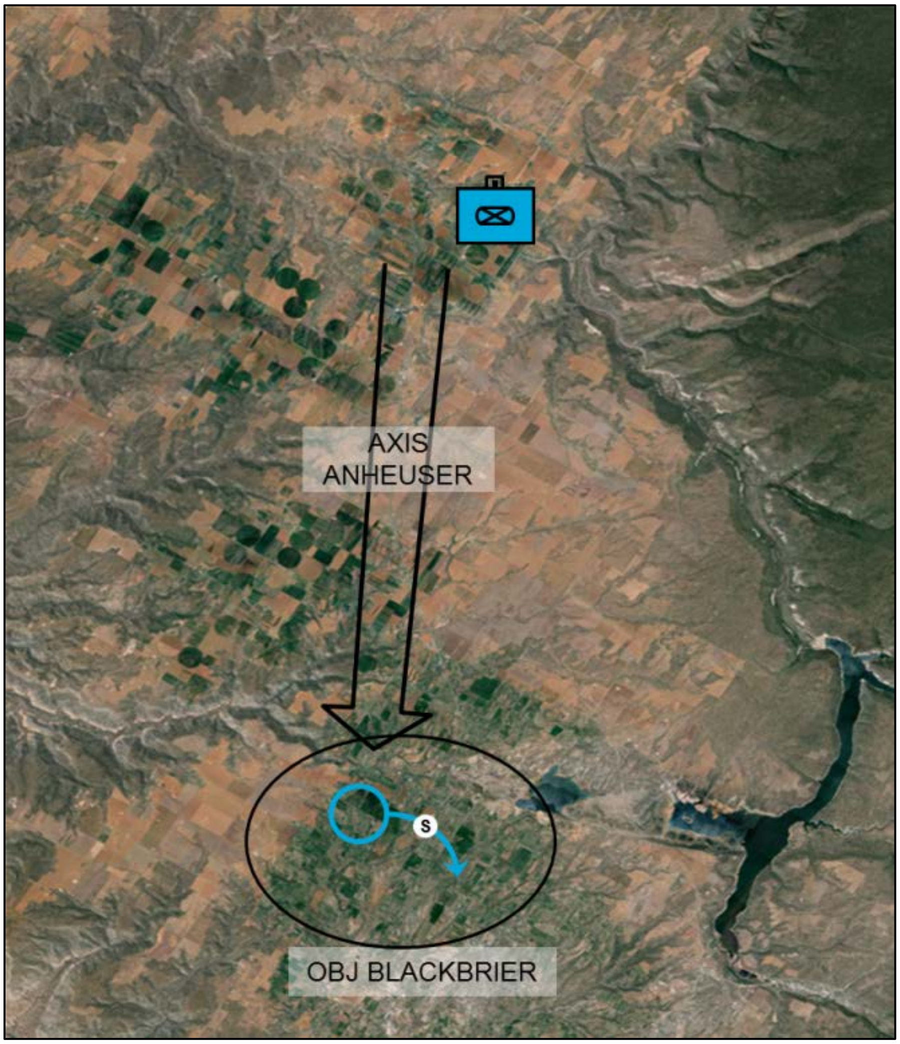
The adversity mentioned in the definition of operational resiliency entails the element of uncertainty. This uncertainty exists in the presence of the three operational scenarios utilized in this study. Each of the operational scenarios was developed based on selected factors from the Army mission variables of mission, enemy, terrain and weather, troops and support available, time available, and civilian considerations (METT-TC). The use of mission variables help refine leaders' understanding of the operational situation and ensure they consider the most "relevant information about conditions that pertain to the mission" (Department of the Army 2012a, 1–2). Specifically, each scenario was developed with a distinct mission, enemy, and terrain.

A. SCENARIO 1—MOUNTAIN ATTACK

1. Mission

The mission each unit configuration executes in this first scenario is an attack. Specifically, the mission statement is Company A attacks to seize Objective (OBJ) Blackbrier in order to allow the battalion's main effort freedom of maneuver on Objective Cheshire. The Army defines seize as a "tactical mission task that involves taking possession of a designated area using overwhelming force" (Department of the Army 2012b, 1–33). Further, attack is defined as an "offensive task that destroys of defeats the enemy forces, seizes and secures terrain, or both" (Department of the Army 2012b, 1–4). The focus for this mission is the seizure of OBJ Blackbrier, accomplished via the offensive task of attack. A graphical depiction of this mission is illustrated in Figure 16.

Figure 16. Scenario 1 Operational Mission Graphics



2. Enemy

The enemy developed for this scenario is modeled after the force designed by Treml (2013). The enemy force each company team faces in this scenario represents what this research considered a near-peer threat, meaning that it more closely matches the friendly elements in weaponry, organization, communications, and ability than do the other scenarios. This force contains a platoon-plus sized element with armored tank support. The platoon is comprised of three dismounted infantry squads of eight personnel each, complimented by two medium-caliber machine guns, an anti-armor section, and two dismounted anti-aircraft missile systems. Figure 17 depicts the disposition of the platoon on the battlefield, with two distinct locations. The two anti-armor sections are placed north of the platoon's main element, in an ambush position. They are each secured by an infantry team from one of the dismounted infantry squads. The remainder of the force is located on OBJ Blackbrier in dug-in defensive positions. The centerpiece of the position is the platoon-sized defensive position occupied by the tanks. On their left and right flanks are squad-sized defensive positions of a dismounted infantry. Co-located with these squads is an anti-aircraft team each.

Figure 17. Scenario 1 Enemy Force Disposition

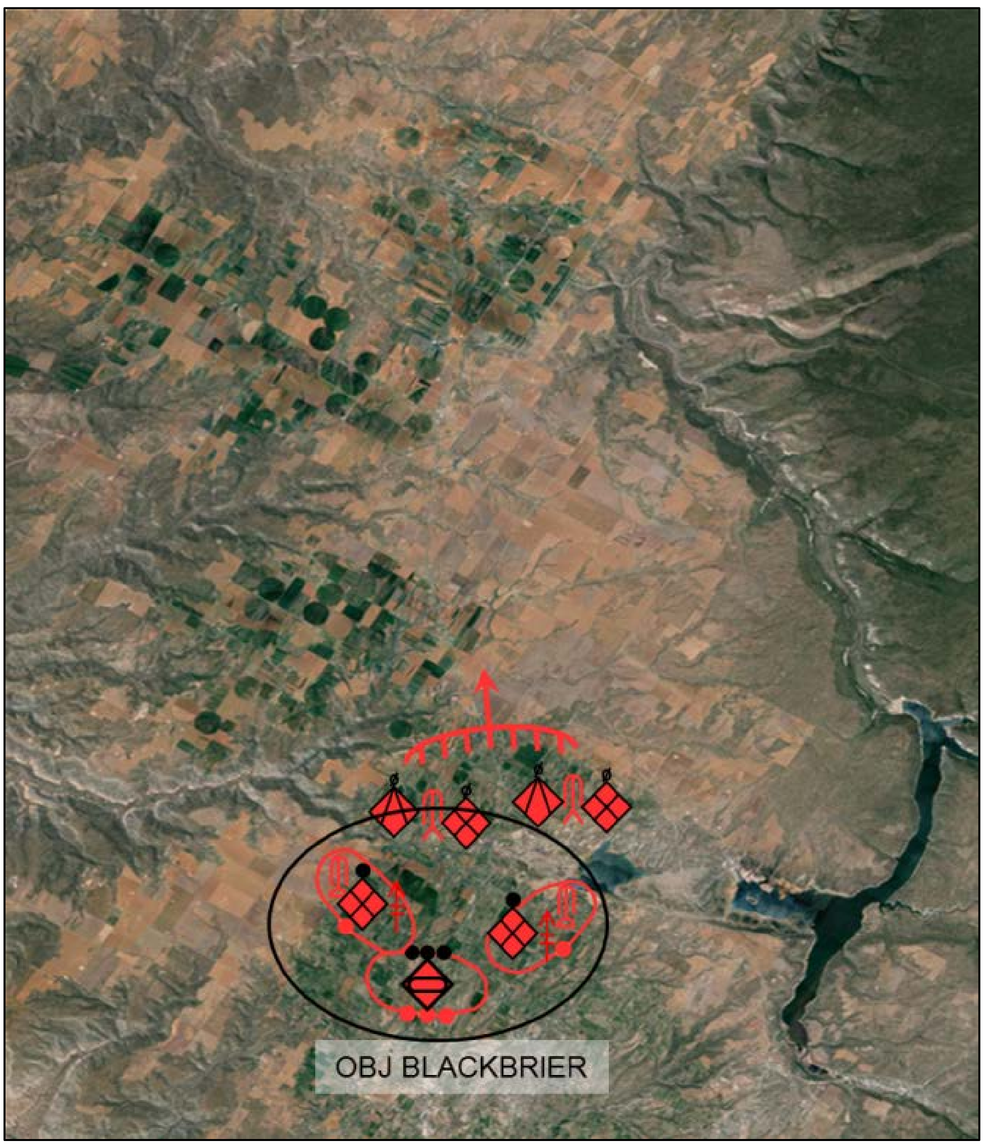


Table 2 provides the strength of the enemy force in terms of the weapons systems. The capabilities of each of the enemy's weapon systems and sensors can be found in Appendix A.

Table 2. Scenario 1 Enemy Force Weapon Systems

Weapon System	Element	Qty per Element	Number of Elements	Total Qty
AK-47	Dismounted Infantry Squad	8	3	28
	Anti-Aircraft Missile Team	1	2	
	Anti-Armor Section	1	2	
PKM Med MG	Machine Gun Team	1	2	2
12.7mm Heavy MG	Tank Platoon	4	1	4
125mm Cannon	Tank Platoon	4	1	4
Kornet Anti-Tank Missile	Anti-Armor Section	1	2	2
SA-18	Anti-Aircraft Missile Team	1	2	2

3. Terrain

The terrain for this scenario mirrors the one employed in Treml (2013). The battlefield modeled is a 30 kilometer by 40 kilometer box generically described as rural countryside with mountainous elevation near the objective. The northern portion of the terrain map allows for unrestricted tactical movement by the friendly force mechanized and armor vehicles as well as for the employment of weapon systems and sensors at their maximum effective range. Increased elevation and vegetation in the southern area of the map, particularly in and around OBJ Blackbrier, favors the established defense. It reduces mobility for the tracked vehicles and provides cover for the enemy. The specific values for how mobility, cover, concealment, and elevation were modeled in this terrain are provided in Appendix B.

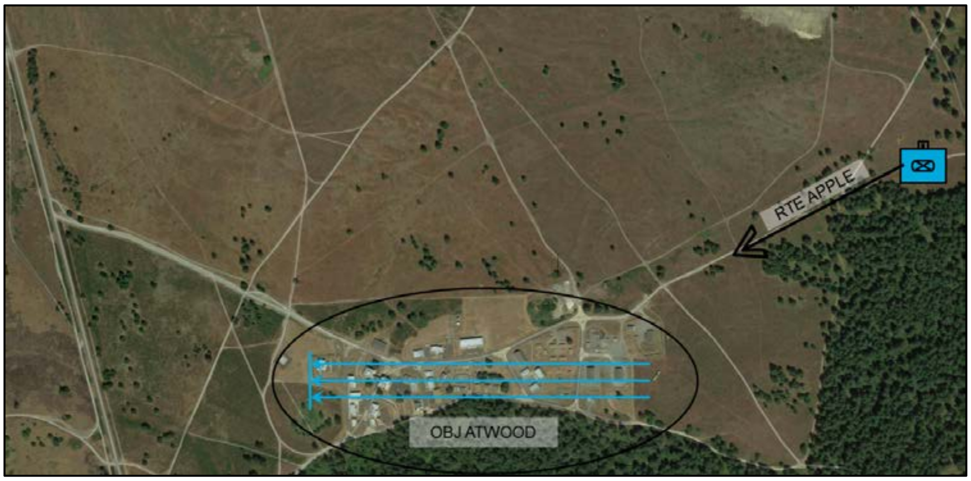
B. SCENARIO 2—URBAN CLEAR

1. Mission

The mission each unit configuration executes in the second scenario is the clearance of an urban town. Specifically the mission statement is Company A clears OBJ Atwood in order to deny the enemy a foothold in the battalion's area of operation. The

Army defines clear as a "tactical mission task that requires the commander to remove all enemy forces and eliminate organized resistance within an assigned area" (Department of the Army 2012b, 1–7). A graphical depiction of this mission is illustrated in Figure 18.

Figure 18. Scenario 2 Operational Mission Graphics



2. Enemy

The enemy force modeled for this scenario represents a loose collection of dismounted infantry teams spread throughout an urban city. They have unreliable communications, are not very well organized, and present the least capable threat of the three scenarios. This enemy is essentially a platoon-sized element, augmented by machine gun teams and indirect fire support. The platoon is comprised of six three-man teams each with a rocket-propelled grenade (RPG), four machine gunners, a two-man observation post (OP), and a single 120mm mortar firing position. Figure 19 depicts the disposition of the enemy throughout the town. The OP is emplaced on the eastern edge of the town, closest to the anticipated direction of attack from the friendly forces. This two-man position is watching over two improvised explosive devices (IEDs) emplaced along the main avenues of approach into the town. The six dismounted teams are disbursed throughout the town. The four machine guns are located at positions that provide observation over and the ability to place direct fire along the main roads in the town.

Finally, the enemy's indirect fire support is located to the west of the town in a small grove of trees, able to place fire on the entirety of the objective and on any possible approach into the town from the east.

Figure 19. Scenario 2 Enemy Force Disposition

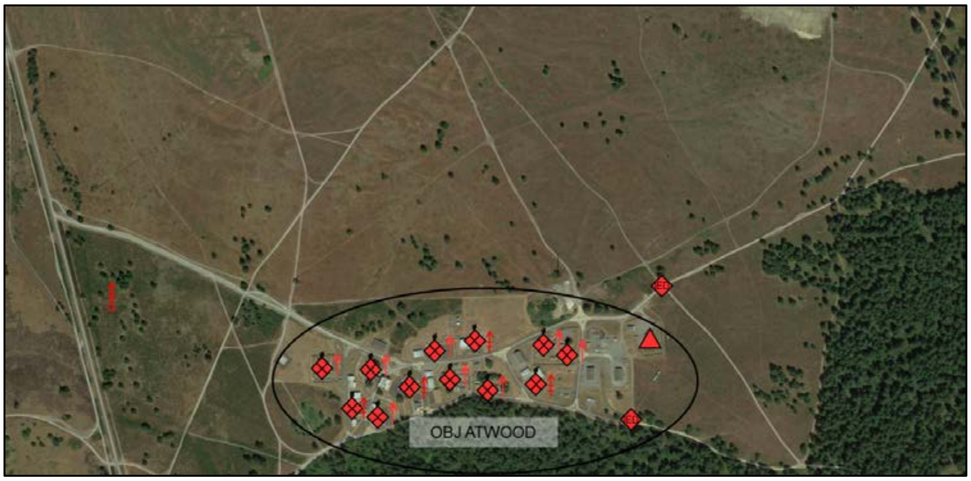


Table 3 provides the strength of the enemy force in terms of the weapons systems. The capabilities of each of the enemy's weapon systems and sensors can be found in Appendix A.

Table 3. Scenario 2 Enemy Force Weapon Systems

Weapon System	Element	Qty per Element	Number of Elements	Total Qty
AK-47	Dismounted Infantry Team	3	6	24
	RPG Team	1	6	
RPG-7	Dismounted Infantry Team	1	6	6
PKM Med MG	Machine Gun Team	1	4	4
IED	Observation Post	2	1	2
120mm Mortar	Indirect Fire Team	1	1	1

3. Terrain

The terrain for this scenario was developed uniquely by this research. It is modeled after the military operations on urban terrain (MOUT) training site at Joint Base Lewis-McChord, Washington. The battlefield modeled is a four kilometer by two kilometer box, mostly flat urban terrain that is boarded by dense forest on the eastern and southern sides. The forest represents severely restricted terrain for both mounted and dismounted troops but provides excellent cover. The terrain to the north and west of the town is flat with intermittent scrub brush that provides no cover or concealment, but allows for the long-range use of sensors and weapon systems. Improved one-lane roads led into and throughout the town. The town itself is comprised of a variety of two and three-story concrete buildings that provide cover and concealment to those that occupy them. The urban setting restricts the use of ground based sensors and weapon systems to line of sight. The specific values for how mobility, cover, concealment, and elevation were modeled in this terrain are provided in Appendix B.

C. SCENARIO 3—DESERT AMBUSH

1. Mission

The mission each unit configuration executes in the third scenario is to conduct a tactical movement through a desert terrain to a key leader engagement (KLE). Specifically, the mission statement is Company A secures the Company Commander along Route Berry to the Afghan district headquarters in order to facilitate a governmental KLE. The Army defines secure as a "tactical mission task that involves preventing a unit, facility, or geographical location from being damaged or destroyed as a result of enemy action" (Department of the Army 2012b, 1-33). A graphical depiction of this mission is illustrated in Figure 20.

Figure 20. Scenario 3 Operational Mission Graphics

2. Enemy

This is a unique enemy force for this study as it is one that is on the tactical offense. This force establishes a deliberate position along RTE Berry in order to ambush the friendly forces as they travel along the route. The enemy force modeled here is not as well equipped as depicted in the first scenario but is more so than that of the enemy in Scenario 2. This force has more reliable communications and increased capabilities. This enemy, too, is the equivalent of a platoon-sized element, augmented by medium tactical vehicles and anti-aircraft weapons. The platoon is comprised of two dismounted infantry squads each complimented with an RPG gunner and a machine gun, a third squad manning the heavy machine guns on the tactical vehicles, two anti-aircraft missile system teams, and a two-man OP. Figure 21 depicts the disposition of the enemy in their coordinated ambush positions. The OP is placed on the eastern edge of the elevated ridgeline just to the south of RTE Berry, overlooking the approach to the designated engagement area. The two dismounted squads have established ambush positions along the same ridgeline, one on each side of the RTE. The anti-aircraft missile teams are located at the highest point of each piece of elevated terrain flanking the road. Finally, the two medium tactical vehicles are hidden behind defilade positions on either side of the road and once the ambush has been initiated, will assume the support by fire positions indicated by the dashed icons.

Figure 21. Scenario 3 Enemy Force Disposition

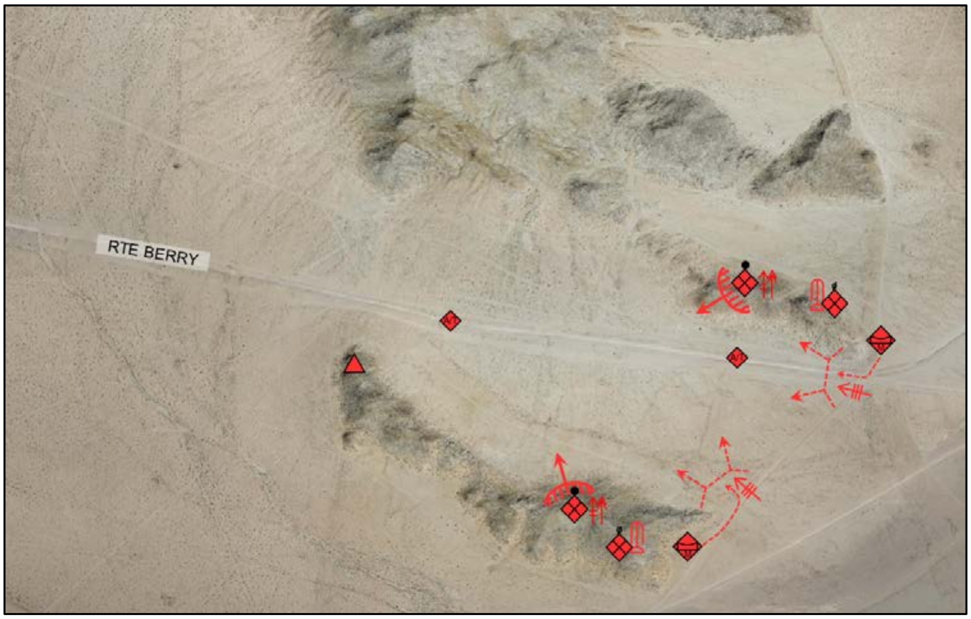


Table 4 provides the strength of the enemy force in terms of the weapons systems. The capabilities of each of the enemy's weapon systems and sensors can be found in Appendix A.

Table 4. Scenario 2 Enemy Force Weapon Systems

Weapon System	Element	Qty per Element	Number of Elements	Total Qty
AK-47	Dismounted Infantry Squad	8	2	20
	RPG Team	1	2	
	Anti-Aircraft Missile Team	1	2	
RPG-7	RPG Team	1	2	2
PKM Med MG	Machine Gun Team	1	2	2
12.7mm Heavy MG	Med Tactical Vehicle	1	2	2
IED	Observation Post	1	2	2
SA-18	Anti-Aircraft Missile Team	1	2	2

3. Terrain

The terrain for this scenario was developed uniquely by this research. It is modeled on a known ambush training location at the National Training Center located at Fort Irwin, California. The battlefield modeled is an eight kilometer by five kilometer box with rolling desert terrain that leads into a small valley created by elevated terrain, notably the ridgelines, along either side of the road. The open desert provides little in the way of cover and concealment, is unrestricted to mounted and dismounted forces, and allows for the long-range use of sensors and weapon systems. The route is an un-improved two-lane road that allows for high-speed movement in either direction. The ridgeline provides excellent observation of the valley and the road leading into it, along with cover and concealment to forces on the backside facing away from the road. The elevation also affords the enemy the long-range use of its weapons and sensors, along with the tactically advantageous position of the high ground. The specific values for how mobility, cover, concealment, and elevation were modeled in this terrain are provided for in Appendix B.

D. CONCEPT OF THE OPERATIONS

This research ensures that the actions of both the friendly and enemy units in each of the three scenarios remain as doctrinally realistic as possible. In an effort to replicate those tactics in a simulation model that an Army company team employs, this research implements priorities of fire for weapon systems and leverages the operational experience of the research group members gained from leading soldiers in combat in Iraq and Afghanistan.

United States Army doctrine provides succinct summaries of current tactics that guide simulation development in this research. "The Infantry company commander must effectively plan to focus, distribute, and shift the overwhelming mass of his direct fire capability at critical locations and times to succeed on the battlefield" (Department of the Army 2006, 9-1). Part of the tactics involved in effectively employing direct fire assets are direct fire control measures, which the Army defines as "the means by which the Infantry company commander…control[s] direct fires" (Department of the Army 2006, 9-9). There exist a number of direct fire control measures, with some being terrain-based and others threat-based. This research uses a threat-based control measure called priorities of fire. This type of control measure provides specific guidance for which type of enemy targets a weapon can engage. The use of priorities of fire in a modeling construct such as MANA-V serves to also drive the tactical movements of forces, as agents move to engage targets based on these prescribed priorities. This research employs priorities of fire for both enemy and friendly weapons systems.

1. Friendly Forces Priorities of Fire

Armored vehicles such as the Abrams tanks and Bradley infantry fighting vehicles prioritize their heavy-caliber main guns first on enemy armored/tactical vehicles and then on the enemy's most casualty-producing weapons such as machine guns, RPGs, and anti-air and armor systems. The machine guns mounted on the tanks and Bradleys are then focused on dismounted troops. Machine gunners place their emphasis on enemy machine guns and RPGs first and then seek to engage dismounted troops.

The close-combat-aviation assets in the form of the AH-64 Apache helicopters prioritize their Hellfire-missile engagements on enemy vehicles. The employment of their 30mm machine starts with high-casualty-producing weapons and progresses down to dismounted troops. Finally, friendly indirect-fire assets prioritize the engagement of enemy indirect-fire assets followed by the engagement of vehicles.

2. Enemy Forces Priorities of Fire

A similar approach is applied to enemy forces. Enemy vehicles focus their efforts on friendly armored forces. Anti-armor forces only engage friendly armored elements while anti-aircraft weapons target only the Apaches. To replicate the operational employment of the RQ-7 Shadow UAVs, which flies at an elevation that makes them nearly impossible to be heard or seen, they are not able to be detected or engaged by any enemy forces. Enemy RPGs focus their efforts initially on armored vehicles and then transition to machine-gun teams. The IEDs are designed to be triggered by the OPs and thus target vehicles only, in an effort to inflict the most significant damage possible. Dismounted troops, both enemy and friendly, employ their small arms against dismounted elements.

3. Other Tactical Considerations

The other method this research utilizes to replicate real-world tactics in the models is to leverage the personal operational experience of the research group. This manifests in such ways as the order-of-movement of friendly units, means-of-employment of aerial elements, and reactions to enemy contact. Armor units lead the ground force movement in each of the three scenarios as they are ideally suited to survive initial contact with an enemy force, contain enough inherent offensive capability to suppress the enemy, and thus allow the remaining forces to maneuver on the enemy.

Prior operational experience suggests that both Shadows and Apaches are capable reconnaissance elements. They each provide a valuable picture of the terrain leading up to and on the mission objective. They are also used to observe and report on pieces of key terrain and natural choke points that create advantageous positions for the enemy. The Apaches are also uniquely suited to engage targets they identify forward of the ground element to reduce the risk to soldiers on the ground.

In reacting to enemy contact, it is a typical tactic, technique, and procedure (TTP) to stop personnel carriers, such as the Bradley, to allow the soldiers in the back to dismount and begin to maneuver on the enemy. Once the enemy localized in that location no longer presents a threat, the soldiers re-mount the vehicles and continue on to their objective. These efforts are incorporated into the modeling of each scenario in an effort to replicate the actual tactics that an Army company team would employ in combat.

E. SIMULATION DESCRIPTION

To facilitate subsequent research in replicating this research's models, two points stand worth mentioning—the number of runs and the stopping conditions employed for each scenario.

1. Number of Iterations

This research conducts 500 iterations for each of the nine configuration-scenario simulations for a total of 4,500 iterations. Based on the speed of an average computer's central processing unit, a single iteration for any of the nine simulations runs to completion in approximately 60 seconds. MANA-V does possess a multi-run feature that expedites each iteration, but not significantly. Due to the stochastic nature of MANA-V, 500 replications are necessary to capture the variability within each scenario and to determine the statistical significance of the results.

2. Stopping Conditions

Stopping conditions are used to control the length of each iteration while simultaneously allowing enough simulation to occur. The stopping conditions present the point at which the scenario-specific mission objectives would be achieved. Stopping conditions for Scenarios 1 and 2 are event-based, while Scenario 3 is time-based. For Scenarios 1 and 2, the stopping-condition event is the force level at which point the unit becomes combat-ineffective. It is at this point that a unit is no longer capable of continuing its mission and would stop forward movement, attempt to establish fire superiority and pass another unit onto the objective, or simply withdraw from the engagement. Combat ineffectiveness is determined by unit strength; specifically, if a unit is reduced to 50-70% of its initial strength, it is considered to be combat ineffective (Department of the Army 1997, C-2). In Scenarios 1 and 2, an enemy would withdraw when reduced to 50% of its initial strength and the friendly forces would successfully complete their mission. Conversely, if the friendly forces are reduced to 70% strength, then the commander would be forced to withdraw or call for reinforcements, either way effectively ending the mission for the company team.

As previously stated, Scenario 3's stopping condition is time-based. The mission in Scenario 3 is to secure the company commander to a KLE. The essence of the unit's ability to secure the commander, however, is illustrated in whether or not they can fight their way out of the enemy's ambush. The research determines that after 5,000 model steps, the unit reaches a point where they either successfully defeat the enemy in the ambush location or are themselves defeated. The enemy in this scenario employs a fight-to-the-death mentality and thus do not withdraw even if rendered combat-ineffective. Thus, the time-based condition is prudent for this final scenario.

V. DATA ANALYSIS

A. RESULTS BY INDIVIDUAL MOE

The research conducted preliminary data analysis to examine the variability of each MOE within each scenario. This analysis demonstrates that there is a significant difference between the performance of at least one configuration for at least one MOE in each scenario, which emphasizes that detailed analysis of each MOE and each scenario is necessary to identify the most operationally resilient configuration.

1. Means and Confidence Intervals

As described in Chapter IV, the research simulates 500 runs for each of the nine configuration-scenario combinations. The relevant data from the various MANA-V output files produces 500 data points for each of the 27 configuration-scenario-MOE combinations. The means and 95% confidence intervals for those 27 configuration-scenario-MOE data sets are presented in Tables 5-7, with each table containing a different scenario's statistics. Upon first review of the data, the raw values come in generally as expected with MOE values affected by scenario. The research does not find any outliers in these data sets.

Table 5. Scenario 1 Data Summary by Configuration and MOE

			Configuration		
			A	**B**	**C**
MOE	**FER**	Mean 95% C.I.	1.47 (1.44, 1.50)	1.78 (1.76, 1.80)	1.86 (1.84, 1.88)
	IDK	Mean 95% C.I.	4.80 (4.44, 5.15)	4.45 (4.10, 4.80)	4.58 (4.19, 4.97)
	INTEL	Mean 95% C.I.	981.35 (963.95, 998.75)	879.63 (865.51, 893.76)	1013.87 (999.66, 1028.09)

Table 6. Scenario 2 Data Summary by Configuration and MOE

			Configuration		
			A	B	C
MOE	FER	Mean	1.11	1.30	1.31
		95% C.I.	(1.09, 1.13)	(1.28, 1.32)	(1.29, 1.33)
	IDK	Mean	12.97	10.89	9.67
		95% C.I.	(12.36, 13.58)	(10.41, 11.37)	(9.23, 10.11)
	INTEL	Mean	940.54	678.14	690.26
		95% C.I.	(930.56, 950.52)	(674.67, 681.62)	(686.78, 693.73)

Table 7. Scenario 3 Data Summary by Configuration and MOE

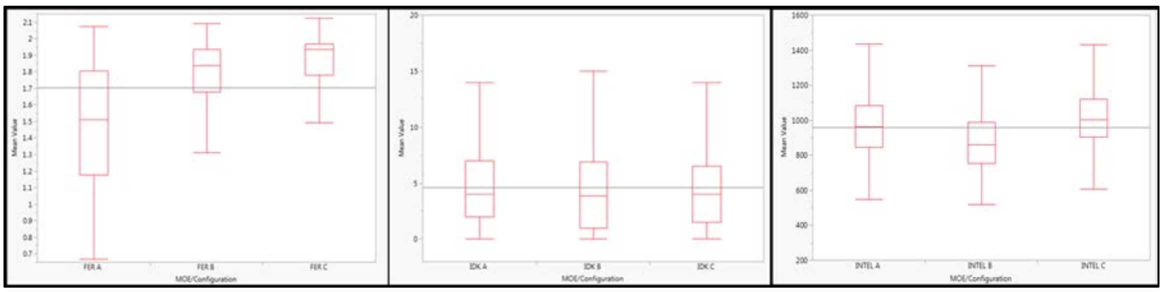
			Configuration		
			A	B	C
MOE	FER	Mean	4.33	6.18	5.02
		95% C.I.	(4.18, 4.48)	(5.95, 6.40)	(4.83, 5.22)
	IDK	Mean	5.91	6.60	6.59
		95% C.I.	(5.78, 6.04)	(6.45, 6.74)	(6.41, 6.77)
	INTEL	Mean	1488.55	1495.42	1516.73
		95% C.I.	(1478.81, 1498.29)	(1483.97, 1506.87)	(1504.63, 1528.84)

2. Data Distribution and Boxplots

The comparison of boxplots shows the reader the similarities and differences in data distributions. When analyzing Figures 22-24, note that MOE values for a particular configuration vary according to scenario. This emphasizes the purpose for assessing performance across multiple scenarios. Overall, most of the distributions are fairly symmetric, with the exceptions noted below. Additionally, it is pertinent to note that Configurations B and C experience the most similarity in raw values and distributions. This is expected due to their similarity in unit configuration.

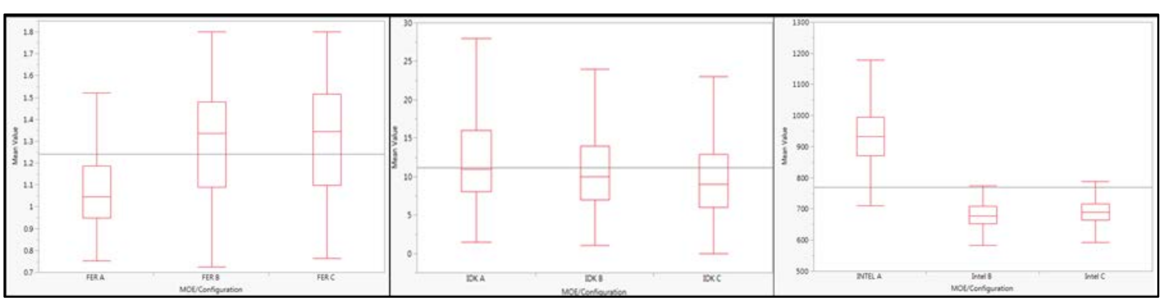
Figure 22 shows the boxplots for Scenario 1 data grouped by MOE (FER, IDK, INTEL left to right) with Configurations A, B, and C individual boxplots ordered left to right as well. Note the much larger distribution spread of Configuration A-FER data in the left box compared to the other two configurations' FER data. This highlights Configuration A's poor performance where 25% of its runs yield lower results than any found in the other two configurations. Separately, IDK and INTEL boxplots (middle and right, respectively) for the three configurations each show similar distributions across the configurations. Of these two, IDK data appears to be the most similar among the configurations with all three being slightly skewed.

Figure 22. Scenario 1 Boxplots grouped by MOE (left to right FER, IDK, INTEL)



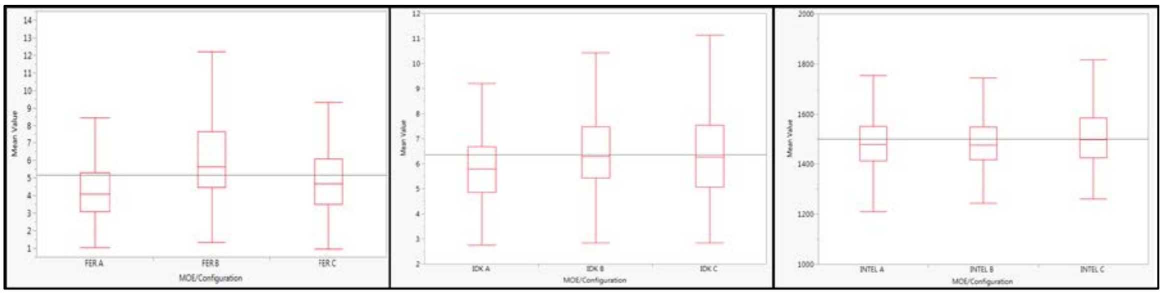
Boxplots for Scenario 2 are organized the same as for Scenario 1 and shown in Figure 23. In this scenario, the boxplots across all three MOEs seemingly show similarities between Configurations B and C. Note also that Configuration A's INTEL data distribution is significantly higher than the same data for the other configurations, highlighting its lesser ability to gather enemy intelligence during simulation.

Figure 23. Scenario 2 Boxplots grouped by MOE (left to right FER, IDK, INTEL)



In Figure 24, none of Scenario 3's MOE-specific boxplots show disparity among the configurations. These boxplots have the most symmetric distributions of the three scenarios. In particular, INTEL data for the three configurations appear the most identical of all the MOE boxplots presented.

Figure 24. Scenario 3 Boxplots grouped by MOE (left to right FER, IDK, INTEL)



3. IDK Variable Transformation

Note that raw values on a given run for two of the MOEs (FER and IDK) have the possibility of being undefined due to the potential zero in the denominator. Fortunately, in the case of FER [see Equation (1.1)], stopping conditions prevent the situation that all enemy forces are killed and therefore result in no FER calculations with a zero denominator. Unfortunately, in the case of IDK [see Equation (1.2)], at least one of the 500 runs in every set of runs results in zero enemy killed by artillery fire. Even when no enemy is killed by artillery, it is still important to account for those rounds fired. In order to preserve the data in those runs, the research employs a variable transformation as recommended in Hayter (2012). As a result, a one is added to the denominator for all IDK values as shown in Equation (1.4).

$$IDK = \frac{\text{\# friendly artillery rounds fired}}{\text{\# enemy killed by artillery} + 1} \qquad (0.4)$$

The variable transformation is incorporated in all values for IDK in this chapter (Chapter V). As such, the data-distribution analyses and pairwise comparisons use these transformed IDK values.

B. PAIRWISE COMPARISONS

The research employed additional statistical methods to make inferences about the data. Specifically, the research conducted pairwise comparisons (Hayter 2012, 511) of the MOE means to analyze parity of the data. In each scenario, the mean for a configuration's MOE raw value is compared to the means of the other two configurations' MOE raw values. For Scenario 1, Tables 8 and 10 show that two of the MOEs (FER and INTEL) are statistically different, evident by the significant p-values (all less than 0.01). Conversely, Table 9 shows that the IDK values in each configuration are not significantly different from each other, as evident by the large p-value (all above 0.18).

Table 8. Scenario 1 FER Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
FER C	FER A	0.3886800	0.0166828	0.3559559	0.4214041	<.0001*
FER B	FER A	0.3127092	0.0166828	0.2799851	0.3454333	<.0001*
FER C	FER B	0.0759708	0.0166828	0.0432467	0.1086949	<.0001*

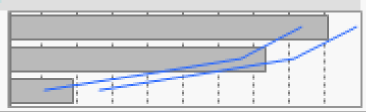


Table 9. Scenario 1 IDK Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
IDK A	IDK B	0.3463817	0.2634789	-0.170445	0.8632088	0.1888
IDK A	IDK C	0.2185595	0.2634789	-0.298268	0.7353866	0.4069
IDK C	IDK B	0.1278222	0.2634789	-0.389005	0.6446493	0.6277

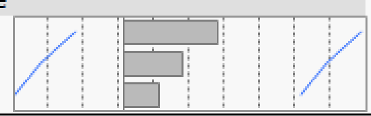


Table 10. Scenario 1 INTEL Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
INTEL C	INTEL B	134.2420	11.05519	112.5567	155.9273	<.0001*
INTEL A	INTEL B	101.7140	11.05519	80.0287	123.3993	<.0001*
INTEL C	INTEL A	32.5280	11.05519	10.8427	54.2133	0.0033*

The analysis results for Scenario 2 are substantially different from the analysis results for Scenario 1. In Scenario 2, Tables 12 and 13 show that two of the MOEs (IDK and INTEL) are statistically different, resulting in significant p-values (all less than 0.01). Similarly, Table 11 shows the statistical difference for FER from Configurations C to A and Configurations B to A. The FER values between Configurations C and B are the only data not statistically different (p-value of 0.3872).

Table 11. Scenario 2 FER Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
FER C	FER A	0.1986014	0.0153861	0.168421	0.2287820	<.0001*
FER B	FER A	0.1852924	0.0153861	0.155112	0.2154730	<.0001*
FER C	FER B	0.0133090	0.0153861	-0.016872	0.0434897	0.3872

Table 12. Scenario 2 IDK Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
IDK A	IDK C	3.301667	0.3712284	2.573484	4.029850	<.0001*
IDK A	IDK B	2.079333	0.3712284	1.351150	2.807516	<.0001*
IDK B	IDK C	1.222333	0.3712284	0.494150	1.950516	0.0010*

Table 13. Scenario 2 INTEL Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
INTEL A	Intel B	262.3960	4.640450	253.2935	271.4985	<.0001*
INTEL A	Intel C	250.2820	4.640450	241.1795	259.3845	<.0001*
Intel C	Intel B	12.1140	4.640450	3.0115	21.2165	0.0091*

In Scenario 3, Tables 14–16 show that seven of the nine MOE comparisons are statistically different, evident by the significant p-values (all less than 0.01). The IDK values between Configurations B and C (p-value of 0.9323) and the INTEL values between Configurations A and B (p-value of 0.3933) are the notable exceptions.

Table 14. Scenario 3 FER Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
FER B	FER A	1.847789	0.1379992	1.577097	2.118482	<.0001*
FER B	FER C	1.152813	0.1379992	0.882120	1.423505	<.0001*
FER C	FER A	0.694977	0.1379992	0.424284	0.965669	<.0001*

Table 15. Scenario 3 IDK Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
IDK B	IDK A	0.6854079	0.1108126	0.468043	0.9027724	<.0001*
IDK C	IDK A	0.6759927	0.1108126	0.458628	0.8933572	<.0001*
IDK B	IDK C	0.0094153	0.1108126	-0.207949	0.2267797	0.9323

Table 16. Scenario 3 INTEL Pairwise Comparisons

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Intel C	Intel A	28.18600	8.049394	12.3967	43.97529	0.0005*
Intel C	Intel B	21.31200	8.049394	5.5227	37.10129	0.0082*
Intel B	Intel A	6.87400	8.049394	-8.9153	22.66329	0.3933

Note that traditional analysis would lead the research to disregard an MOE that shows parity across configurations. As an example, if only Scenario 1 is examined, one would conclude there is no difference in terms of IDK for any of the configurations. Examining the data in terms of operational resiliency leads to a different conclusion. Looking at IDK in Scenario 2, it is clear there is a significant difference between IDK values from the configurations. By examining the performance of three different configurations in three different scenarios for the three different MOEs, the resultant recommended configuration is not sensitive to a single scenario or MOE.

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VI. MULTI-OBJECTIVE DECISION ANALYSIS

A. ADDITIVE VALUE MODEL PROCESS

The research uses the additive value model within multi-objective decision analysis to evaluate the operational resiliency of the three alternative configurations. As Gregory Parnell and Timothy Trainor (2009, 284) point out, “the additive value model quantitatively assesses the trade-offs between objectives by evaluating the alternative’s contribution to the value measures (a score converted to value by single-dimensional value functions) and the relative importance of each value measure (weight).” Equation (1.5) is used to evaluate each configuration’s operational resiliency, called the Operational Resiliency Score (OR Score), as adapted from the general additive model (Parnell 2007, 629). An important note is that since “neither the value functions...or the weights...depend on the alternatives,” then this method is very useful “when comparing significantly different system concepts, architectures, designs, and alternatives in any life cycle state” (MacCalman and Parnell 2015, 6).

$$OR_i = \sum_{j \in J} \sum_{k \in K} w_{jk} \times v_k(x_{ijk}), \text{ for } i \in I \tag{0.5}$$

where

$I = \{A, B, C\}$ is the set of configurations

$J = \{1, 2, 3\}$ is the set of scenarios

$K = \{FER, IDK, INTEL\}$ is the set of MOE*s*

OR_i is the i^{th} configuration's Operational Resiliency Score

w_{jk} is the normalized swing weight of the k^{th} MOE in the j^{th} scenario

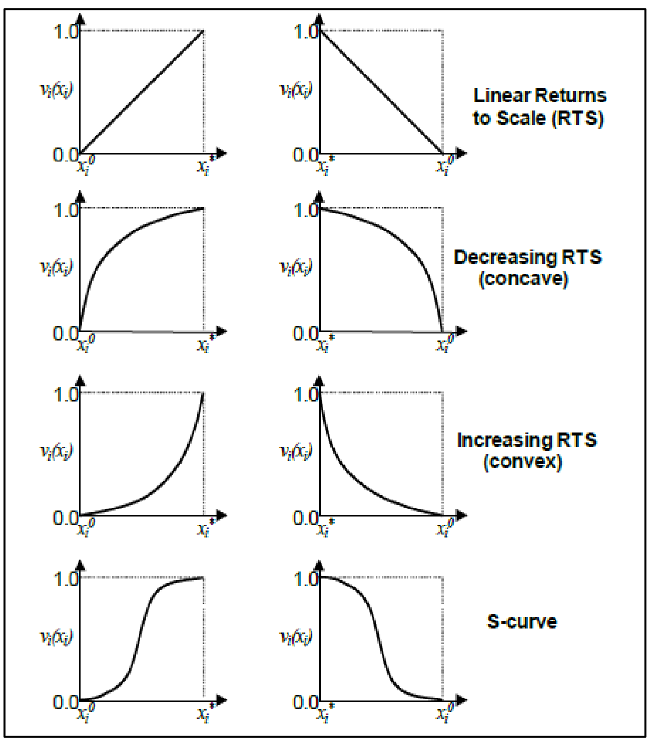
$v_k(x_{ijk})$ is the single-dimensional value of x_{ijk}

x_{ijk} is the i^{th} configuration's raw value in the j^{th} scenario for k^{th} MOE

and $\sum_k w_{jk} = 1$ for each j^{th} scenario

The value functions, or value curves, show the "returns to scale of the value measures" by translating "the raw value measure data into a common scale typically between 0 and 100 (0 and 1 or 0 and 10 are also frequently used)" (MacCalman and Parnell 2015, 5). For this project, a scale of 0 to 1 is used for all value curves. The research employs Parnell's (2007, 629) suggested technique to develop the value curves by first "determining the shape of the value curve: linear, concave, convex, or S-curve" and then using "value increments to identify several points on the curve." Figure 25 shows the four general shapes previously mentioned. Value curves are generated for each of the three MOEs (FER, IDK, INTEL) based on the authors' collective experience and generally-accepted Army TTPs. Moreover, the value curves are consistent across the scenarios and account for the expected and relevant range of raw-value data from each MOE. The specific value curves are found in Section B of this chapter.

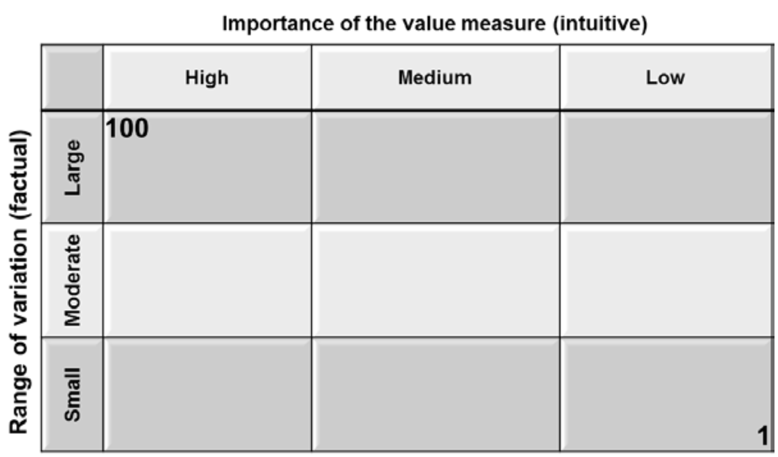
Figure 25. Value Curve Shapes that represent Returns to Scale



Source: MacCalman, Alex, and Gregory Parnell. 2015. "Multiobjective Decision Analysis with Probability Management for Systems Engineering Trade-off Analysis." *Paper is scheduled to be presented at the Hawaii International Conference on System Sciences in Kauai, Hawaii in January 2016.*

Although a myriad of weight-assessment techniques exist, the research utilizes Parnell's Swing Weight Matrix Method (2007, 630). This method "explicitly defines the two major weighting factors: importance and variation prior to the weighting assessment" (631). Figure 26 is an example shell matrix that shows the value-measure importance across the top and the range of value-measure variation along the left side. While employing this method, the "levels of importance and variability...should be defined in terms appropriate for the systems decision" (Parnell, Driscoll, and Henderson 2011, 334). In this project, swing weight values range from one to 100 with the highest swing weight occupying the upper-left corner and the lowest swing weight occupying the lower-right corner. Within each matrix, "weights should descend in magnitude as we move in a diagonal direction from the top left to the bottom right" (336). Moreover, the only strict relationship governing each matrix is that the measures placed in any single cell must be greater than all those measures placed in cells to the right and below it (336).

Figure 26. Generic Swing Weight Matrix



Adapted from Parnell, Gregory S. 2007. "Value-focused Thinking." In *Methods for Conducting Military Operational Analysis*, edited by Andrew G. Loerch, 619–56. Virginia: Military Operations Research Society.

For each scenario, the research places the three MOEs in one of the nine cells based on the intersection of their importance and range of variation. Once all three are placed in their cells, they are assigned non-normalized swing-weight values of one to

100, where f_{jk} is the non-normalized swing weight of the k^{th} MOE value measure in the j^{th} scenario. Each swing weight is subsequently normalized by using Equation (1.6).

$$w_{jk} = \frac{f_{jk}}{\sum_k f_{jk}} \qquad (0.6)$$

This technique of generating a swing-weight matrix per scenario is appropriate in this context of operational-resiliency evaluation. This highlights the point that depending on the mission or scenario, certain functionalities, and therefore their corresponding MOEs, may be more critical to a unit's mission success. For example, indirect fire capability would be more valuable in reacting to an ambush than it would be in clearing an urban environment. Accordingly, one would expect the non-normalized swing-weight values for IDK to reflect that value difference across the scenarios. Further discussion of the varying importance of MOE per scenario as well as the specific swing-weight matrices are found in Section C of this chapter (Chapter VI).

Overall, the additive value model yields values in a specific range dictated by the scale used in the value curves. This is due to the fact that the normalized swing weights use a ratio scale and sum up to one; therefore, they are not a driver for the range. As such, a scale of zero to 10 or zero to 100 will produce scores commensurate with those values. Since this research selects value-function scales with a maximum value of one, the OR Score follows accordingly. For a configuration's OR Score, the score can range from zero to three, with three representing the highest operational resiliency.

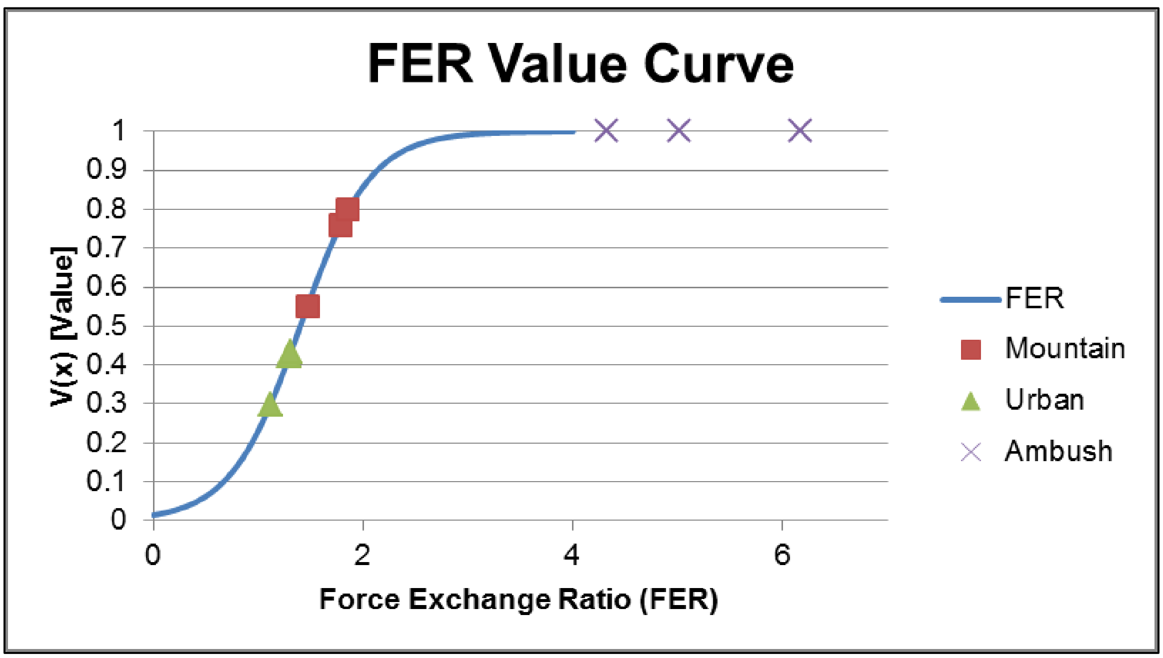
B. VALUE CURVES

As discussed in Section A of this chapter (Chapter VI), value curves translate raw value data into a common scale. This research generates unique values curves for each of the three MOEs by employing Parnell's (2007) technique for value-curve development. Operational experience first determined the initial shape of each value curve and second, identified points along the curve for further refinement.

1. Force Exchange Ratio (FER)

The nature of FER dictates an S-curve to represent its value function. A value of one reflects poor operational performance—friendly and enemy forces attrite at an equal rate—and as such has little to no value. The value of a specific FER above one then increases dramatically, following the shape of the S-curve, until reaching a plateau at an FER value of two. Any FER value greater than two is equally exceptional, as it represents friendly-to-enemy attrition at a 2:1 ratio or better. The inflection point for this value curve lies at an FER value of 1.4. This represents the point at which both the friendly and enemy forces have become combat ineffective as discussed in Chapter IV, Section E, where friendly forces reduce to 70% and enemy forces to 50%. As such, the research assesses the value of 0.5 to an FER value of 1.4. Figure 27 depicts the value curve for the FER MOE with the nine scenario-configuration points displayed.

Figure 27. FER Value Curve



The points from Scenario 3 (Ambush scenario) are all above four and achieve the maximum value of one. Being that the enemy is on the tactical offensive in this scenario, one would expect the FER to be much lower. However, the capabilities of the company team overcome that tactical advantage for each of the scenarios. The Apaches and Shadows operate out in front of the ground element, are able to identify targets earlier, and pass their locations through the company headquarters to the field artillery element. With the enemy determined to inflict as much damage as possible and not withdraw, the company team configurations are also better able to find, fix, and finish the enemy.

Based on the value function assignment presented earlier, Equation (1.7) displays the mathematical expression for FER.

$$v_{FER}(x_{ij,FER}) = \frac{1}{1+e^{-3(x_{ij,FER}-1.4)}} \tag{0.7}$$

Figure 28 provides a demonstration of how the value curve is used to determine the FER single-dimensional value for Configuration A in Scenario 1.

Figure 28. FER Single-Dimensional Value Determination Example

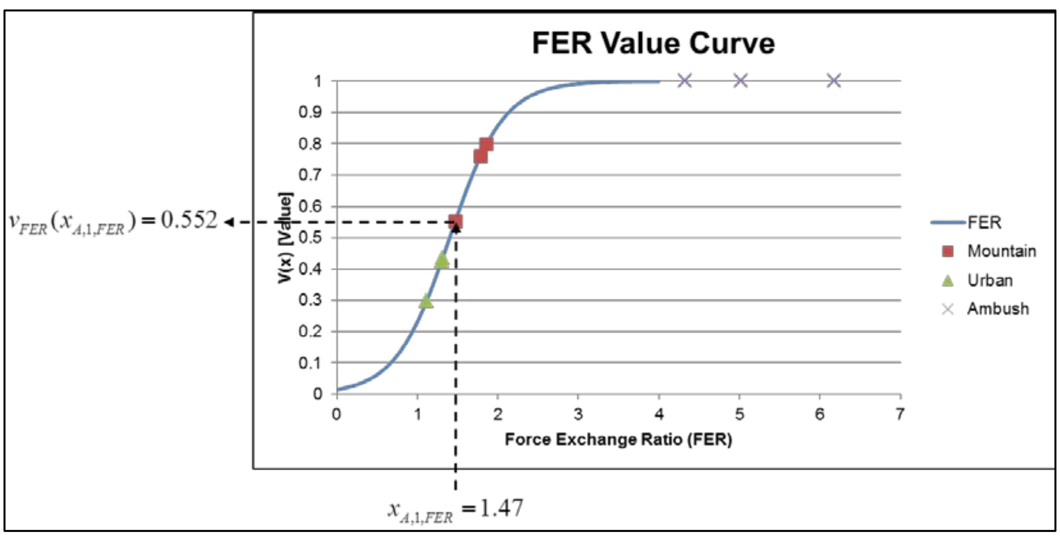


Table 17 presents the remaining single-dimensional values for FER.

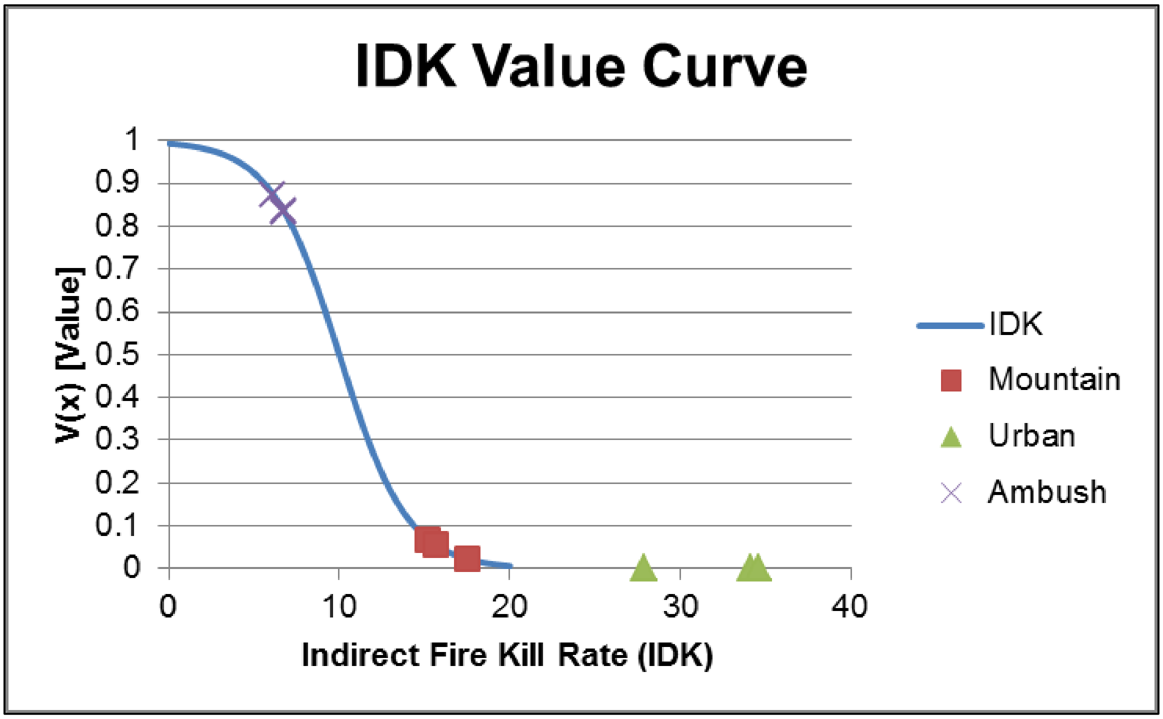
Table 17. FER Single-Dimensional Values by Configuration and Scenario

	Configuration A	Configuration B	Configuration C
Scenario 1	$v_{FER}(x_{A,1,FER}) = 0.552$	$v_{FER}(x_{B,1,FER}) = 0.759$	$v_{FER}(x_{C,1,FER}) = 0.799$
Scenario 2	$v_{FER}(x_{A,2,FER}) = 0.297$	$v_{FER}(x_{B,2,FER}) = 0.424$	$v_{FER}(x_{C,2,FER}) = 0.434$
Scenario 3	$v_{FER}(x_{A,3,FER}) = 0.999$	$v_{FER}(x_{B,3,FER}) = 0.999$	$v_{FER}(x_{C,3,FER}) = 0.999$

2. Indirect Fire Kill Ratio (IDK)

The nature of IDK dictates the value curve shape is an inverse S-curve. This shape demonstrates that smaller IDK raw values are better (i.e., it takes fewer indirect-fire rounds to eliminate an enemy threat). The two points used to develop this curve are the IDK raw values of four and 10. IDK raw values of four or less are all given single-dimensional values of 0.95 and above, as they represent it taking at most a single round-per-gun for a battery of four 155mm-howitzers to destroy a target. The IDK raw value of 10 represents the inflection point for this curve and is assessed a single-dimensional value of 0.5. This valuation is based upon the assumption that a single 155mm-artillery round carries a percent of incapacitation (PI) of 10% out to a distance of 125 meters (Department of the Army 2007, 2-11). A PI of 10% therefore implies that one soldier in ten will be rendered incapacitated by the effects of the 155mm round at that distance. Taken from the inverse perspective, on average, it takes ten rounds to incapacitate or destroy a single target. Figure 29 depicts the IDK value curve with the points from the nine scenario-configuration combinations.

Figure 29. IDK Value Curve



Notably, the three data points for Scenario 2 (Urban scenario) are all above 25 and achieve the minimum value of zero. In this instance, the indirect fire assets have much fewer targets to engage, their ability to engage targets within the town is restricted by concerns over collateral damage, and the town's buildings provide excellent cover for the enemy to use to protect themselves from the incoming rounds. For those reasons, the raw values for IDK in that scenario are high, yielding very low single-dimensional values.

Note that these IDK values differ from those in Chapter V because they omit the transformation and instead they sum the totals across the 500 runs for the number of friendly artillery rounds fired and the number of enemy killed by artillery. Those totals are then divided appropriately according to Equation (1.2) to yield the IDK raw values used by this value function. Based on the value function assignment presented earlier, Equation (1.8) displays the mathematical expression for IDK.

$$v_{IDK}(x_{ij,IDK}) = -\left(\frac{1}{1+e^{-0.5(x_{ij,IDK}-10)}}\right)+1 \quad (0.8)$$

The process for determining the single-dimensional values for all nine scenario-configuration combinations for the IDK remains unchanged from that described in the previous section. Thus, the single-dimensional values for IDK are displayed in Table 18.

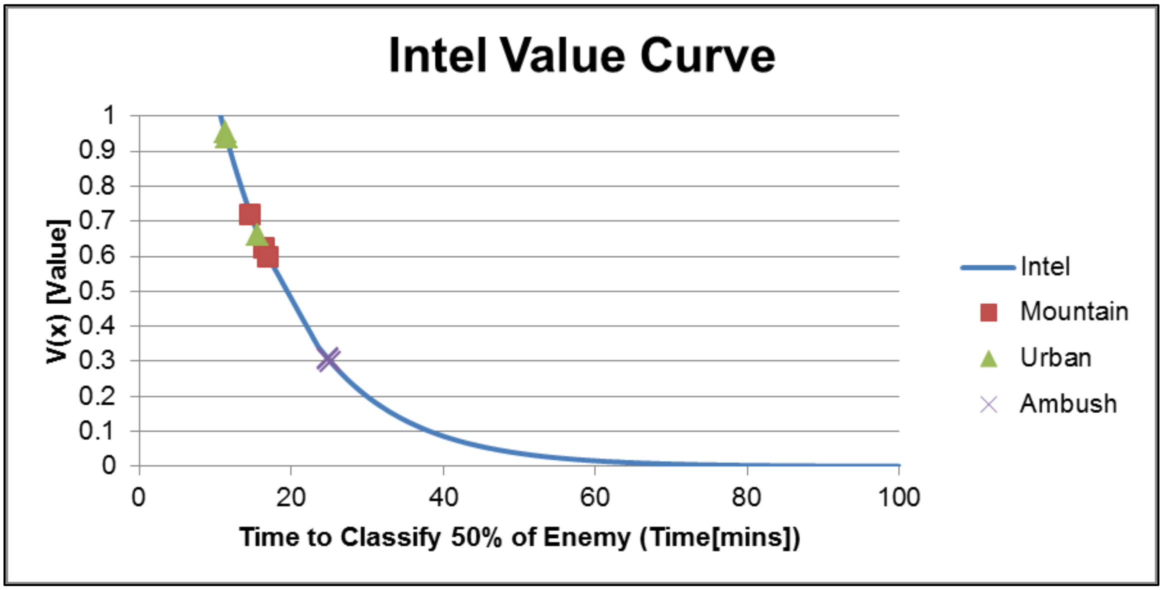
Table 18. IDK Single-Dimensional Values by Configuration and Scenario

	Configuration A	Configuration B	Configuration C
Scenario 1	$v_{IDK}(x_{A,1,IDK}) = 0.069$	$v_{IDK}(x_{B,1,IDK}) = 0.056$	$v_{IDK}(x_{C,1,IDK}) = 0.023$
Scenario 2	$v_{IDK}(x_{A,2,IDK}) = 0.000$	$v_{IDK}(x_{B,2,IDK}) = 0.000$	$v_{IDK}(x_{C,2,IDK}) = 0.000$
Scenario 3	$v_{IDK}(x_{A,3,IDK}) = 0.875$	$v_{IDK}(x_{B,3,IDK}) = 0.834$	$v_{IDK}(x_{C,3,IDK}) = 0.837$

3. Intelligence Time to Detect 50% of Enemy Forces (INTEL)

For the final value curve, the nature of INTEL dictates a convex increasing return-to-scale curve. The shape of this curve reflects the notion that the longer it takes to develop a picture of where the enemy is on the battlefield, the significantly less value that information carries to an operational commander. The two points chosen to further refine the curve correspond to INTEL times of 15 minutes and 30 minutes. Based on the authors' personal experience, a highly-trained quick reaction force (QRF) can deploy to reinforce another unit-in-contact within 15 minutes of notification. Thus, if a commander or battle captain knows the location of at least 50% of the enemy forces in contact with their unit, he or she can make a well-informed decision as to whether or not to launch the QRF. This time is assessed a single-dimensional value of 0.7, meaning that this time is good enough to make an effective decision but could most certainly be improved upon. The second time of 30 minutes, double that of the threshold length of 15 minutes, illustrates how little value the information carries the longer it takes to gather and is assessed a single-dimensional value of 0.2. Take note that the raw values for INTEL used in the value curve equation are in minutes. Figure 30 displays the INTEL value curve with the points from the nine scenario-configuration combinations.

Figure 30. INTEL Value Curve



Based on the value function assignment presented, Equation (1.9) displays the mathematical expression for INTEL.

$$v_{INTEL}(x_{ij,INTEL}) = 2.45 * (0.91987486)^{x_{ij,INTEL}} \qquad (0.9)$$

The single-dimensional values for INTEL are determined by the same process used for the other two MOEs. As such, the single-dimensional values for INTEL are displayed in Table 19.

Table 19. Intel Single-Dimensional Values by Configuration and Scenario

	Configuration A	Configuration B	Configuration C
Scenario 1	$v_{INTEL}(x_{A,1,INTEL}) = 0.625$	$v_{INTEL}(x_{B,1,INTEL}) = 0.720$	$v_{INTEL}(x_{C,1,INTEL}) = 0.597$
Scenario 2	$v_{INTEL}(x_{A,2,INTEL}) = 0.662$	$v_{INTEL}(x_{B,2,INTEL}) = 0.953$	$v_{INTEL}(x_{C,2,INTEL}) = 0.937$
Scenario 3	$v_{INTEL}(x_{A,3,INTEL}) = 0.309$	$v_{INTEL}(x_{B,3,INTEL}) = 0.306$	$v_{INTEL}(x_{C,3,INTEL}) = 0.297$

C. SWING WEIGHTS

As mentioned in Section A, the swing weight matrices must factor in the relative importance and range of variation of the MOEs in each scenario. For an Army company team, the relative importance of an MOE depends on how critical it is to mission success. Therefore, in each matrix, the columns represent the level of criticality to mission success. Furthermore, since each MOE measures a specific functionality of the company team, the criticality of the MOE is driven by how critical the matching warfighting function is to mission accomplishment in each scenario.

The range of variation is a function of the data and is calculated for each MOE in each scenario using Equation (1.10). An MOE's range of variation is then compared against the other two MOEs within each scenario to determine small, moderate, and large variation. Note that the numerical value for range of variation does not dictate the specific classification as small, moderate, or large variation. For example, the Scenario 2-INTEL range of variation of 0.341 is assessed as moderate (see Table 21) whereas the Scenario 3-FER range of variation of 0.357 is assessed as large (see Table 22). Although similar in value, the Scenario 3-FER range of variation is significantly higher when compared to the other MOEs within Scenario 3, justifying the large assessment. This highlights the subjectivity inherent in any decision analysis in general, which is accounted for in the sensitivity analysis in Section E.

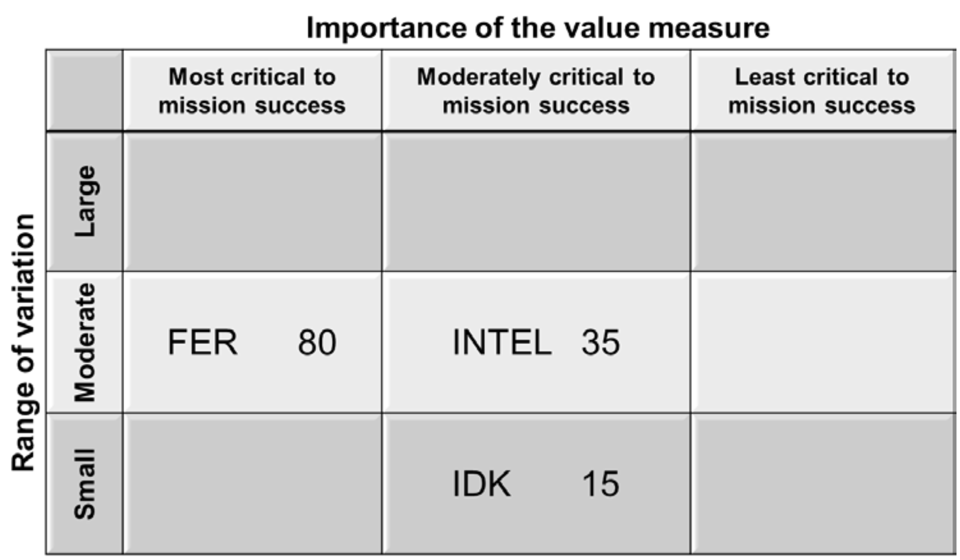
$$\text{range of variation} = \frac{\text{max value - min value}}{\text{average value}} \qquad (0.10)$$

In Scenario 1, the ability to move and maneuver is most critical to success, followed equally by the indirect fire and intelligence warfighting functions. As such, FER is considered most critical while IDK and INTEL are considered moderately critical to mission success. Table 20 displays the range-of-variation results and criticality-to-mission-success values for each MOE. Those values are placed in the swing weight matrix shown in Figure 31 and assigned non-normalized swing weight values accordingly.

Table 20. Scenario 1 Range of Variation and Level of Criticality Values

Scenario 1			
MOE	**Range of Variation**		**Criticality to MSN success**
FER	0.228	moderate	most critical
IDK	0.075	small	moderately critical
INTEL	0.140	moderate	moderately critical

Figure 31. Scenario 1 Swing Weight Matrix



For Scenario 2, due to the change to an urban terrain with smaller-unit enemy fighters, the intelligence and movement-and-maneuver warfighting functions are the most critical to success. Conversely, indirect-fire capability is of little value due to the inherent collateral-damage considerations. As a result, FER and INTEL are valued as most critical while IDK receives a least-critical valuation. Table 21 displays the range-of-variation results and criticality-to-mission-success values for each MOE. Those values are placed in the swing weight matrix shown in Figure 32 and assigned non-normalized swing-weight values accordingly.

Table 21. Scenario 2 Range of Variation and Level of Criticality Values

Scenario 2			
MOE	**Range of Variation**		**Criticality to MSN success**
FER	0.160	moderate	most critical
IDK	0.295	moderate	least critical
INTEL	0.341	moderate	most critical

Figure 32. Scenario 2 Swing Weight Matrix

Importance of the value measure

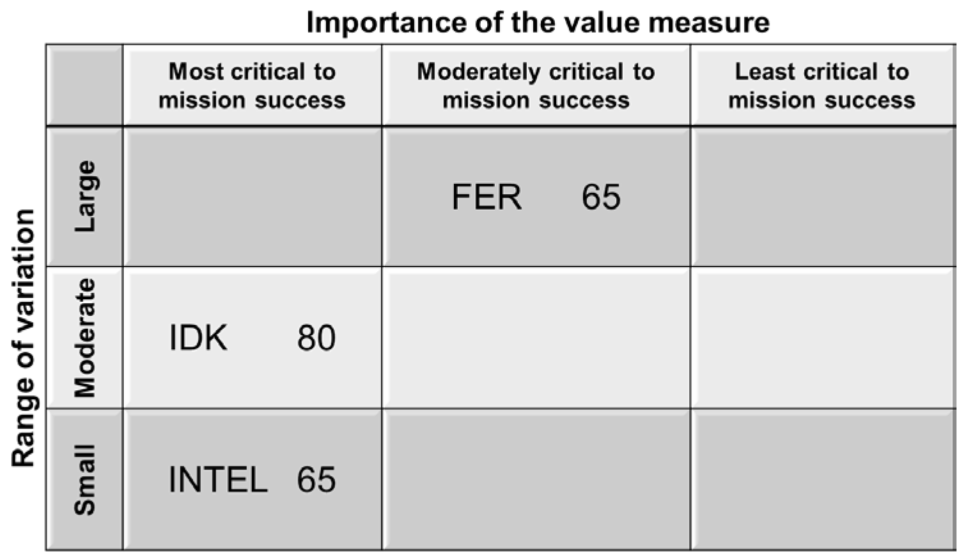
Range of variation	Most critical to mission success	Moderately critical to mission success	Least critical to mission success
Large			
Moderate	FER 80 INTEL 80		IDK 10
Small			

The mission in Scenario 3 calls for the three configurations to quickly react and respond to an ambush through a desert-like environment. In this scenario, it is most critical to locate the enemy and deliver accurate artillery fire to allow the friendly forces to move through the kill zone expeditiously. As a result, INTEL and IDK are found to be most critical to mission success, while FER is moderately critical. Table 22 displays the range-of-variation results and criticality-to-mission-success values for each MOE. Those values are placed in the swing-weight matrix shown in Figure 33 and assigned non-normalized swing-weight values accordingly.

Table 22. Scenario 3 Range of Variation and Level of Criticality Values

Scenario 3			
MOE	**Range of Variation**		**Criticality to MSN success**
FER	0.357	large	moderately critical
IDK	0.108	moderate	most critical
INTEL	0.019	small	most critical

Figure 33. Scenario 3 Swing Weight Matrix



To calculate the normalized swing weights that are used to determine each configuration's OR Score, Equation (1.6) is used as described earlier in Section A. To demonstrate, the calculation for FER in Scenario 1 is shown in Equation (1.11). Accordingly, the remaining normalized swing weights are displayed in Table 23.

$$w_{1,FER} = \frac{f_{1,FER}}{f_{1,FER} + f_{1,IDK} + f_{1,INTEL}} = \frac{80}{80+15+35} = 0.615 \quad (0.11)$$

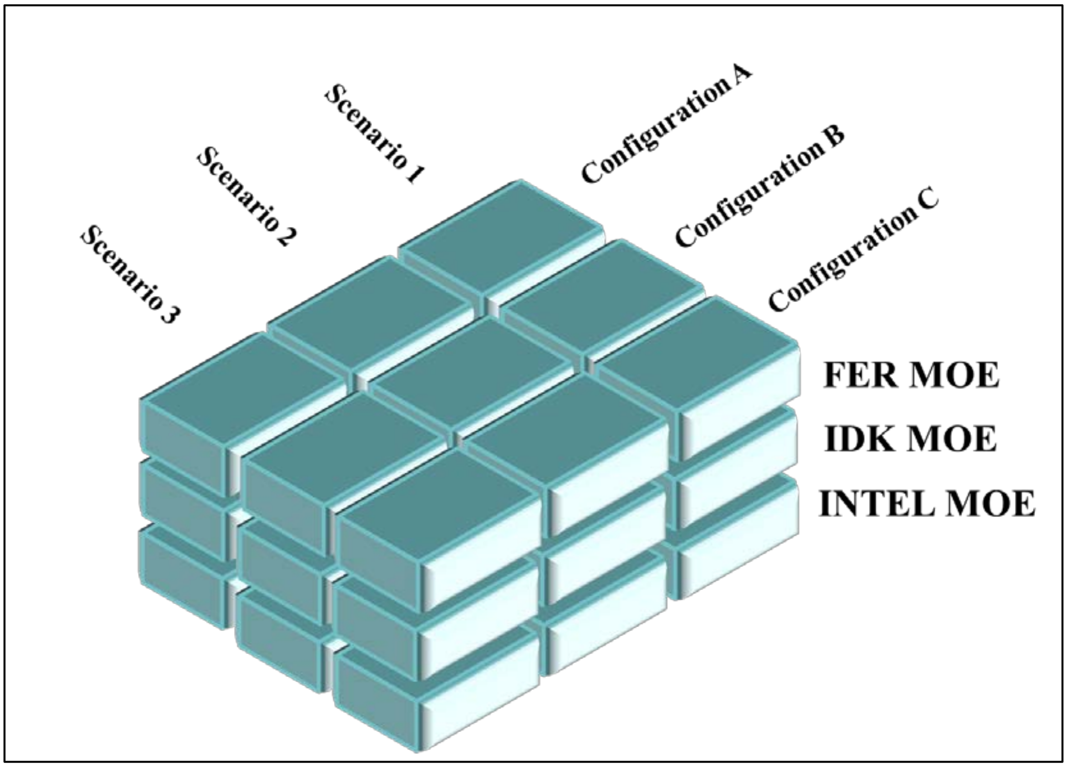
Table 23. Normalized Swing Weights for each Scenario

Scenario 1	Scenario 2	Scenario 3
$w_{1,FER} = 0.615$	$w_{2,FER} = 0.471$	$w_{3,FER} = 0.310$
$w_{1,IDK} = 0.115$	$w_{2,IDK} = 0.059$	$w_{3,IDK} = 0.381$
$w_{1,INTEL} = 0.269$	$w_{2,INTEL} = 0.471$	$w_{3,INTEL} = 0.310$

D. OPERATIONAL RESILIENCY DECISION BLOCK

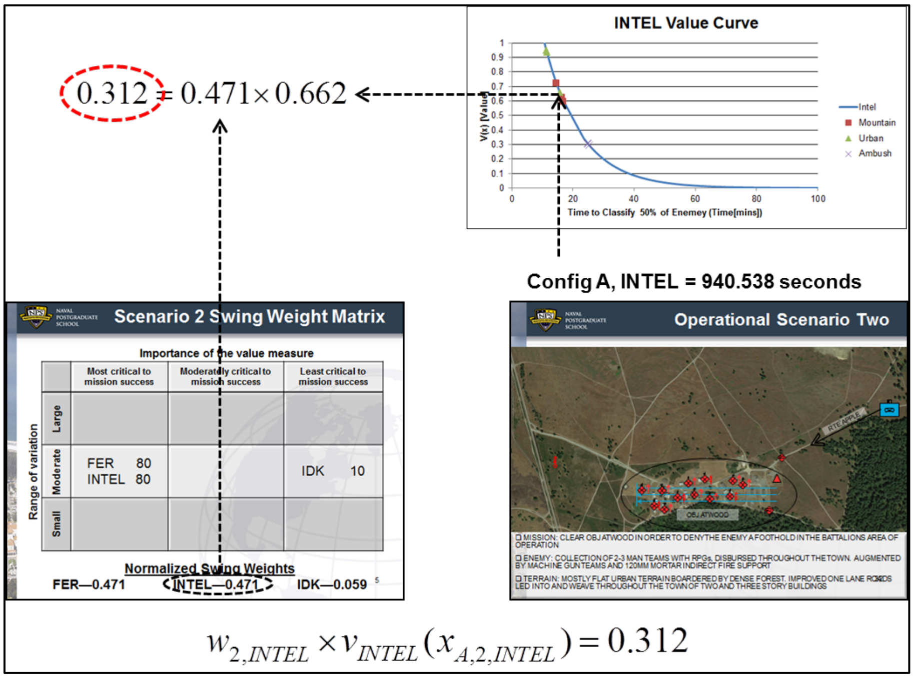
This research develops the Operational Resiliency Decision Block as not only a visual representation of the process, data, and results, but as a tool that provides a decision maker the opportunity to draw additional conclusions from the results. The block is a three-dimensional block with configurations along the length, scenarios along the width, and MOEs along the height. The block for this research is three-by-three-by-three, but the design allows it to be expanded in any direction to encompass additional configurations, scenarios, or MOEs as the process of obtaining the OR Score remains unchanged. Figure 34 presents the Operational Resiliency Decision Block.

Figure 34. Operational Resiliency Decision Block



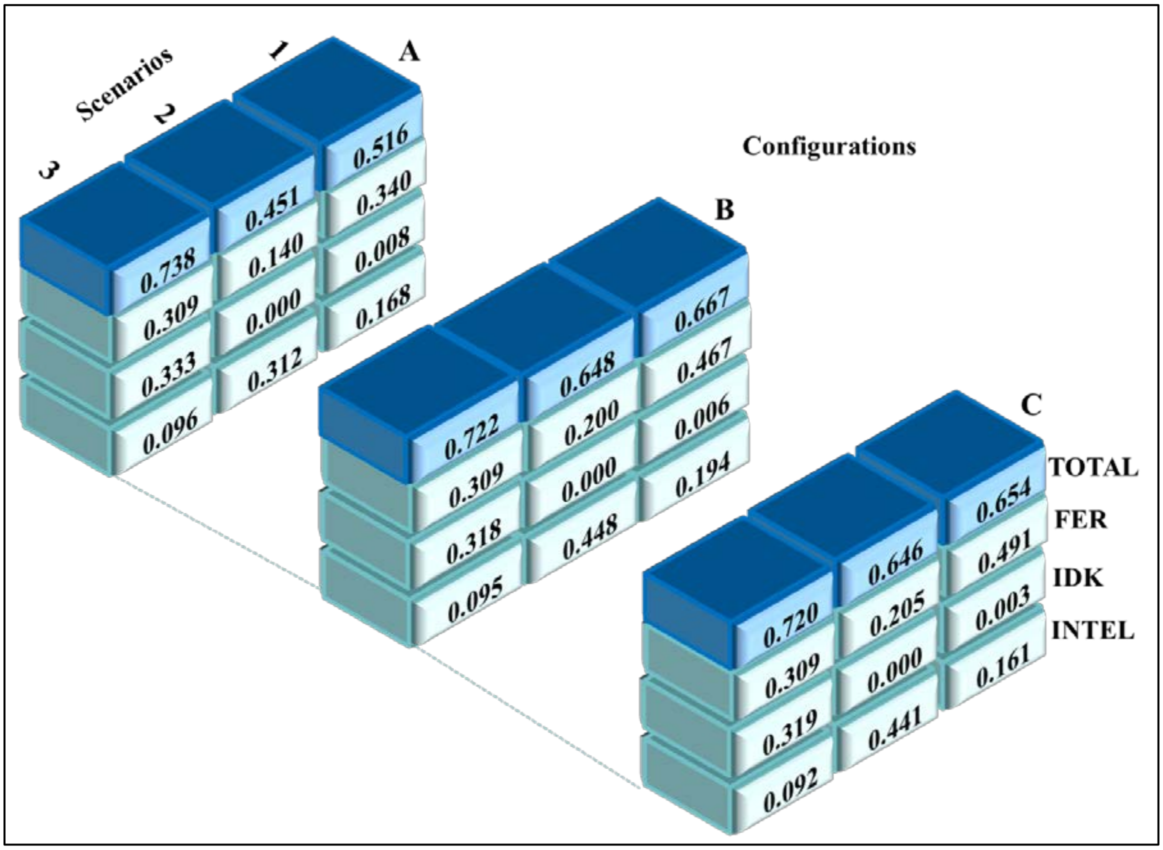
The 27 spaces in the block are filled with the 27 MOE-scenario-configuration weighted values calculated according to Equation (1.5). To demonstrate one of the 27 calculations, begin with the INTEL raw value for Configuration A in Scenario 2 ($x_{A,2,INTEL} = 940.538$). Equation (1.9) is then used to normalize the raw value to a single-dimensional value ($v_{INTEL}(x_{A,2,INTEL}) = 0.662$). The normalized swing weight for INTEL in Scenario 2 is determined ($w_{2,INTEL} = 0.471$) from the swing weight matrix method (from Table 23). These values combine so that the single-dimensional value is multiplied by the normalized swing weight ($w_{2,INTEL} \times v_{INTEL}(x_{A,2,INTEL}) = 0.471 \times 0.662 = 0.312$). The resultant weighted value of 0.312 is the actual contribution to Configuration A's OR Score (OR_A) from the INTEL MOE in Scenario 2, and thus will be placed in the appropriate space in the decision block. This example is illustrated in Figure 35.

Figure 35. Partial Calculation of OR Score for Configuration A



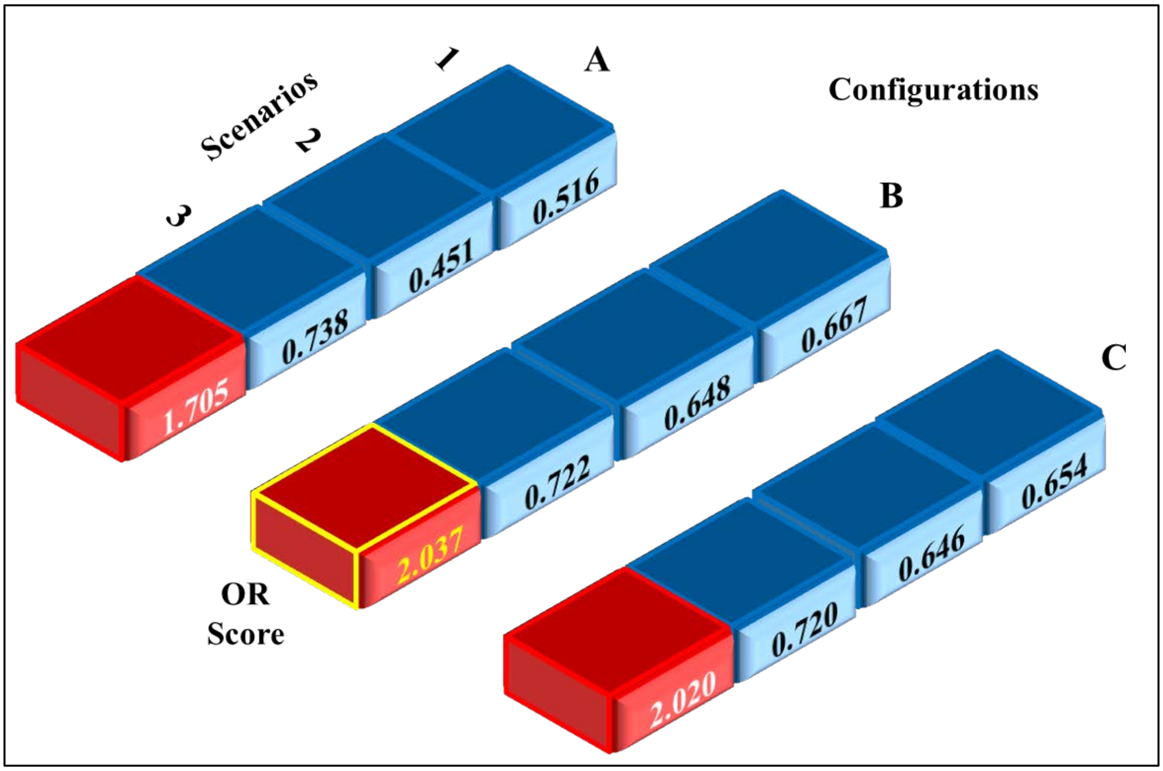
The remaining weighted values of the OR Scores for each of the MOE-scenario-configuration combinations are calculated accordingly and placed in the block. The next step in determining the OR Score is to sum weighted values across the MOEs for each scenario-configuration combination. These totals are displayed in the darker blue boxes along the top of the block in Figure 36.

Figure 36. Operational Resiliency Decision Block with Scenario-Configuration Total Scores



Stepping through one of the calculations, the weighted-value contribution to Configuration A's OR Score (OR_A) from Scenario 1 is 0.516 ($0.340+0.006+0.168$) by summing across the MOEs. The last step to determine the full OR Score for Configuration A is to sum weighted values across the scenarios. As such, the OR Score for Configuration A comes out to 1.705 ($OR_A = 0.516+0.451+0.738 = 1.705$). The other two configurations' OR Scores are computed similarly and highlighted in red in Figure 37.

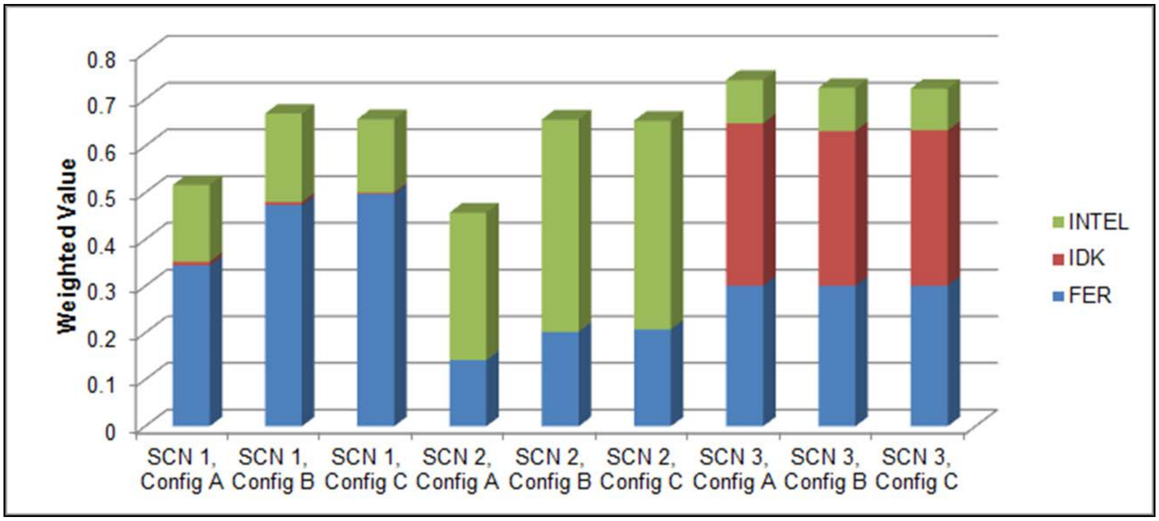
Figure 37. OR Score for each Configuration



Therefore, this research finds that Configuration B, with an OR Score of 2.037, is the most operationally resilient. Configuration C is nearly numerically equivalent to Configuration B with an OR Score of 2.020 while Configuration A is dominated by the other two with an OR Score of 1.705, making it clearly the least operationally resilient. Recall that operational resiliency measures the ability of a company team to preserve its warfighting capability when operating in different operational scenarios comprised of distinct mission, enemy, and terrain requirements. Note that this comprehensive look at the operational resiliency of each configuration produces a different conclusion than would be reached through examination of the scenarios in isolation. For example, although Configuration A is least operationally resilient, it actually performs better than the other two configurations in Scenario 3. The decision block affords the decision maker that ability to analyze performance across the scenarios.

The value component chart in Figure 38 shows another view of the data in the Operational Resiliency Decision Block that is useful to the decision maker. Each bar in the chart represents a particular configuration-scenario combination's contribution to the OR Score from each of the MOEs. Note that all 27 values from the decision block are accounted for in the chart. In this view, several points are evident. FER is the most influential MOE in Scenario 1 while INTEL is the most influential in Scenario 2. Alternatively, IDK is nearly non-existent in the first two scenarios, and only becomes a factor in Scenario 3. This view gives decision makers and their staffs the ability to quickly visualize a configuration's performance.

Figure 38. Value Component Chart of the Operational Resiliency Decision Block

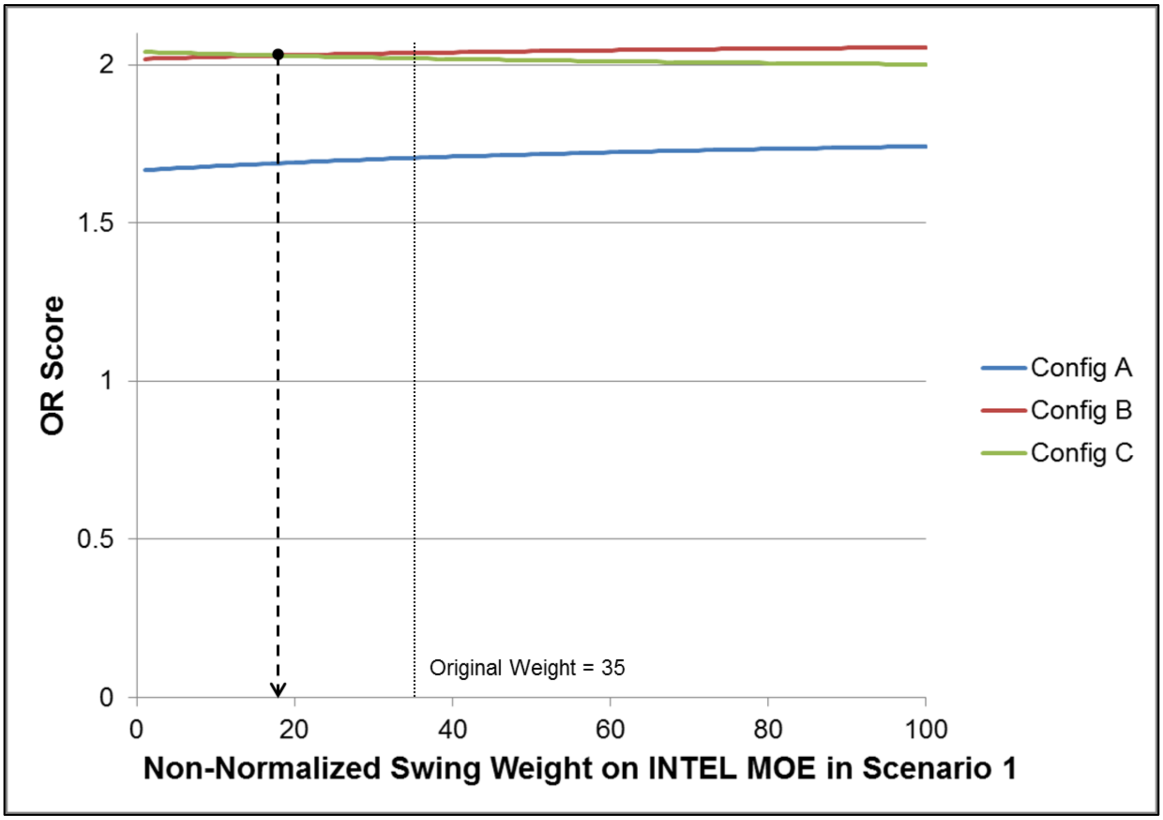


E. SENSITIVITY ANALYSIS

Note that the recommendations developed in the Operational Resiliency Decision Block can be examined to determine the impact of the weighting scheme on the recommended configurations. As Parnell, Driscoll, and Henderson (2011, 409) point out, "When dealing with complicated decisions...systems engineers must be cognizant of the robustness of their analysis." Moreover, "systems engineers must conduct sensitivity analysis to modeling assumptions and candidate system scoring uncertainty" (410). This sensitivity analysis assesses the sensitivity of the weights that are utilized in the additive model. The three largest assumptions made during the research manifest themselves in the swing weight matrices. Specifically, one assumption is made in assessing the level of importance (criticality) to the MOEs. A second assumption is made in assessing the range-of-variation valuations. Those two assumptions result in the placement of the MOE in the swing weight matrix and become the basis for the third assumption. The third assumption is made in assessing the non-normalized swing-weight value of one to 100 to the MOE. The goal of this sensitivity analysis is to see how adjusting the non-normalized swing-weight value for each MOE in each scenario affects the selection of the most operationally resilient configuration.

To conduct the sensitivity analysis, each of the nine scenario-MOE non-normalized swing weight values are varied one at a time from one to 100 at increments of one. While one swing-weight value varies, the other eight values are held at their original values in their respective swing weight matrices from Figures 31-33. As a result, the research finds that the most operationally-resilient configuration is sensitive to the weight assessment of only one of the nine scenario-MOE swing weight values—Scenario 1, INTEL. Figure 38 graphically shows the OR Score of each configuration as the non-normalized swing weight assessed to INTEL in Scenario 1 is varied from one to 100.

Figure 39. Weight Sensitivity of Scenario 1-INTEL MOE for Operational Resiliency



As is evident, when the non-normalized swing-weight value for Scenario 1-INTEL MOE falls to 17 or below, Configuration C becomes the most operationally resilient. With an original weight of 35, the relative value of the INTEL MOE in Scenario 1 would have to be reduced in half in order for a change in outcome to present itself. The remaining eight charts from the sensitivity analysis are found in Appendix C. Note that although Configuration C's OR Score is nearly numerically equivalent to Configuration B's OR Score, the sensitivity analysis affirms that Configuration B is the recommended alternative based on this analysis.

VII. CONCLUSIONS

A. SIGNIFICANT FINDINGS

The purpose of this project was to provide a practical example of how to assess a company team's operational resiliency. The research first defined operational resiliency for an Army company team, and subsequently developed the MOEs with which to evaluate the configurations. Using MANA-V agent-based software, the research developed nine meta-models pitting three company team configurations against three distinct enemy and terrain scenarios. The research conducted a value-focused multi-objective decision analysis of the three alternative configurations by developing MOE-specific value functions and scenario-specific swing-weight matrices. To ensure robustness of the results, the research analyzed the weights for sensitivity.

In the end, Configuration B achieved the highest OR Score of the three configurations analyzed. This result highlights the need to screen for operational resiliency in the first place. Referring to Figure 37, if these configurations were assessed only by their performance on Scenario 3 (Desert Ambush), Configuration A would have been the clear outright winner. It is only when evaluating performance across multiple scenarios does it become clear that Configuration A is actually the least operationally resilient of the three and that Configuration B is the recommended alternative. Screening for operationally resiliency in this manner thus provides a potentially valuable approach for evaluating future Army combat systems.

The research employed MBSE in designing and analyzing the nine meta-models. One of the major benefits realized from MBSE was the ease with which the nine meta-models were generated. Instead of having to start from scratch to create each model, the research was able to essentially insert the three alternative configurations into the three distinct scenarios while adjusting for maneuver tactics. Throughout the SE process, MBSE facilitated the inherent iterations that would have otherwise taken significantly longer and most likely limited the scope of the project. As a result, these nine meta-models can be utilized for further analyses and link directly into the NPS SE department's dashboard. This project stands as a practical example in the development of a SoS synthesis model in concert with the application of MBSE to early life-cycle-design decisions.

B. CHALLENGES

While this study experienced few technical challenges during its course, two are worth further discussion. The first relates to the inherent complexity of the agent-based simulation modelling software and the research groups' unfamiliarity with it at the onset of the study. The second relates to the extraction and compilation of requisite data produced by the simulations.

1. MANA-V Agent Behavior

The ABS MANA-V, which plays an integral role in the conduct of this research, is an intricate and complex system. The authors faced a steep learning curve in developing the capability to generate meta-models that accurately reflect the doctrinal tactics and weapons systems of an Army company team, its potential adversaries, and the terrain on which they operate. The research necessitated the creation and troubleshooting of nine distinctly-unique meta-models. Each meta-model contained specific mission- and terrain-oriented interactions between friendly and enemy agents that required significant time resources to ensure accuracy, feasibility, and plausibility.

2. Data Extraction and Statistical Analysis

To gather the necessary data for the MOEs, the authors culled together data from four separate MANA-V output files for every run. This amounted to a total of 18,000 data files for the 500 runs conducted on each of the nine scenario-configurations combinations. Commonly available software packages such as Microsoft Excel proved cumbersome and inefficient in aggregating that volume of data and conducting the subsequent statistical analysis. Therefore, this research employed such advanced software packages as R and JMP. Some expertise in these software packages is necessary to write and execute coded scripts in R that pull and combine all the MOE data from the output files and also in JMP to conduct statistical analysis and produce all charts and plots.

C. FUTURE RESEARCH

This study developed a method to determine the operational resiliency of a company team. Having discovered a method that is reproducible and relevant, future work can be performed that employs the methods used in the study and refines and expands the scope of this study.

1. Altering the Unit Configurations

The configurations used in this study were leveraged from the three highest ranking alternatives developed by the Vehicle Survivability Team's project (Basala et al. 2013). That team used a design of experiments (DOE) to create the various configurations they tested. Some of these configurations created do not fall in line with current Army force structuring. Future work could focus on tailoring the configurations that represent actual or planned task organizations of combined arms teams. This analysis could inform maneuver commanders' decisions regarding company-level force structures and training given the need to fight and win in an uncertain future.

2. Expanding the Decision Block

The design of the Operational Resiliency Decision Block and the analytical method contained therein provides the ability to seamlessly incorporate an expansion of the decision space. Thus, one could easily expand the decision block to include additional unit configurations, operational scenarios, MOEs or any combination of the three, all based on the needs of the decision maker. Future work could expand this study to include more scenarios based on potential conflict regions as well as additional company team configurations. This could also be used to inform future force structure requirements.

3. Technical Injects—MUM-T

Unmanned systems have become a permanent asset available to maneuver commanders in the services. The U.S. Army has integrated Unmanned Aerial Systems (UAS) as a part of its maneuver elements. Those UAS assets have recently been integrated with Army Aviation platforms in a concept referred to as Manned Unmanned Teaming (MUM-T). In this concept, AH-64E aircraft are paired with UAS platforms in a manner that provides the AH-64E aircrew with multiple levels of control of the UAS platforms including payload and sensor packages from the AH-64E (Whittle 2015). In the context of this research, this can be modeled by allowing for a communication link directly between the Apaches and the Shadows to share enemy classifications. This direct communication link eliminates the Company HQ relay and provides for the potential for significantly reduced engagement times by the Apaches. The operational resiliency of each configuration can then be compared in its current state against the same configuration where the MUM-T concept has been implemented.

APPENDIX A. WEAPONS SYSTEMS AND SENSORS CAPABILITIES

In order to ensure the accuracy of the performance characteristics for both the friendly and enemy units, the research group derives the capabilities of both their weapons systems and sensors from their published capabilities. That being stated, in developing each of the scenarios, maximum effective ranges of weapons are tailored to fit the specifics of the scenario terrain and do not always match stated maximums. The capabilities of the sensors are determined based on the personal operational experience of the research group members.

Table 24 displays the capabilities of the complement of weapons employed by each of the three friendly force configurations. The table provides the caliber of each weapon system, both the practical and cyclical rate of fire in rounds per minute (RPM), what a typical combat load is in number of rounds, and the maximum effective range of the weapon system in meters.

Table 24. Friendly Forces Weapon Systems Capabilities

Weapon System	Caliber (mm)	Rate of Fire Practical/Cyclic (RPM)	Combat Load, Typical	Max Effective Range (m)
M-4	5.56	16/800	210	580
M240B Med MG	7.62	750	600	1,100
M2A2 Bradley	7.62 (COAX)	750	800 / 3600 (stowed)	900
	25 (Bushmaster)	100-200	300 / 600 (stowed)	2,000-3,000
M1A2 Abrams	.50cal (Heavy MG)	40/500	1,000	1,600
	120 (Smooth Bore)	3/10	40	2,500
M777 Howitzer	155	2/4	64	14,600
AH-64 Apache	30 (Heavy MG)	250	1,200	4,000
	Hellfire Missile	4/6	16	8,000

Adapted from United States Army Training and Doctrine Command (TRADOC) Intelligence Support Activity, 2014. *World Wide Equipment Guide. Volumes 1 and 2.* Fort Leavenworth, Kansas: Department of the Army.

Table 25 presents the capabilities of the sensors for each of the element types in the three configurations. Each element is provided with two different sensors, one that detects vehicles and another to detect dismounted infantry troops. The table further displays the maximum ranges out to which each sensor can detect the specified type of target.

Table 25. Friendly Forces Sensor Capabilities

Element	Sensor Type	Max Range (m)
Dismounted Infantry	Vehicle	1,500
	Dismounted Infantry	800
Machine Gun	Vehicle	1,500
	Dismounted Infantry	1,500
M2A2 Bradley	Vehicle	3,000
	Dismounted Infantry	1,000
M1A2 Abrams	Vehicle	3,000
	Dismounted Infantry	1,000
RQ-7 Shadow	Vehicle	1,000
	Dismounted Infantry	1,000
AH-64 Apache	Vehicle	8,000
	Dismounted Infantry	8,000

The capabilities for the enemy forces for each scenario are displayed in Table 26 in the same manner as for friendly forces.

Table 26. Enemy Forces Weapon Systems Capabilities

Weapon System	Caliber (mm)	Rate of Fire Practical/Cyclic (RPM)	Combat Load, Typical	Max Effective Range (m)
AK-47	7.62	100	120	300
PKM Medium Machine Gun	7.62	250/650	1,000	1,000
NSV Heavy Maching Gun	12.7 (.57 cal)	100/800	300	800 (armor) / 2,000 (troops)
RPG-7	40	4-6	5	500
Kornet	Anti-Armor Missile	2-3	4	2,500-5,500
SA-18 Igla	Anti-Aircraft Missile	3-4	3	500-6,000
T-90 Main Battle Tank	125 (Smooth Bore)	8	43	4,000
	7.62 (COAX)	250	1250	1,000
	12.7 (.57cal)	100	500	800 (armor) / 2,000 (troops)
IED	Mine	N/A	1	35
Anti-Tank Mine	Mine	N/A	1	75
120mm Mortar	120	10/18	70	7,200

Adapted from United States Army Training and Doctrine Command (TRADOC) Intelligence Support Activity, 2014. *World Wide Equipment Guide. Volumes 1 and 2.* Fort Leavenworth, Kansas: Department of the Army.

Table 27 displays the capabilities for the sensors of each of the enemy force element types in the much the same manner as friendly forces.

Table 27. Enemy Forces Sensors Capabilities

Element	Sensor Type	Max Range (m)
Dismounted Infantry	Vehicle	1,500
	Dismounted Infantry	800
RPG	Vehicle	1,500
	Dismounted Infantry	800
Machine Gun	Vehicle	1,500
	Dismounted Infantry	800
Anti-Armor	Vehicle	2,500
	Dismounted Infantry	-
SA-18	Vehicle	1,500
	Dismounted Infantry	-
Observation Post	Vehicle	1,500
	Dismounted Infantry	800
Tank	Vehicle	3,000
	Dismounted Infantry	1,000
Tactical Vehicles	Vehicle	1,500
	Dismounted Infantry	800

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APPENDIX B. SCENARIO TERRAINS

The specifics for how the terrain is modeled for each scenario are presented in this appendix. In MANA-V, terrain is developed by providing each different terrain type a numerical value in three categories—going, cover, and concealment. The values range from zero to one, with zero representing the least effect and one the most. Going relates to movement restrictions, therefore a terrain type with a going value of one presents unrestricted movement. Cover equates to the ability of a terrain feature to protect an agent from weapons effects. A terrain feature with a value of one means would provide maximum cover to agents. Concealment is the ability to prevent an agent from being ‘seen,’ or in the case of the model being detected and classified. The higher the value the more concealment the terrain feature provides.

The specific values associated with the various terrain features for Scenario 1 is displayed in Table 28. The terrain for this scenario reaches a maximum elevation of 2,150 meters and has a minimum of 1,760 meters.

Table 28. Scenario 1 Terrain Features

Scenario 1		
Terrain Type	*Key*	*Value*
Road	Going	1.00
	Cover	0.00
	Concealment	0.00
Water	Going	0.00
	Cover	0.00
	Concealment	0.00
Typical Terrain	Going	0.80
	Cover	0.30
	Concealment	0.60
Canyon Rocks	Going	0.10
	Cover	0.60
	Concealment	0.90
Forest	Going	0.40
	Cover	0.20
	Concealment	0.90

The specific values associated with the various terrain features for Scenario 2 is displayed in Table 29. The terrain for this scenario reaches a maximum elevation of 15 meters and has a minimum of zero meters.

Table 29. Scenario 2 Terrain Features

Scenario 2		
Terrain Type	*Key*	*Value*
BilliardTable	Going	0.95
	Cover	0.00
	Concealment	0.00
Wall	Going	0.00
	Cover	1.00
	Concealment	1.00
Road	Going	1.00
	Cover	0.00
	Concealment	0.00
Dense Bush	Going	0.20
	Cover	0.30
	Concealment	0.90
Building	Going	0.05
	Cover	0.80
	Concealment	0.80

The specific values associated with the various terrain features for Scenario 3 is displayed in Table 30. The terrain for this scenario reaches a maximum elevation of 155 meters and has a minimum elevation of zero meters.

Table 30. Scenario 3 Terrain Features

Scenario 3		
Terrain Type	*Key*	*Value*
BilliardTable	Going	1.00
	Cover	0.00
	Concealment	0.00
Dirt	Going	0.90
	Cover	0.00
	Concealment	0.00
Hilltop	Going	0.65
	Cover	0.10
	Concealment	0.95
Road	Going	1.00
	Cover	0.00
	Concealment	0.00

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APPENDIX C. SENSITIVITY ANALYSIS CURVES

The remaining eight sensitivity charts show the OR Scores for each configuration as each respective scenario-MOE non-normalized swing-weight value is varied from one to 100. The charts can be seen in Figures 40–46 with their initial (or original) weight noted by the dashed line.

Figure 40. Weight Sensitivity of Scenario 1-FER MOE for Operational Resiliency

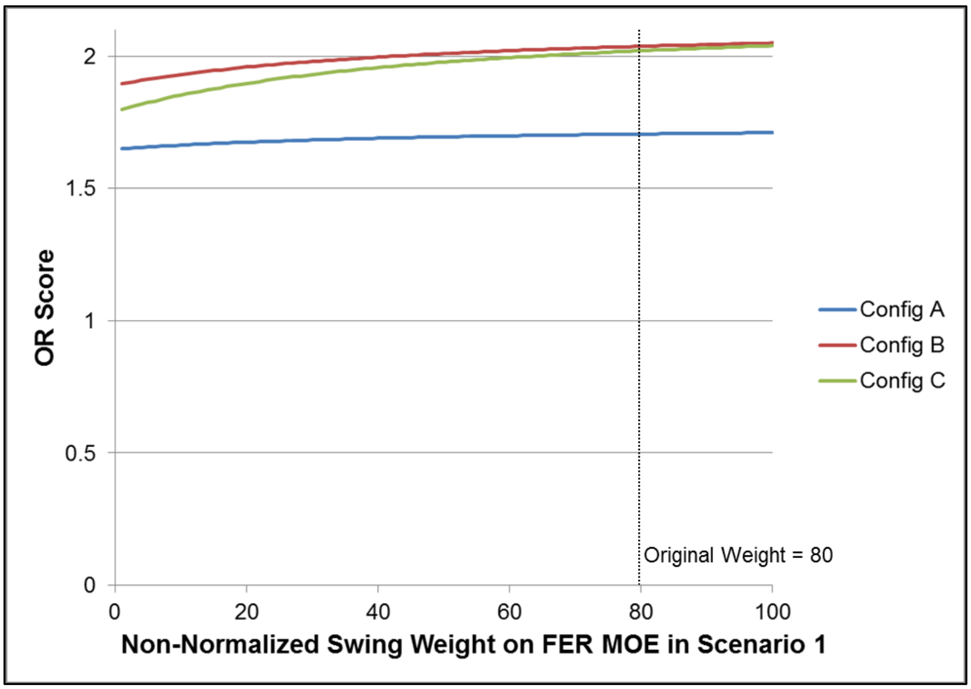


Figure 41. Weight Sensitivity of Scenario 1-IDK MOE for Operational Resiliency

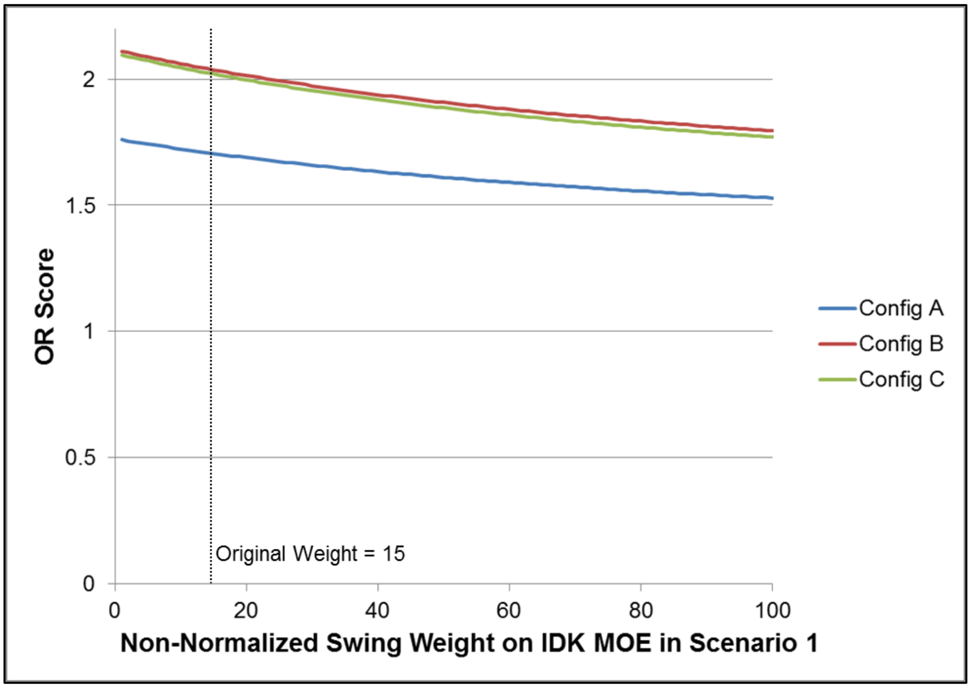


Figure 42. Weight Sensitivity of Scenario 2-FER MOE for Operational Resiliency

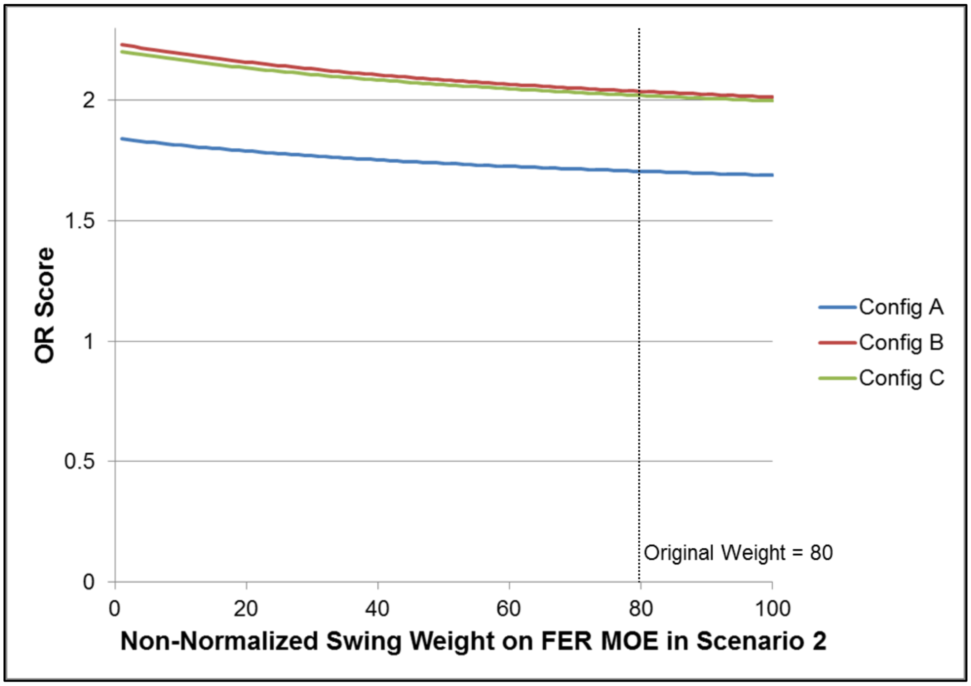


Figure 43. Weight Sensitivity of Scenario 2-IDK MOE for Operational Resiliency

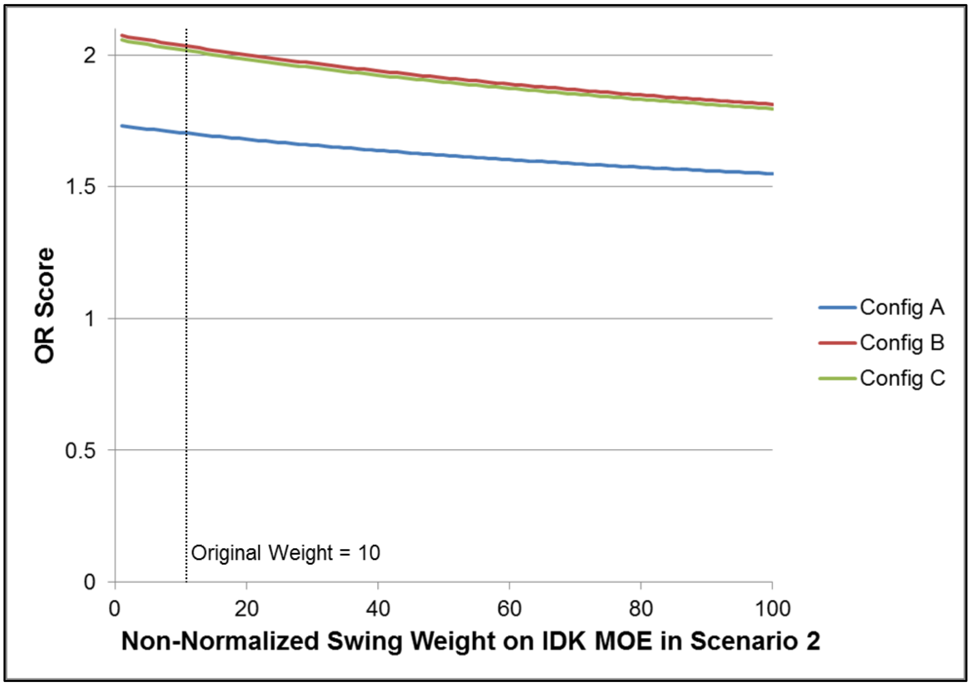


Figure 44. Weight Sensitivity of Scenario 2-INTEL MOE for Operational Resiliency

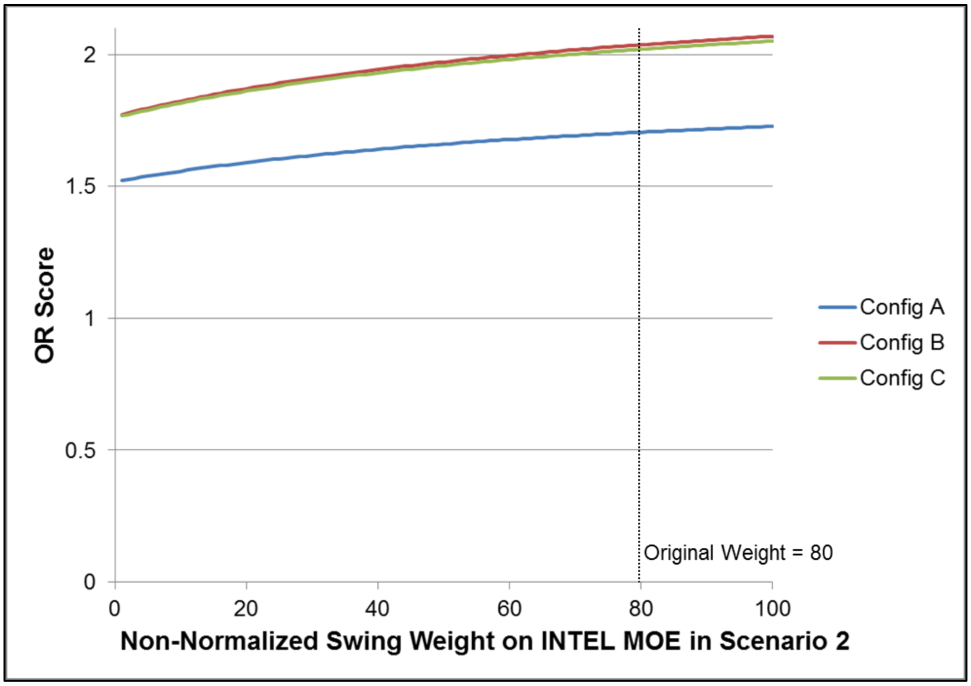


Figure 45. Weight Sensitivity of Scenario 3-FER MOE for Operational Resiliency

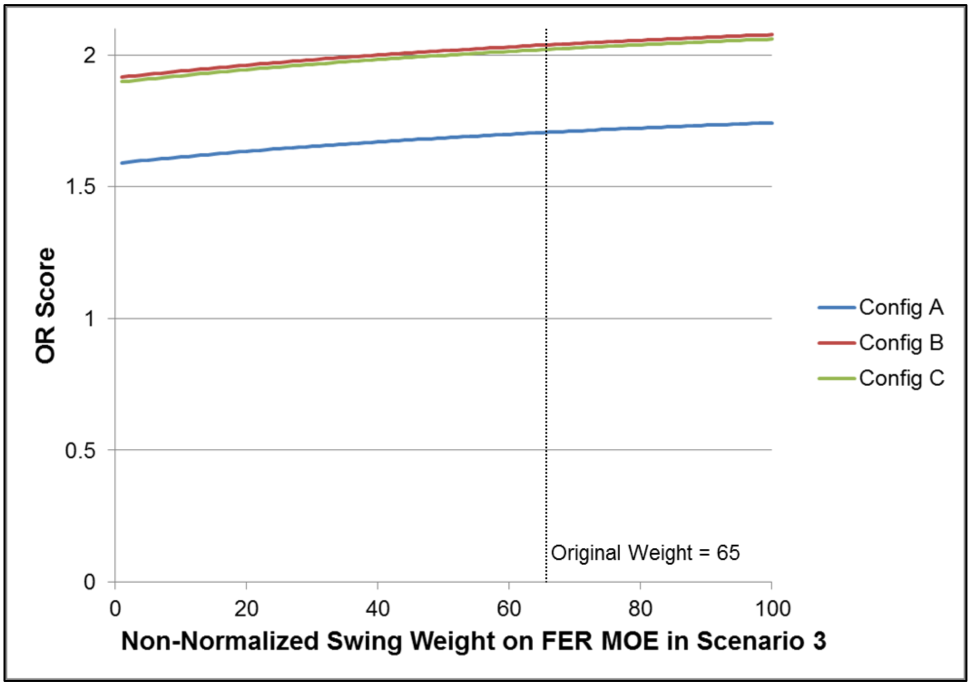


Figure 46. Weight Sensitivity of Scenario 3-IDK MOE for Operational Resiliency

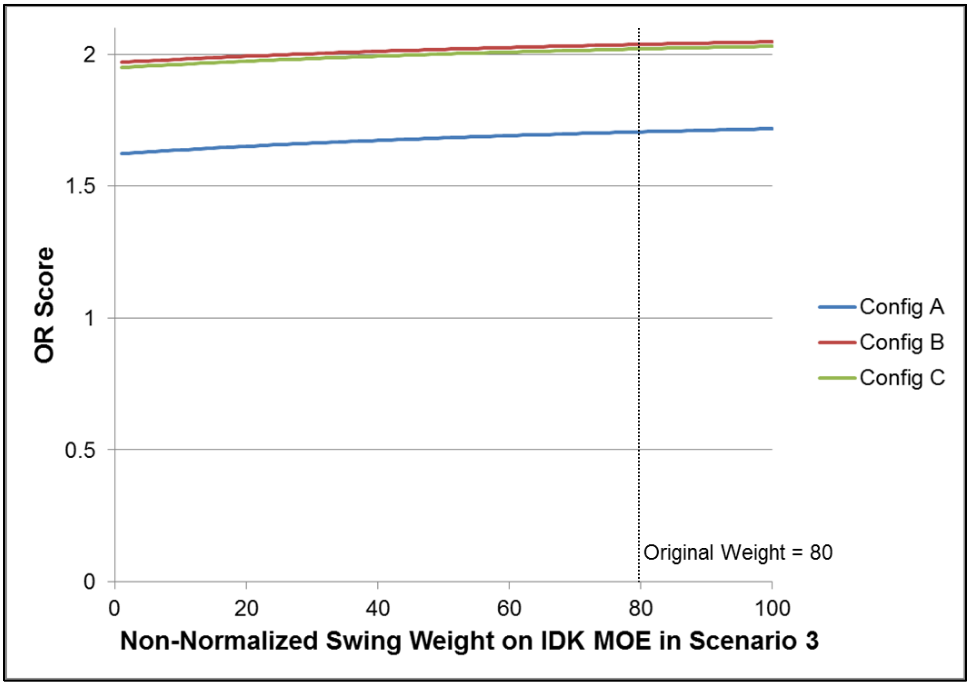
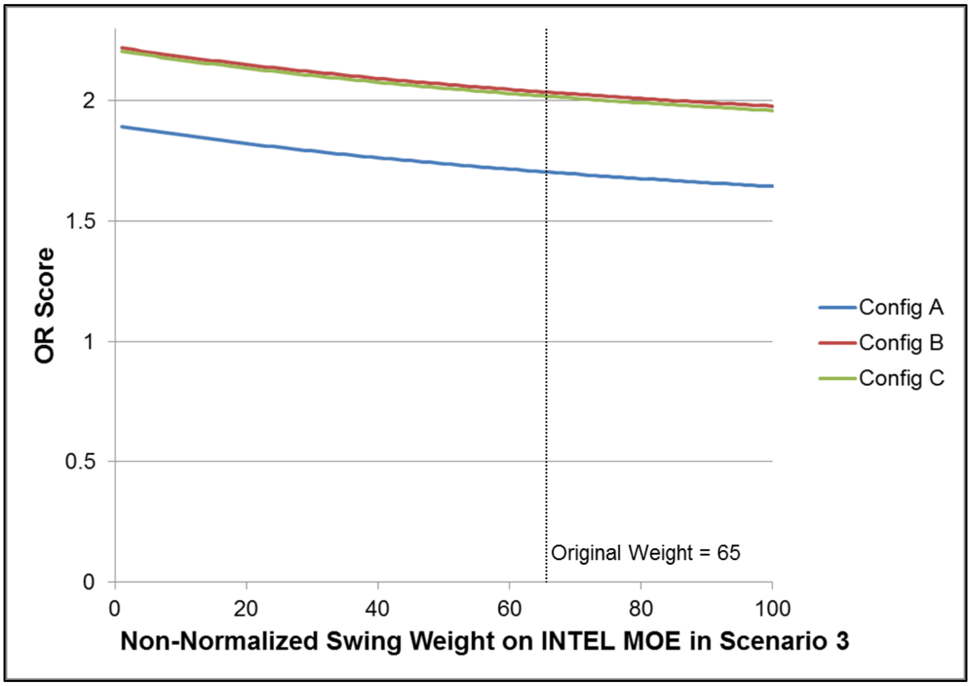


Figure 47. Weight Sensitivity of Scenario 3-INTEL MOE for Operational Resiliency



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