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THESIS

**ROBUST ANALYSIS OF CRITICAL FACTORS FOR
CANNON ARTILLERY LETHALITY AND
SURVIVABILITY IN PEER CONFLICT**

by

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June 2021

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**ROBUST ANALYSIS OF CRITICAL FACTORS FOR CANNON ARTILLERY
LETHALITY AND SURVIVABILITY IN PEER CONFLICT**

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Submitted in partial fulfillment of the
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ABSTRACT

Guided by the Commandant's Planning Guidance and Force Design 2030, the Marine Corps is currently undergoing aggressive organizational change to evolve into a more disruptive force within the context of great power competition. An increase of rocket artillery batteries from seven to 21 is planned to expand deterrence capability, and a divestment in cannon batteries from 21 to five parallels this focus. The retention of cannon artillery, although reduced, can be improved to offer tactical maneuver-based offensive and defensive firepower to Marines across the range of military operations. This thesis explores which equipment and tactics, techniques, and procedures (TTPs) are most critical for USMC cannon artillery lethality and survivability in a Russia counterbattery scenario. Furthermore, this study proposes potential artillery configurations that are resilient to uncontrollable variations of the Russian artillery force. Using agent-based simulation, efficient designs of experiments, and cluster computing, over 1.3 million artillery battles were simulated and analyzed. The findings include that the equipment currently fielded by USMC artillery battalions is largely in line with the most significant factors for lethality and survivability (caliber and range). However, significant changes to current TTPs, specifically increased segmentation and dispersion, are necessary for force protection and mission success.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	Anti-Access and Area Denial
ACE	Air Combat Element
ADA	Air Defense Artillery
AGL	Above Ground Level
BTG	Battalion Tactical Group
C2	Command and Control
CFF	Call for Fire
CPG	Commandants Planning Guidance
DOE	Design of Experiment
EABO	Expeditionary Amphibious Base Operations
EW	Electronic Warfare
FD30	Force Design 2030
FDC	Fire Direction Center
FIRECAP	Fire Capable
FO	Forward Observer
FSCC	Fire Support Coordination Center
GUI	Graphical User Interface
IADS	Integrated Air Defense System
MANA	Map Aware Non-Uniform Automata
MCWL	Marine Corps Warfighting Lab
MEB	Marine Expeditionary Brigade
MLRS	Multiple Launch Rocket System
MOE	Measure of Effectiveness
MOP	Measure of Performance
MOS	Military Occupational Specialty
MTVR	Medium Tactical Vehicle Replacement
NDS	National Defense Strategy
NOB	Nearly Orthogonal and Balanced
OAD	Operations Analysis Directorate
SEED	Simulation Experiments and Efficient Designs

TTP
UAV

Tactics, Techniques, and Procedures
Unmanned Aerial Vehicle

EXECUTIVE SUMMARY

After more than 19 years of fighting insurgencies in the global war on terrorism, the Marine Corps has found itself inadequately prepared to address a high-end fight against a peer threat. Guided by the Commandants Planning Guidance and Force Design 2030, the Marine Corps is currently undergoing aggressive organizational change to evolve into a more disruptive force within the context of great-power competition.

With responsibilities spanning the globe and spectrum of conflict, the Marine Corps aims to field and equip a force capable of integrating with the U.S. Navy to deter evolving threats, specifically using China as the premier pacing threat. The premise assumed by the Marine Corps is that by designing a force using China as the pacing threat, the force can scale to any assigned responsibility across the range of military operations.

The Commandants Planning Guidance and Force Design 2030 place a large emphasis on rocket-delivered anti-ship fires. An increase of rocket artillery batteries from seven to 21 is planned to expand deterrence capability, ensure access in a challenging anti-access and area denial environment, and increase the probability of naval campaign success. In a fiscally constrained environment with finite resources, a planned divestment in cannon batteries from 21 to five parallels this focus on rocket delivered fires.

Cannon artillery is the longest-range fires asset that is capable of offering persistent, all weather fire support. If cannon artillery were to be removed completely, one echelon lower than rocket delivered artillery is an M252 81mm mortar. The retention of cannon artillery, although reduced, can be improved to offer tactical maneuver-based offensive and defensive firepower to Marines across the contingent range of military operations that the Marine Corps may be called upon to address. Furthermore, by modernizing the cannon artillery force during a period of divestment, legacy institutional knowledge of cannon artillery can be retained and focused rather than atrophy. To enable force scalability, improvements must be made to retained cannon artillery.

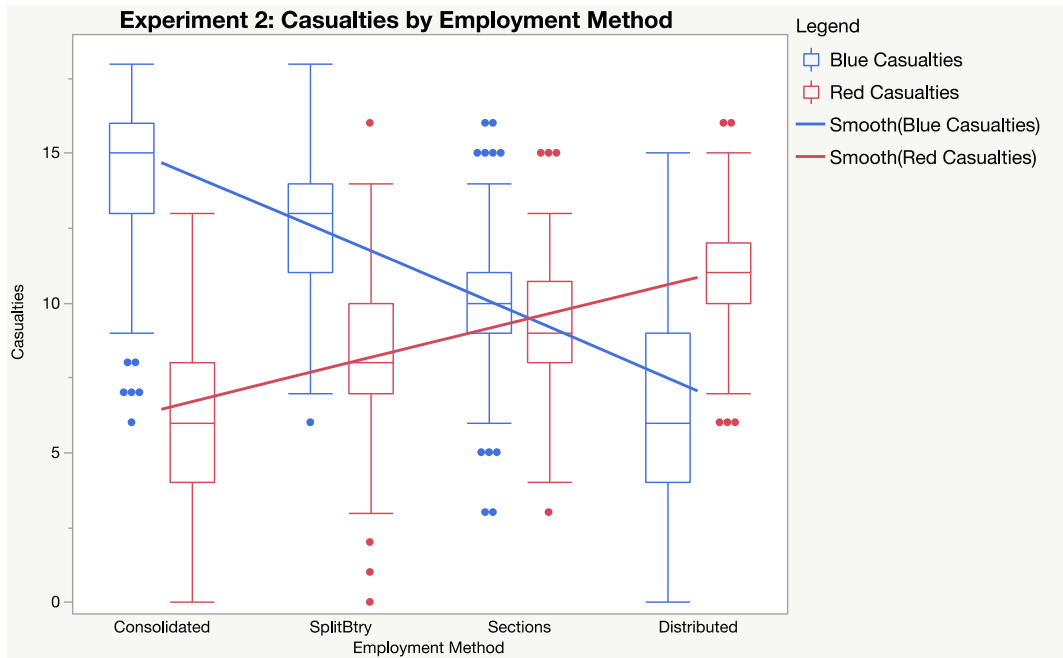
Of the two great power competitors, Russia presents the most formidable artillery threat. While China serves as an appropriate service pacing threat due to its economic and

technological base, Russia maintains the most capable and practiced fires community. Similar to how the Marine Corps assumes a force developed to counter the high-end Chinese fight will scale to lower spectrum conflict, this thesis assumes that an artillery force capable of countering the most sophisticated and challenging artillery threat will scale to threats around the globe.

This thesis explores which equipment and tactics, techniques, and procedures (TTPs) are most critical for USMC cannon artillery lethality and survivability in a Russia counterbattery scenario. Furthermore, this study proposes potential artillery configurations that are resilient to uncontrollable and unknown variations to the Russian artillery force. Using agent-based simulation, efficient designs of experiments, cluster computing, and data analysis, over 1.3 million artillery battles over four sets of experiments are simulated and analyzed across a wide range of artillery configurations.

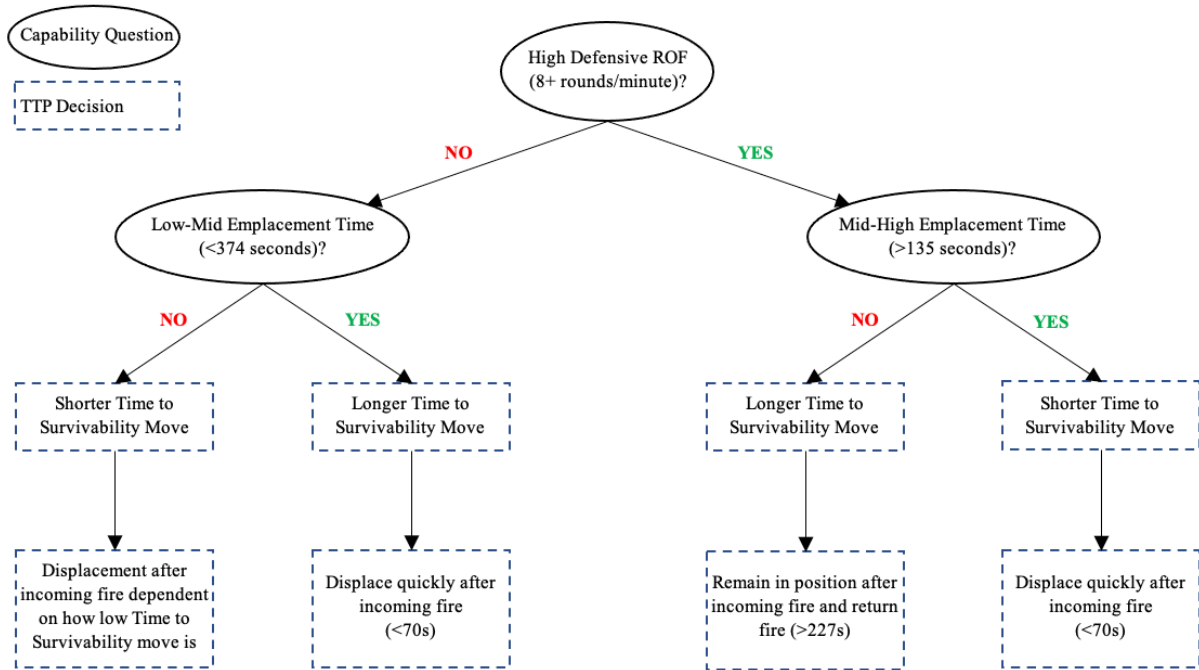
Experiment One: *Fight Tonight* serves as the base case and imagines a counterbattery fight occurring between USMC and Russian forces as currently equipped and employed. The findings are that the current USMC construct is not postured for success in a counterbattery engagement with Russian forces.

Experiment Two: *Train Tomorrow* evaluates the efficacy of altering the most rapidly affectable factor of employment method. The findings are that increased segmentation and dispersion for Marine Corps firing units contributes significantly to both lethality and survivability and that training to more dispersed employment methods alone is sufficient for gaining a tactical advantage. In the following figure it can be seen that as USMC cannon artillery batteries grow more segmented and dispersed, more Russian casualties are produced and fewer USMC casualties are sustained, on average.



Effect of USMC Battery Employment Method on Blue (USMC) and Red (Russian) Artillery Casualties (a Casualty is Defined as a Destroyed Artillery Piece)

Experiment Three: *Optimize the Force* considers all controllable USMC factors to determine which are most important to lethality and survivability. The conclusions from experiment three are that it is critical that a USMC artillery battalion employ 155mm weapon systems, disperse as much as possible, and employ tactics based on the operational capabilities of the unit. A TTP decision tree based on operational capabilities is developed and presented below.



Operational Capability Based TTP Decision Tree

Experiment Four: *Hedge the Construct* considers controllable USMC factors and uncontrollable Russian factors to determine the most significant factors for USMC performance over a range of unknown or future Russian capabilities and tactics. Included in this experiment is the consideration of a Russian hybrid cannon-MLRS construct and a Russian cannon-pure construct. The methodology used in experiment four enables the analysis of robust USMC constructs that consistently perform well while remaining resilient across a wide range of Russian constructs. Keeping with the findings of experiments one and two, caliber and employment method remain critically important. A USMC force that prioritizes survivability should be nimble, displacing and emplacing quickly, and changing positions frequently; whereas a USMC force that prioritizes lethality should have a staying mentality, remaining in position returning defensive fire if fired upon and changing positions infrequently. These TTP decisions are mutually exclusive, and the author assumes that the commander desires to balance these priorities. The TTP decision tree derived in experiment three is validated in experiment four and is determined to be appropriate in determining TTPs predicated on the operational capabilities of the employed unit.

Ultimately, the findings of this study are that the equipment currently fielded by USMC artillery battalions is largely in line with the most significant factors for lethality and survivability, specifically 155mm caliber and sufficient range capability. However, significant changes to current TTPs are necessary for force protection and mission success. The single most critical change that the Marine Corps can influence is adopting a more segmented and distributed employment of cannon artillery. Beyond employment method, the TTPs used should be determined by operational capability. Finally, although beyond the scope of future USMC cannon constructs, it is found that the inclusion of an MLRS capability by an adversary increases casualties for both sides. Therefore, MLRS should be designated as a high-value target and prioritized for targeting.

While this thesis does conclude that segmented and distributed battery operations are critical for cannon artillery lethality and survivability, logistics and command and control complexity are beyond the scope of this study. The author recommends that further analysis be conducted to examine the feasibility of increased dispersion in three ways. First, further analytic research can be conducted at the Naval Postgraduate School and appropriate USMC analytic branches. Second, operational units should test distributed battery operations in a realistic training environment to assess feasibility, human factors, and weaknesses. Finally, wargames should occur at the operational level to determine the capability gaps associated with the reduction of cannon artillery, current artillery constructs, and robust cannon constructs presented in this study. These three independent efforts are mutually supporting and can synchronize to modernize the artillery force while preserving fundamental capabilities.

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THESIS DISCLAIMER

The contents of this thesis are for academic uses only. All scenarios, force structures, and employment methods are derived from unclassified materials. All modeling conducted during research was internally verified and validated without third party review. The views expressed in this thesis are those of the author alone, and do not represent those of the Department of Defense, United States Marine Corps, or other government entities.

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I. INTRODUCTION

A. GREAT POWER COMPETITION MODERNIZATION

As good as we are today, we will need to be even better tomorrow to maintain our warfighting overmatch. We will achieve this through the strength of our innovation, ingenuity, and willingness to continually adapt to and initiate changes in the operating environment to affect the behavior of real-world pacing threats.

—General David H. Berger, CMC
(USMC 2019)

1. USMC Modernization

After more than 19 years of fighting insurgencies in the global war on terrorism, the Marine Corps has found itself inadequately prepared to address a high-end fight against a peer threat. The reemergence of the great power competition in the modern age requires structural, technological, and doctrinal changes to the Marine Corps in order to accomplish the charges of the *National Defense Strategy*. Through years of wargaming experience and insight, the commandant of the Marine Corps concluded that “the Marine Corps is not organized, trained, equipped, or postured to meet the demands of the rapidly evolving future operating environment” and that “modest and incremental improvements to our existing force structure and legacy capabilities would be insufficient to overcome evolving threat capabilities, nor would they enable us to develop forces required to execute our approved naval concepts” (United States Marine Corps [USMC] 2020, p. 3).

The 38th commandant of the Marine Corps, General David H. Berger, issued the *Commandant’s Planning Guidance* (CPG) in July 2019 and the accompanying Force Design 2030 (FD30) document in 2020. The CPG is a document which charts the priorities for modernization of the Marine Corps, and the FD30 provides context for how this vision will be achieved through a redesigned force. A dominating theme of both documents is modernization in weapons systems, doctrine, and employment to focus on naval operations to counter the growing Chinese threat in the Western Pacific. Expeditionary Amphibious Base Operations (EABO) and stand-in forces coupled with a strategic realignment with the Navy are critical to the desired end state of effective deterrence and persistence and are

heavily emphasized. To accomplish this, an aggressive force redesign is being implemented.

2. Enduring Responsibilities

The great power competition outlined in the *National Defense Strategy* includes China and Russia as priority revisionist power threats. The Department of Defense has the concurrent objective of “[sustaining] efforts to deter and counter rogue regimes such as North Korea and Iran [and] defeat terrorist threats to the United States” (Department of Defense [DOD] 2018).

Under United States Code Title 10, the Marine Corps is tasked with the responsibilities of seizing and defending advanced naval bases, conducting land operations essential to the prosecution of a naval campaign, and “performing all such duties as directed by the President” (10 U.S.C. § 8063). The Marine Corps serves as the nation’s Expeditionary Force in Readiness, and the Commandant has reaffirmed that the Marine Corps “will continue to serve as the nation’s premier crisis response force around the globe, and contribute to the deterrence and warfighting needs of all combatant commands” (USMC 2020).

With responsibilities spanning the globe and spectrum of conflict, the CPG and FD30 aim to build a force with adequate capabilities to address a high-end fight. The premise assumed by the Marine Corps is that by designing a force using China as the premier pacing threat, the force can scale to any assigned responsibility across the range of military operations (Berger and Evans 2020).

Mark F. Cancian, a senior advisor in the International Security Program at the Center for Strategic and International Studies, concludes that

the lack of hedging means that the Marine Corps will not field the broad set of capabilities it has in the past. It will be poorly structured to fight the kind of campaigns that it had to fight in Korea, Vietnam, and Iraq. The history of the last 70 years has been that the United States deters great power conflict and fights regional and stability conflicts...The Marine Corps might plan to defer these conflicts to the Army, but that has not worked in the past. Army forces have been too small to keep the Marine Corps out of sustained ground combat. (Cancian 2020).

The challenge of designing a Marine Corps capable of addressing both the Chinese pacing threat and concurrent responsibilities in a fiscally constrained environment is not trivial. Adding to the complexity of the problem is the question of how a great-power conflict may emerge. At the extreme end of the spectrum is the most dangerous course of action—high-intensity war between the United States and a peer threat. The more likely course of action is a series of proxy wars and insurgencies incited by China or Russia (Vrolyk 2019).

Regardless of the form of future conflict, the Marine Corps force is being designed to counter the most dangerous course of action. If the assumption of scalability is to hold true, then capabilities must be retained or developed that will foster success proportionally.

3. Rocket and Cannon Fires

The CPG and FD30 place a large emphasis on rocket-delivered anti-ship fires. An increase of rocket artillery batteries from seven to 21 is planned to expand deterrence capability, ensure access in a challenging anti-access and area denial (A2/AD) environment, and increase probability of naval campaign success. In a fiscally constrained environment with finite resources, a planned divestment in cannon batteries from 21 to five parallels this focus on rocket delivered fires (USMC 2020).

A rocket-artillery based force optimized to create a swath of mutually contested space will promote access in an A2/AD environment. However, long-range anti-ship missiles do not scale in economy of force. A multi-million-dollar anti-ship missile is unlikely to be utilized against a land-based threat to personnel. If cannon artillery were to be removed completely, one echelon lower than rocket delivered artillery is an 81mm mortar. The retention of cannon artillery, although reduced, can be improved to offer tactical maneuver-based offensive and defensive firepower to Marines across the contingent range of military operations that the Marine Corps may be called upon to address. Furthermore, by modernizing the cannon artillery force during a period of divestment, legacy institutional knowledge of cannon artillery can be retained and focused rather than atrophy. To enable force scalability, improvements must be made to retained cannon artillery.

4. Most Capable Artillery Pacing Threat

Of the two great power competitors, Russia presents the most formidable artillery threat. While China serves as an appropriate service pacing threat due to its economic and technological base, Russia maintains the most capable and practiced fires community. Similar to how the Marine Corps assumes a force developed to counter the high-end Chinese fight will scale to lower spectrum conflict, this thesis assumes that an artillery force capable of countering the most sophisticated and challenging artillery threat will scale to threats around the globe. Results and insights gained through analysis of the Russian threat can be evaluated for effective integration into the Pacific theater, enabling a cannon artillery force that is capable of successful operations against all potential adversaries.

B. PURPOSE

This study seeks to identify factors and interactions which are critical to USMC cannon artillery success in a Russia counterbattery scenario. Success is defined by the following Measures of Effectiveness (MOEs):

- Lethality: The destruction of 50% of adversary artillery forces.
- Survivability: Friendly artillery units remain combat capable for future operations following the termination of the simulation (no more than 50% casualties sustained).

Both equipment and tactics, techniques, and procedures (TTPs) are evaluated against the MOEs. The following questions are answered through simulation and analysis:

- Which equipment factors are most critical to success in a counterbattery fire scenario?
- Which TTP factors are most critical to success in a counterbattery fire scenario?
- Can cannon artillery succeed by operating within enemy threat rings?

C. METHODOLOGY

Using open-source weapons data and TTPs, a scenario is built using Map Aware Non-Uniform Automata (MANA) (McIntosh et al. 2007). An efficient design of experiments (DOE) is implemented to evaluate various factor levels over the design space. Later chapters discuss factors to be considered, levels to be evaluated, the MANA simulation environment and scenario, and DOE construction.

Data are generated and collected through simulation, with insights solidified through analysis using the statistical analysis software JMP (SAS 2021). These insights are compared to current TTPs and equipment in order to offer suggestions to modernization efforts and inputs to future wargames.

D. ORGANIZATION

Chapter II presents a literature review of the artillery process, USMC and Russian artillery, employment considerations, factors to be evaluated, and previous research that informs this study.

Chapter III introduces the tactical scenario, conceptual model, modeling environment, and computer model.

Chapter IV defines the factors to be evaluated, presents the location within the computer model in which each factor is affected, and establishes an incremental experiment methodology.

Chapter V discusses the construction of efficient DOEs for each experiment and concludes with a brief discussion about the significance of efficient DOE to computational run time and explanatory information acquired.

Chapter VI presents analysis on each experiment, progressively drawing insights into equipment and TTP factor significance, factor interactions, and TTP decisions to support a more capable cannon artillery force.

Chapter VII summarizes the findings from analysis and draws final conclusions into the most critical factors for cannon artillery lethality and survivability in a counterbattery fight against a peer adversary. Recommendations for future analytic work

are presented, and suggestions for extending findings through USMC wargaming and experimentation are discussed.

II. BACKGROUND AND LITERATURE REVIEW

This chapter provides a summary of the artillery process, a review of USMC and Russian artillery, a recent vignette of Russian fires employment, and definition of broad factors that are evaluated in this thesis, drawing insight and context from reports and studies.

A. ARTILLERY BACKGROUND

The mission of the Field Artillery is to destroy, neutralize, or suppress the enemy by cannon, rocket, and missile fires and to help integrate all fire support assets into combined arms operations.

— MCWP 3-16.4
(USMC 2016a)

1. The Artillery Process

The execution of artillery operations requires three general synergistic components: target acquisition, weapon systems, and command and control (C2) systems. By Marine Corps convention, “target acquisition is detecting, identifying, and locating a target in sufficient detail to effectively employ munitions. The weapon systems provide the means to engage the target. The C2 systems provide the required facilities, equipment, communications, and personnel that enable the commander to plan, direct, and control fires” (USMC 2016a, p. 1-1).

Historically, forward observers (FOs) have acted as the primary target acquisition agency. When an FO detects a target, they generate and transmit a Call for Fire (CFF). The CFF is transmitted to the Fire Support Coordination Center (FSCC) for deconfliction and prioritization. The FSCC forwards the request for fires to an appropriate firing agency Fire Direction Center (FDC). The FDC calculates a ballistic firing solution, selects munitions and the quantity of projectiles to fire, and transmits firing data to the gunline. The gunline applies technical firing data and fires at the target according to instructions given by the FDC. Upon effects assessment, the FO either terminates the fire mission, adjusts fires, or calls for a repeated mission.

The process from target acquisition to effective munition effect is referred to as the kill chain. Various countries and uniform services possess different acquisition platforms, weapons systems, and communication architecture and technology. These various agencies also employ differing tactics, techniques, and procedures (TTPs). When taken in summation, these various aspects affect the speed of the kill chain and the method by which artillery is employed on the battlefield. Figure 1 provides a graphic of the generalized artillery kill chain.

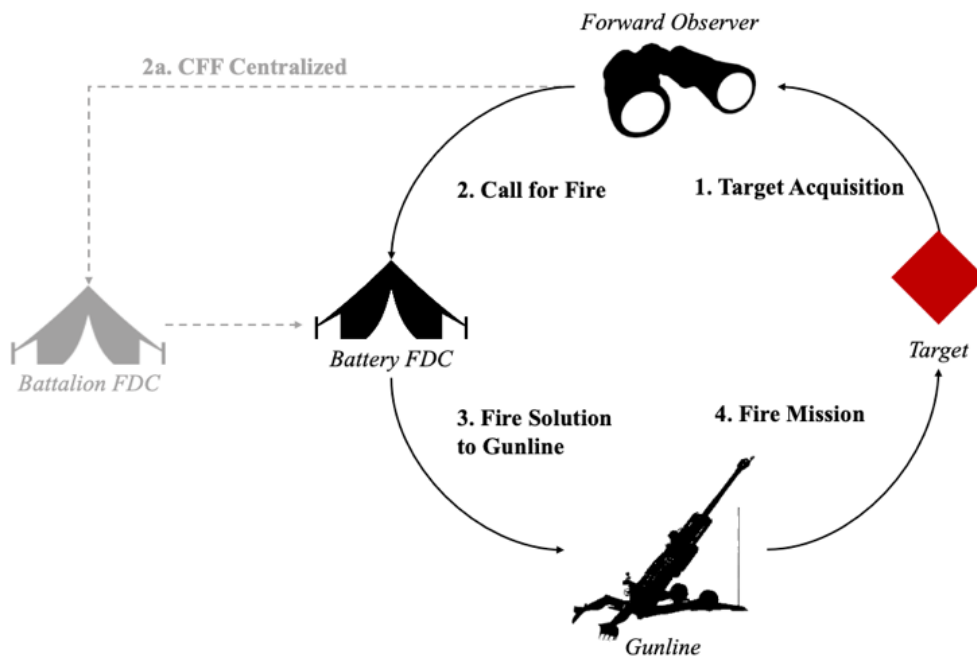


Figure 1. Simplified Artillery Kill Chain

Technologic advancements in target acquisition, weapon systems, and command and control (C2) systems are quickly producing an exceedingly complex environment. No longer is the forward observer the only, or best, option. Unmanned aerial vehicles (UAVs) offer an extended vantage, counterbattery radars detect points of origin, and radio and cellular emissions reveal even dormant and concealed units. For example, on 11 July 2014, during the Russo-Ukrainian War Battle of Debal'tseve at Zelenopillya, Russian forces used both UAS and offensive cyber capabilities to identify, target, disrupt, and destroy

Ukrainian forces in an attack that injured more than 100 and killed 30. The attack was “perhaps the apogee of Russian rocket and artillery doctrine” (Fox 2017).

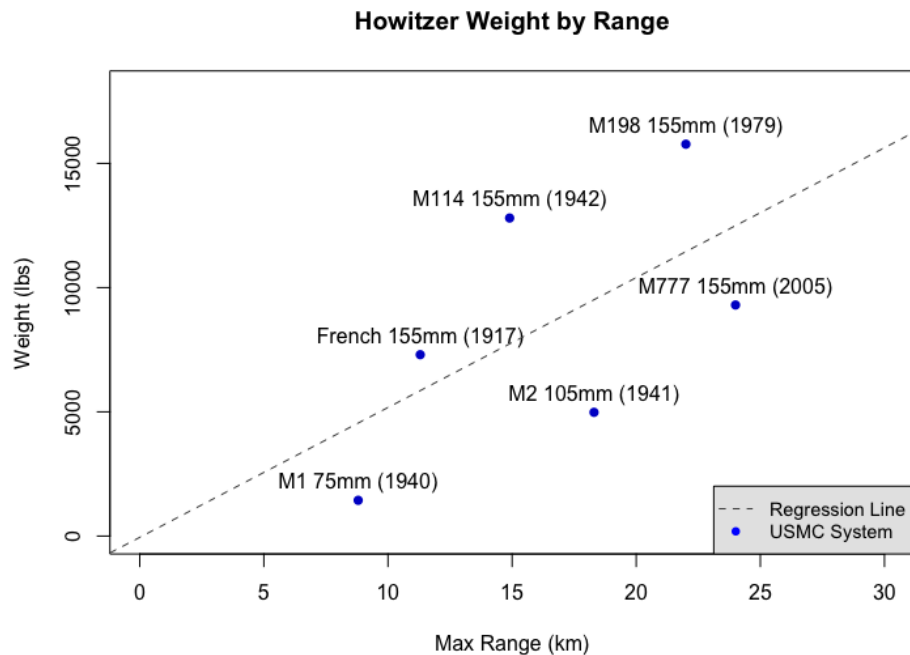
2. USMC Artillery

There has long been a desire and incentive to increase the range of cannon artillery systems. This is largely a hold-over capability requirement from the last 19 years of the Global War on Terrorism. The Marine Corps enjoyed the benefits of air superiority and stable fire base operations. These variables created an environment that necessitated and promoted increased range and accuracy. GPS-guided munitions provided increased accuracy and base bleed projectiles provided a range increase without significant modification to the intrinsic cannon range. Despite this desire for range, peer and near-peer adversaries can currently outrange our cannons, and their targeting cycle and tactical employment can overwhelm existing operating concepts (Gordon et al. 2019).

The M777A2 lightweight 155mm towed howitzer currently fielded by the Marine Corps has long relative range, but emplacement and displacement times are lengthy, and the cannon can only be moved with the heavy Medium Tactical Vehicle Replacement (MTVR). These slower displacement times equate to an environment where unmasking (firing resulting in successful adversary counterbattery radar target acquisition) results in counterbattery fires that out-cycle current abilities to displace. Additionally, current Marine Corps tactics of consolidated battery sized elements leave a significant portion of available firepower vulnerable to a single massed strike.

a. The Range-Speed Dilemma

The desire for range and rapid emplacement and displacement times are at conflict. As seen in Figure 2, historical and current Marine Corps towed cannon systems gain range to the disadvantage of additional weight.



Adapted from Janes (2020a), (2020f), (2020g), (2020h); Wikipedia (2020a), (2020b).

Figure 2. Range-Speed Dilemma, Towed Cannon Weight versus Range.

The desire for further organic range (without rocket assisted projectiles) requires an inherently heavier cannon. Heavier towed cannons produce longer emplacement and displacement times. Conversely, lighter towed cannon systems that are capable of more rapid emplacement and displacement have less organic range.

Technological advances have aimed to reduce weight and increase range, most seen in the progression from the M198 to M777A2. Although weight has been decreased significantly, the prime mover for the M777A2 remains the MTVR. The powerful, albeit heavy, MTVR is often retrofitted with armor and a troop carrier, further increasing dimension and weight. The M777A2/MTVR pair is a sizable couple, proving challenging to rapidly embark, transport, and employ.

While helo-inserted artillery raids are technically possible, the loss of the prime mover renders inserted artillery incapable of movement until aircraft are able to extract. In a contested environment with active radar, artillery raids under the current construct are high risk and largely infeasible.

b. Transportation

Self-propelled artillery cannons reside on a vehicle chassis or are developed as a whole system vehicle. The primary benefit of a self-propelled system is the ability to transport as a single unit, significantly decreasing emplacement and displacement time. Traditionally, the Marine Corps has resisted self-propelled artillery systems due to their inherent weight additions. Exceedingly heavy systems prove challenging for an expeditionary and amphibious force to employ. For example, unconstrained by expeditionary weight restrictions, the U.S. Army currently fields the armor protected 155mm M109A6 Paladin. Matching the caliber and range of the M777A2, it weighs 63,352 lbs. compared to the M777A2 at 9,100 lbs. (Jane’s 2016, 2020a).

c. USMC Artillery Organization

With a planned divestment in cannon batteries from 21 to five, an accurate assessment of the near-future organization is not possible. The Marine Corps currently maintains four artillery regiments (three active, one reserve). Although not accurate to current organizational levels, the traditional organization establishes three battalions per regiment. Each battalion consists of three firing batteries with six towed howitzers per battery. Each echelon of cannon artillery unit conventionally supports a higher echelon infantry unit—an artillery regiment supports a division, an artillery battalion supports an infantry regiment, and an artillery battery supports an infantry battalion.

3. Russian Artillery

While the U.S. commonly refers to artillery as the “King of Battle,” the Russian military emphatically declares artillery to be the “God of War.” Russia utilizes long range indirect fires as its main effort, hinging its bid for success on rapid and integrated target acquisition methodologies. The Russian concept of operations “consists of the capability to deliver devastating indirect fires, while maintaining stand off from their enemy, and protecting their own forces through the use of ADA (air defense artillery) and Electronic Warfare (EW). Once adequate fires have been delivered, ground forces begin to maneuver, preferably with an armored element to secure time and space for indirect fire and protection

platforms to move forward and begin the cycle again” (United States Army [USA] 2016, p. 12).

To emphasize the significance that the adversary places on artillery, a Fort Leavenworth based Foreign Military Studies Office report concluded its study of Russian artillery fires with the following:

Precision fires have their place and quick destruction of high-threat targets is optimum for survival, but the Russians have not abandoned their use of massed artillery. Massed artillery not only destroys—it produces paralysis and psychic terror. ‘The experience of modern wars and armed conflicts shows that artillery is still the god of war. Airstrikes cannot replace massed artillery fire. And the most effective way to protect your troops from enemy artillery is to destroy that artillery with counterbattery fire, when enemy artillery positions are detected and instantly suppressed.’ So, the Russians plan to improve their reconnaissance-fire system while retaining their ability to dominate the battlefield through massed artillery fire. (Grau and Bartles 2018)

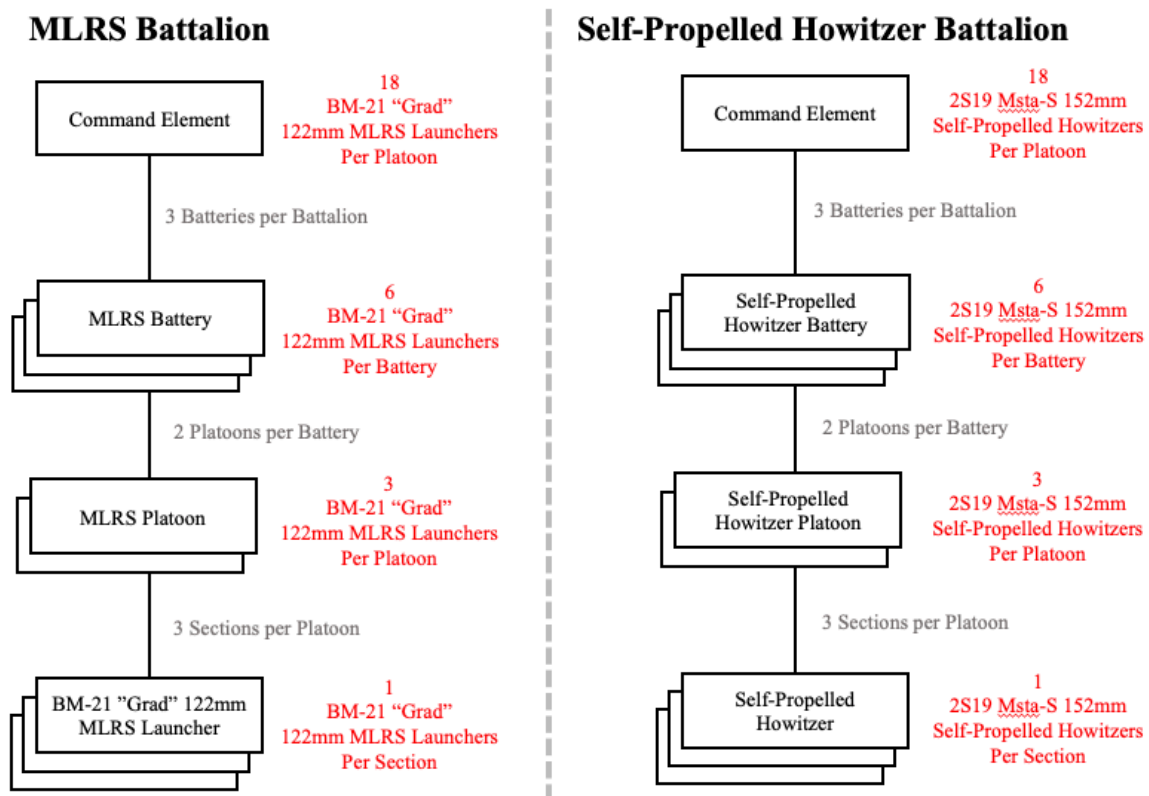
With a preference for mass and standoff, Russia continues to prioritize its artillery modernization efforts. Russia prefers to refurbish and modify existing systems, establishing an economic baseline of proven systems that are rapidly producible and modularly repairable (Grau and Bartles 2016).

a. Transportation

While Russia maintains towed artillery, the preferred broad weapon system of choice is the heavy self-propelled howitzer and self-propelled Multiple Launch Rocket System (MLRS). This preference supports the practiced concept of maneuver by fire. Russia is currently field testing the new 2S35 Koalitsiya-SV 152mm self-propelled howitzer which is projected to enter service in 2021. With a rocket-assisted range of 70km and an automatic loading firing rate of 16 rounds per minute, the 2S35 doubles the range of the M777A2 and triples the rate of fire (Janes 2020b). This newly developed technology is a testament to the priority of artillery modernization given Russia’s historical preference to invest in quantity by refurbishing existing systems.

b. Russian Artillery Organization

Russian forces operate in brigades. Each brigade consists of one MLRS battalion and two self-propelled artillery battalions. The MLRS Battalion consists of three batteries, each with six BM-21 “Grad” 122mm launchers (18 total). Each self-propelled howitzer battalion consists of three batteries, each with six 2S19 Msta-S 152mm self-propelled howitzers (18 guns/battalion, 36 guns/brigade). Figure 3 shows the traditional organization of these MLRS and cannon battalions.



Adapted from The Russian Way of War (Grau and Bartles 2016, p. 234–236).

Figure 3. Russian MLRS and Self-Propelled Howitzer Battalion Organization.

The Battalion Tactical Group (BTG) forms the basis of the Russian combined arms force. Comprised of brigade forces, the flexible BTG is task-organized for a specific mission set. Inherent in every configurable BTG is a heavy contingent of artillery.

B. A RUSSIAN KILL-CHAIN VIGNETTE

Under the cover of darkness on the morning of 11 July 2014, a large Ukrainian force of mechanized vehicles assembled to prepare for an early morning offensive against Russian forces near Zelenopillya along the Ukrainian-Russian border. At 0430 as final preparations were being made, all radio communications were lost and multiple drones were heard overhead. Just minutes later, an intense Russian artillery barrage killed 30 Ukrainian soldiers and destroyed two mechanized battalion's worth of equipment (Fox 2017).

This recent example of the Russian kill-chain at work provides context to the challenge presented by the Russian threat. In the Zelenopillya attack, Russian forces used cyber capabilities to identify approximate Ukrainian force positions, UAV capabilities to refine target locations, EW capabilities to disrupt communications, and mass fires to destroy a large swath of territory (Fox 2017). The first warning that Ukrainian forces had of an impending strike was the audible noise of Orlan-10 reconnaissance drones and simultaneous loss of communications, and within minutes hundreds of missiles and artillery projectiles were impacting positions.

Zelenopillya was unique in the fact that Russia unveiled its Reconnaissance-Fire system in depth. The Russian Reconnaissance-Fire system is an integrated system of reconnaissance drones, cyber capabilities, Integrated Air Defense System (IADS), and long-range mass strike capability that produces a highly efficient kill-chain with devastating effects (Grau and Bartles 2018). Additionally, the attack reinforced the historical Russian doctrine of utilizing its fires capabilities as its primary destructive force "reflecting the bromide that 'artillery conquers, infantry occupies'" (Fox and Rossow 2017).

While Russia does have formidable precision strike capability, it continues to prefer mass over precision. One paper that examined the Reconnaissance-Fire system concludes that "Russian artillery units will expend far more conventional rounds than expensive, high-precision rounds" (Grau and Bartles 2018). This analysis also found that "the primary method of executing reconnaissance-fire missions will be to engage newly-discovered

enemy targets with brief fire assaults and subsequent changes of position to avoid retaliatory fire” (Grau and Bartles 2018).

Insight gained into the Russian kill-chain from the Zelenopillya attack coupled with the knowledge that Russian units prefer to mass fires and make evasive survivability moves lends perspective to what the Marine Corps may have to contend with.

C. FACTORS

In this section, the author introduces seven broad equipment and TTP based factor families that are influential in cannon artillery performance.

1. Employment

Marine cannon artillery is conventionally employed in consolidated battery-sized elements. In consolidated battery operations, six-gun batteries are employed as the smallest tactical unit. The benefits of operating in this manner are a more robust local security, central battery C2, key billet holder centralization, and battalion level operational control. Disadvantages include physical proximity of firing pieces, higher levels of communications emissions, and large proportion of assets incapable of fire when not fire capable (FIRECAP). Higher levels of communication’s emissions increase probability of detection, physical proximity renders units vulnerable to mass strike, and the decision to displace the battery removes availability of a significant amount of assets from the battlefield for a period of time.

Split battery operations are considered based on the tactical situation. In split battery employment, the traditional six-gun battery disperses into two, three-gun platoons with organic platoon FDCs. These platoons operate geographically separated from each other. This increases C2 complexity and decreases local security capability, but units are hedged against single mass strike annihilation and can displace sequentially, maintaining FIRECAP as the sister unit is moving.

Distributed operations consist of individual or pairs of cannons operating geographically separated from the other guns of the battery. All battery guns are controlled by the battery FDC, also geographically separated. Distributed operations represent the

most complex C2 of all employment methods, but the geographic separation of all pieces offers the highest survivability among employment options. Local security is extremely lacking in distributed operations, with individual pieces possessing few assets with which to organically defend itself. A recent study which examined employment options found that simulated distributed operations resulted in a 70% higher probability of victory compared to consolidated battery operations (Turk 2020).

2. Time in Position

Time in position refers to the time spent occupied in a position after firing. Increasingly capable artillery reconnaissance systems present a dilemma between the decision to displace upon firing to increase survivability against the desire to remain FIRECAP. Prior to unmasking by firing, a unit can be located by a forward observer, UAV, or EW. Every round fired from a position has a possibility of being detected by counterbattery radar. Regardless of how a unit is targeted, once the adversary kill chain is initiated, rounds could impact the position within a short period of time.

Remaining in a position keeps that unit FIRECAP and responsive. The size of the unit firing also factors into the adversary decision to counterfire. If the unit is small, a mass strike may not be advisable from a risk perspective. By unmasking their own fire units in a counterbattery strike, the adversary opens itself up to counterbattery fire from previously undetected units.

While it may seem intuitive that the best way to ensure survivability is to fire and immediately displace, this course of action results in a decrease in FIRECAP units, and this may significantly affect the battlefield. Additionally, immediate displacement only increases survivability if the unit is able to clear the area before counterbattery rounds impact. One study found that frequent movement reduces risk at the expense of reduced lethality, and recommends remaining occupied after firing in order to produce lethal effects (Shim 2017). This finding was validated and amplified by Capt Turk, who found that Time in Position was a dominant factor for survivability and that in the cases he examined there was an “increase in survivability when the battery chose to stay in the position and increase the rate of fire” (Turk 2020).

3. Rate of Fire

Measured in rounds per minute, rate of fire is affected by method of load and physical gun limitations. Undergoing enormous pressure and heat exchanges, cannon tubes can maintain a rapid rate of fire for a limited amount of time, and a sustained rate of fire thereafter.

The current M777 is a crew loaded howitzer, requiring a load and ram team. To the expense of weight, some artillery systems possess automatic loading systems, reducing crew requirements and permitting a higher rate of fire (Gordon et al. 2015).

4. Camouflage and Concealment

By utilizing natural concealment such as foliage as well as position improving concealment techniques, Marine artillery decreases its chances of visual detection. Although visual and radar scattering nets reside in the inventory, placing them over an M777A2 and all battery vehicles is a significant task that slows displacement times dramatically. Effective concealment is not currently widely practiced as the requirement for concealment was not a priority in recent conflicts. A recent RAND report that evaluated U.S. Army artillery requirements for high-end conventional war concludes that “against a powerful opponent such as Russia, cover, concealment, and deception will be essential” (Gordon et al. 2019, p. 182).

With an ability to project reconnaissance unencumbered by terrain, Russia utilizes its UAVs to “significantly [supplement] forward observation capabilities, a very important technological development for an artillery-centric post-Soviet army” (Grau and Bartles 2018). Russian use of UAVs as a primary target acquisition method is expected to grow even stronger as Russia develops its Reconnaissance-Fire Complex system (Grau and Bartles 2018).

5. Emplacement and Displacement

Emplacement consists of all actions required from the occupation of a position to the capability to fire. Conversely, displacement consists of all actions from being FIRECAP to movement out of a position. The desire for rapid emplacements and

displacements are twofold: to decrease time when fires are not available and to increase survivability.

A unit is unable to provide responsive fires when it is displacing, transiting, and emplacing. By shortening the time required to emplace and displace, a unit is able to establish itself as a more persistent asset. If a unit is able to displace faster than the adversary kill chain can produce effects on its position, then survivability is increased.

One study that conducted an analysis of alternative artillery systems for the Marine Corps concluded that “until the M777 is replaced with an independently mobile artillery system, training and readiness standards should place a greater emphasis on decreasing emplacement and displacement times, as well as increased use of survivability moves” (Browne 2018).

6. Range

Ideally, a unit possesses organic range greater to that of its adversary, remaining outside of its threat ring while able to produce effects. As discussed in Chapter 1, an increase in range requires an increase in weight. For a highly mobile expeditionary force with unique transportability requirements, weight is a significant constraint. If unable to achieve range greater than the adversary, TTPs should support survivability and lethality within the range of adversary effects.

Recent joint efforts such as the Long Range Cannon project aim to increase the range of current USMC cannon artillery systems. These efforts include both technological advancements to the M777 as well as improved base bleed, rocket-assisted projectiles (Gaitan-Tovar and Bound 2019). One attractive series of modifications doubles current range. However, this benefit to this range increase is at the expense of an additional 1,000 pounds, six additional feet of cannon tube, and expensive GPS guided projectiles (Military News 2018).

This thesis evaluates range as a primary factor to determine whether increased range is a dominant contributor to success or if Marine artillery units can succeed with

reduced range capabilities in exchange for more robust capabilities in areas such as emplacement and displacement speed.

7. Caliber

Although different effects are generated by different projectile types, the kinetic strength of the projectile is generally determined by the caliber of the weapon system. A 155mm cannon fires a larger and more powerful round than that of a 105mm cannon. The caliber of the weapons system has implicit constraining effects on the weight and range of the weapons system. The size and relative power of both the 105mm and 155mm projectile is evaluated in this study.

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III. MODELING

The purpose of the simulation model is to determine which elements of tactics and equipment are most important for survivability and lethality in an air-denied, counterbattery scenario. In this chapter, the researcher develops a theoretical scenario for a post force closure artillery engagement, illustrates the conceptual intent of the model, introduces the chosen modeling environment, and describes the computer simulation.

A. SITUATION

The following scenario is adapted from RAND RR2124: *Army Fires Capabilities for 2025 and Beyond*. The researcher emphasizes that the scenario is purely theoretical and is intended for analysis purposes only.

1. Strategic

Bolstered by strategic success in Ukraine and favorable testing of international response, Red maintained increasing confidence that a swift incursion into neighboring territory would increase its sphere of influence. Seeking a strategic defeat on NATO, Red developed operational plans to attack, occupy, and isolate the Baltic states of Estonia, Latvia, and Lithuania.



Figure 4. Baltic States. Adapted from Gordon et al. (2019).

Due to geographical proximity, Red assumed that it could deny NATO flexibility of action through superior operational tempo and rapid seizure of key terrain. Intending to leverage A2AD and sensor-strike capabilities, Red maneuvered forces within their geographically owned territory to deny deep counterstrike and force a frontal response.

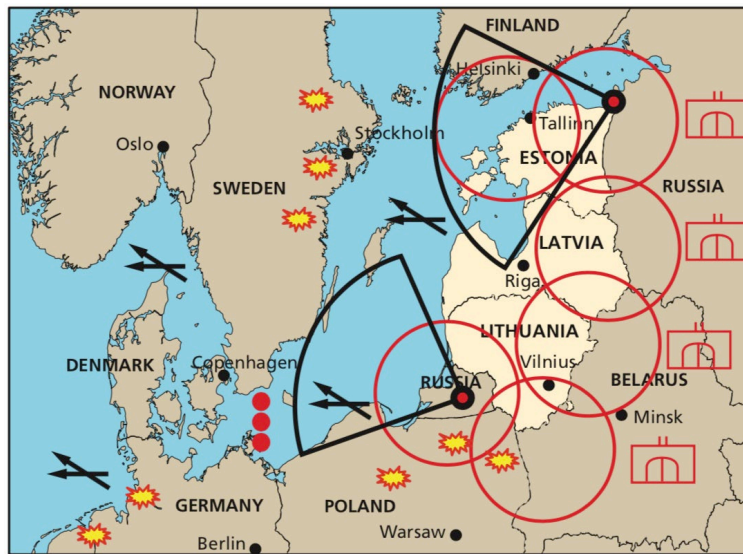


Figure 5. Red A2AD and Sensor-Strike Plan. Source: Gordon et al. (2019).

2. Operational

After gaining access to the Baltic Sea, a Blue Marine Expeditionary Brigade (MEB) conducted an amphibious landing along the western coast of Latvia. Among the assault forces were one cannon artillery battalion. The mission of the Blue cannon artillery battalion is to support the seizure of an improved expeditionary airfield in the vicinity of Riga, Latvia in order to enable follow on MEB force deployment and flexibility of action for the MEB Aviation Combat Element (ACE).

Anticipating the operational value of the expeditionary airfield, Red deployed fires elements of a Brigade Tactical Group (BTG) to establish defensive fires positions. One battalion consisting of two 2S19M2 self-propelled howitzer batteries and one BM21 ‘Grad’ MLRS battery comprise the defensive fires elements.

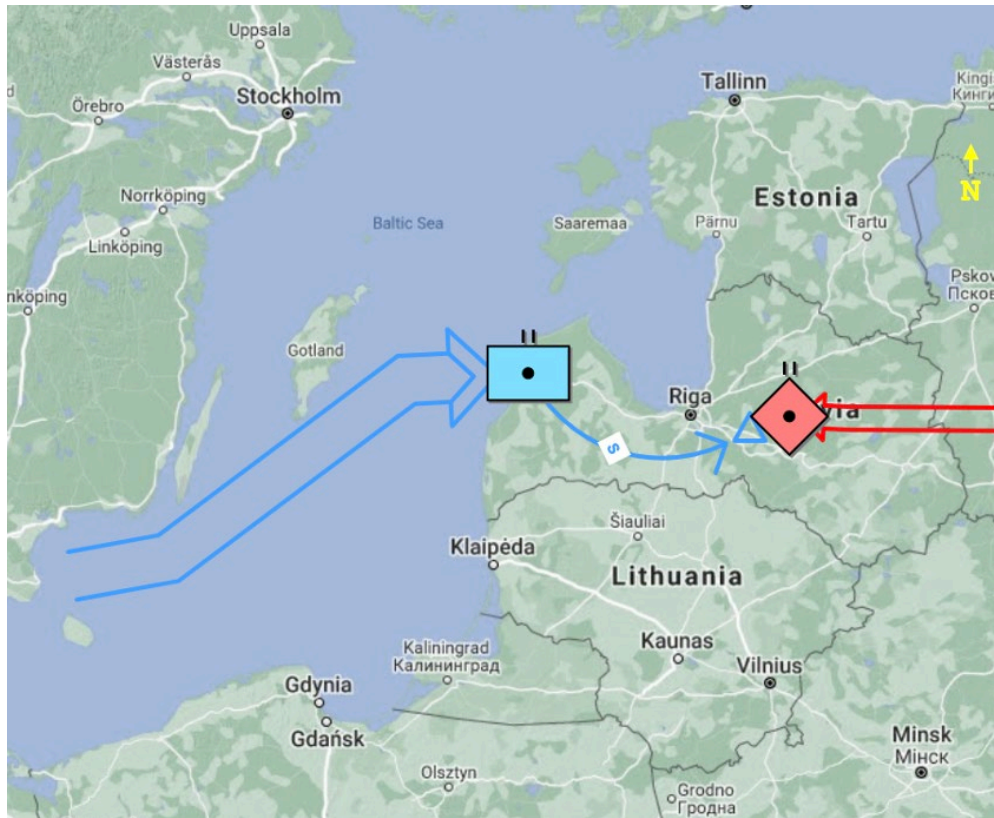


Figure 6. Operational Maneuver of Red and Blue Fires Elements

3. Tactical

Red has taken up defensive positions in unknown locations approximately 6–10 kilometers to the east of the objective area. Airspace remains contested and neither Red nor Blue expect close air support. Terrain is rural and consists of open fields and lightly forested, gently rolling hills. High speed roads border the airfield with unimproved roads interspersed throughout the area of operations, and vehicular traffic is relatively unimpeded when off of roads.

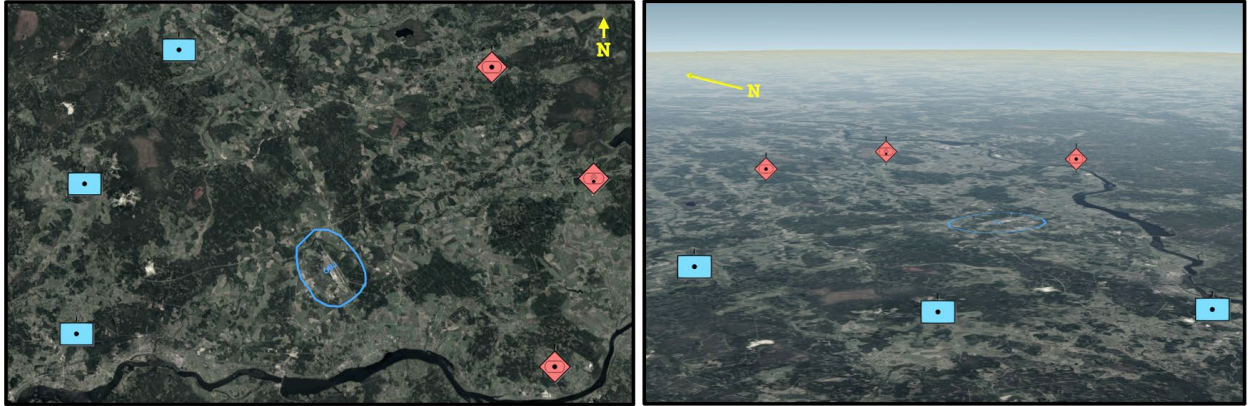


Figure 7. Approximate Red and Blue Battery Locations, Tactical Level

B. CONCEPTUAL MODEL

The model intends to explore the interactions between artillery units in a counterbattery scenario. All units unnecessary to this aim are eliminated from consideration. Both Red and Blue have firing units and target acquisition elements unique to their respective force structure and order of battle.

With an air contested environment, artillery is the highest level of fire support available to Red and Blue. Red leverages artillery as its main effort and intends to prevent Blue's advance to seize the airfield. Having assumed defensive positions, Red will prioritize striking Blue's fires assets in order to gain fire superiority. Conversely, Blue prioritizes the seizure of the objective area and will balance forward movement with adequate FIRECAP units in order to respond proactively to Red units acquired or retroactively to fires received by Red.

As Blue approaches the objective area, both Red and Blue attempt to acquire opposing fires assets through UAS. When a target is acquired, a fire mission is generated to attack the target. Counterbattery radar is active on the battlefield, and any missions executed will unmask the firing element, rendering them vulnerable to radar detection. If an unmasked unit is detected by opposing radar, a call for fire is generated and transmitted to available fires elements for engagement. If rounds impact a position, the unit under attack will briefly attempt to gain fire superiority through an increased rate of fire and subsequently conduct an emergency displacement.

Red will remain in defensive positions as long as no incoming fires are received. Red will conduct emergency displacements to prepared alternate positions if fires are received. Blue will conduct survivability moves toward the objective area if no fire missions are received after a set amount of time. Blue will conduct emergency displacements toward the objective area if fires are received.

C. COMPUTER SIMULATION

This section introduces the modeling environment used in this study and discusses the modeling logic used to create the simulation.

1. Introduction to MANA

The modeling environment selected for this thesis is Map Aware Non-Uniform Automata (MANA), developed by New Zealand's Defense Technology Agency in 2000. MANA is a stochastic, agent-based, time-stepped, mission-level modeling environment that excels at tactical level simulation under certain conditions (Lucas 2020).

While high resolution, physics-based models provide high fidelity analysis of certain aspects of weapons systems performance, they generally lack the ability to integrate dynamic personality-driven decisions, situation awareness, and inter-unit communications. MANA was developed to specifically address these deficiencies (McIntosh et al. 2007).

MANA is an accessible modeling environment with a shallow learning curve. A simple graphical user interface (GUI) enables the modeler to construct a mission-level scenario using an intuitive and logical approach. The modeler is able to watch the simulation run with geographical movement and interactions visually displayed.

The stochastic nature of MANA allows for variance in simulation runs based on a pseudorandom seed. Seed values are captured throughout simulation runs, enabling the modeler to identify and play back anomalous outlier outputs, assisting in unique situation and error detection.

Significantly, MANA is easily data farmable. The modeler is able to develop a design of experiments (DOE) of various factors and levels to run the simulation under differing conditions. The ease of DOE integration and modeler control of output statistics

allows the modeler to quickly generate insights into factor importance in pursuit of an objective.

2. Agent Interaction and Personalities

In MANA, military units are represented by agents. Agents are organized into groups called squads. Each squad is built to model certain capabilities and assume a certain personality, dictating the manner in which the agents of the squad interact with the terrain and friendly, neutral, and enemy agents. As a squad of agents progresses through the simulation, it can assume various states, triggered by events. Each state is built to have its own personality, which dictates the action and priorities of the squad at that point in time. Figure 8 shows an example of the various personality traits that can be defined for a squad.

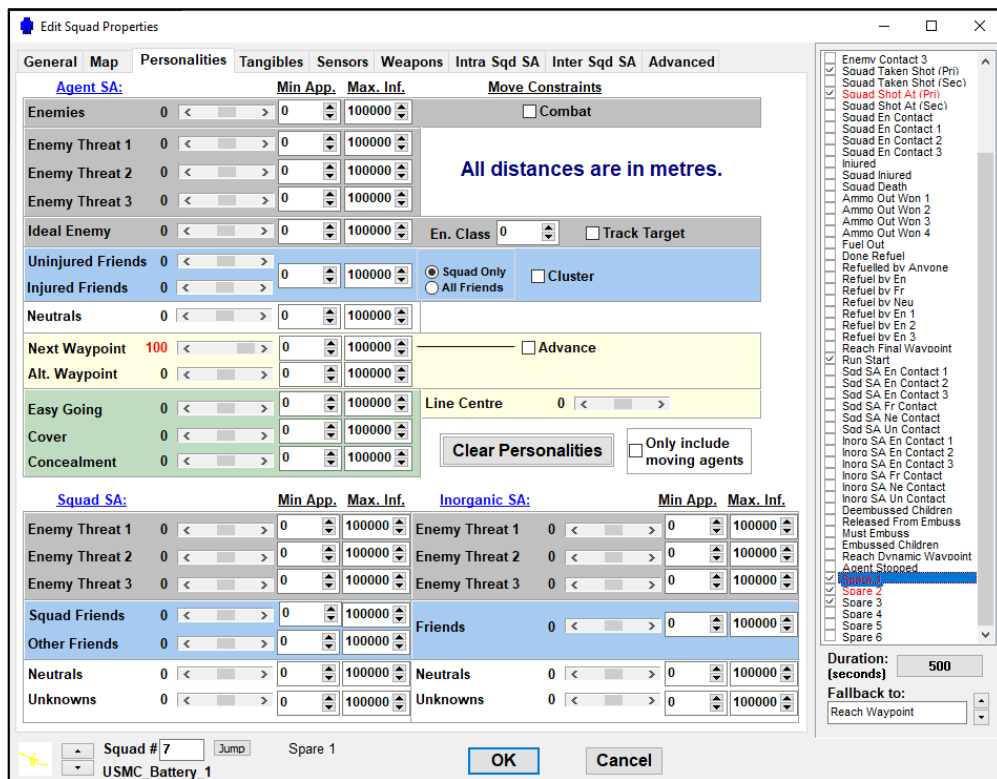


Figure 8. MANA Personality and State GUI

In the above case, USMC_Battery_1 is a squad of six howitzer agents. This squad is built to have a high preponderance to reach the next waypoint when it is in the Spare 1

state. This means that the squad (and agents comprising the squad) will prioritize reaching the next waypoint above other actions.

The manner in which a squad progresses through states—and the personalities of those states—dictate how the squad interacts with all aspects of the simulation. By defining many squads, establishing communication links, placing them in appropriate initial locations, establishing waypoints, and imbuing the squads with personalities based on states, a simulation can be built to approximate a tactical, mission-level engagement within the constraints of MANA.

3. Battlespace, Terrain, and Movement

The tactical scenario terrain and geometry of Riga, Latvia are similar to that of Fort Bragg, North Carolina. The computer model presented in this thesis uses Fort Bragg as the area of operations due to availability of MGRS mapping and possible reader familiarization with the area. The simulation area of operations is 34 kilometers by 20 kilometers in size, and each model time step is one second.

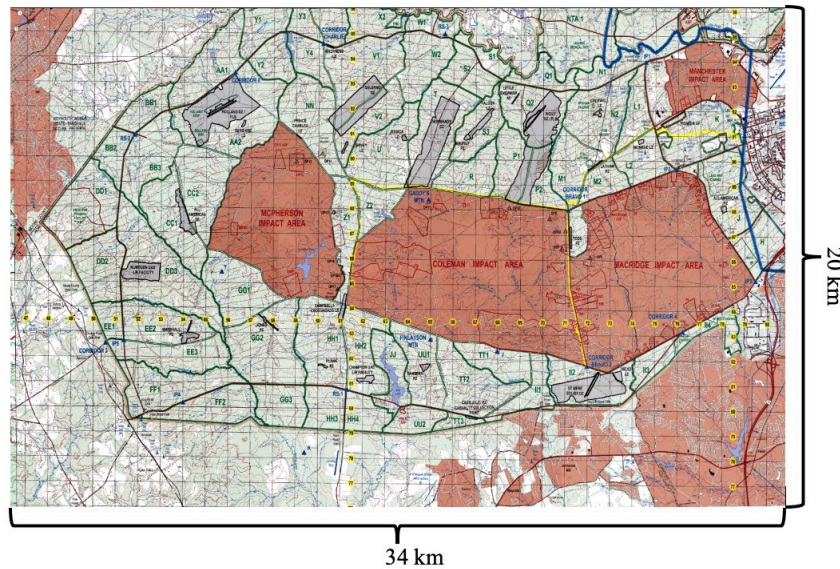


Figure 9. Model Background, Fort Bragg, NC

MANA uses a hidden terrain layer which effects agent movement. The modeler defines three key metrics for each color. The terrain layer for this simulation is shown in Figure 10. Depending on which terrain type (color) an agent is on, its speed (going), cover, and concealment are affected as a percentage of its attributes. For example, yellow depicts high speed roads surrounding the objective area. An agent on a yellow pixel is able to move at full speed, but has no cover or concealment. Similarly, an agent on a dark green (dense bush) pixel can only move at 20% of its attributed speed, but is 30% protected by cover and has 90% concealment. Agents will self-select the best terrain to move on depending on its personality. If an agent is built to have a high preponderance to reach its next waypoint, it will choose the path that allows it to reach the waypoint in the shortest time possible. The agent may elect to travel along a high-speed road, or it may choose a direct path through slower going terrain if the slower path allows for a more optimal arrival time.

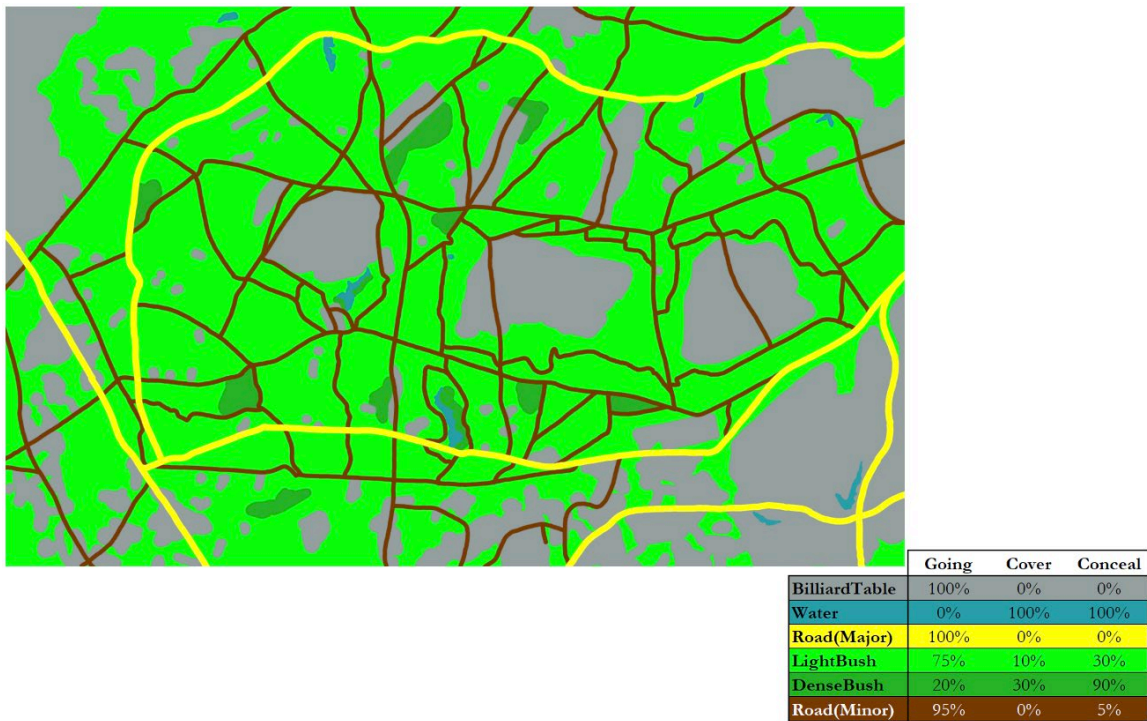


Figure 10. Terrain Effects on Going, Cover, and Concealment

4. Acquisition Agents

The methods of target acquisition available to Blue and Red are UAS and counterbattery radar. UAS and counterbattery radar operate independently, but have complementary effects. Neither can be targeted nor destroyed by opposing action. This section details the modeling logic of each acquisition method, how the agent is involved in the total schema, and workarounds implemented by the modeler to best approximate realistic employment.

In MANA, sensors are established to detect and classify. Detection is the simple case of any agent being sensed by the sensor. Classification is the proper identification of agent loyalty and class of the agent.

The class of firing agents (howitzers or MLRS) is determined by the state that the gun is in. Acquisition agents classify an opposing firing asset based on the firing assets' class. Firing agents change between three distinct classes (Class 1 is reserved for non-firing agents):

- Class 2: Undetectable (Displacing, Moving, Emplacing)
- Class 3: FIRECAP, have not fired (Masked)
- Class 4: FIRECAP, have recently fired (Unmasked)

Both Red and Blue have one UAS, and each shares a similar North-South zig-zag search pattern over the area of unknown emplacement, as seen in Figure 11. The UAS is built with a personality to loiter near detected unknown and enemy agents. The loitering pattern gives the UAS sensor more opportunities to correctly classify the agent. The UAS is capable of detecting firing agents of Class 3 and Class 4 (any FIRECAP unit, regardless of recent firing status). If an opposing firing agent is detected and subsequently classified by the UAS, the UAS will transmit the positive identification location to all FDCs with a 30 second latency. At some point during the loitering pattern, the agent will make a personality-based decision to continue its prescribed search pattern.

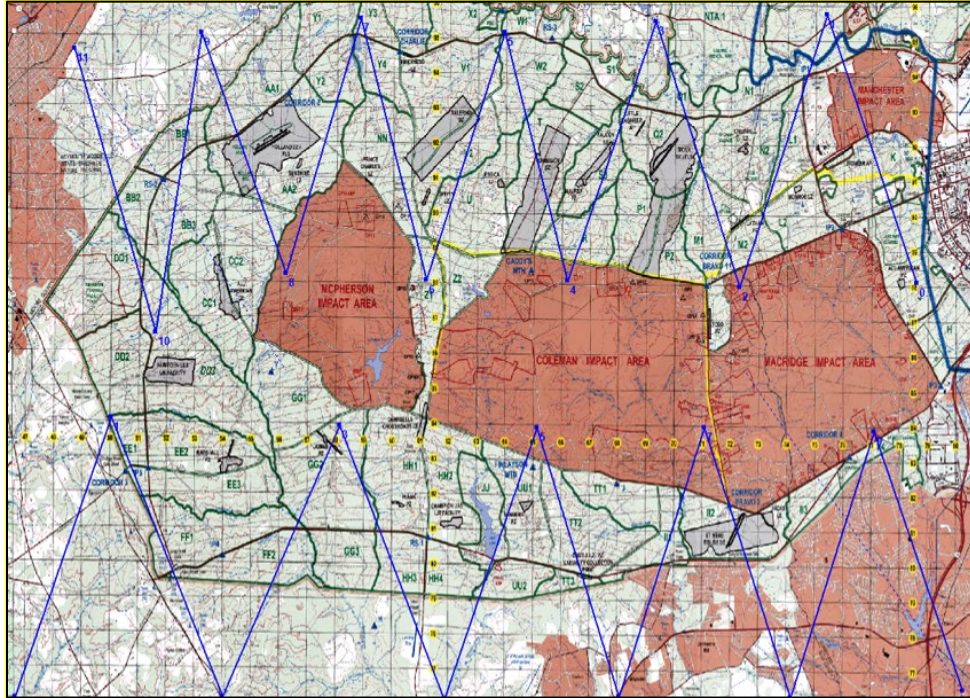


Figure 11. UAS Search Patterns

Due to similarities between the conventional UAS systems, both Red and Blue UASs are modeled after the RQ-21A Blackjack and range classification probabilities were derived from an Operational Test and Evaluation report, discussed in Appendix A.

Counterbattery radar operates by identifying projectile flight trajectories and extrapolating to determine the point of origin. Red and Blue counterbattery radar is only able to detect and classify firing agents of Class 4, the state in which a firing agent has recently fired a round. Upon successful classification, the counterbattery radar transmits the point of origin location to its respective battery FDC with a 30 second latency.

Conventionally, an artillery battalion is supported by a single counterbattery radar. At the battalion headquarters level, counterfire is deconflicted across batteries to ensure that all are not unmasked at once. MANA does not possess adequate functionality to facilitate deconfliction. The modeler coerced deconfliction by instantiating three counterbattery radars with degraded capabilities and assigned one counterbattery radar to each battery. The instantiation time for each counterbattery radar was staggered at the beginning of the simulation run. By increasing the average time between detection and

decreasing the probability of classification, the cumulative functionality of the modeled radar agents is approximately equal to that of one fully functional counterbattery radar in support of a battalion. By staggering instantiation time, relative deconfliction of firing is achieved as each battery will fire only on agents classified by their paired counterbattery radar.

Each battery FDC passively waits for target locations to be transmitted by UAS or counterbattery radar. Upon receipt of a target location, the FDC transmits the location to the firing agents under its control with a latency of 60 seconds. This latency was derived from current Training and Readiness standards as the time for data computation standards. Figure 12 depicts the simulation state diagrams and communication flows for the UAS, counterbattery radar, and FDC.

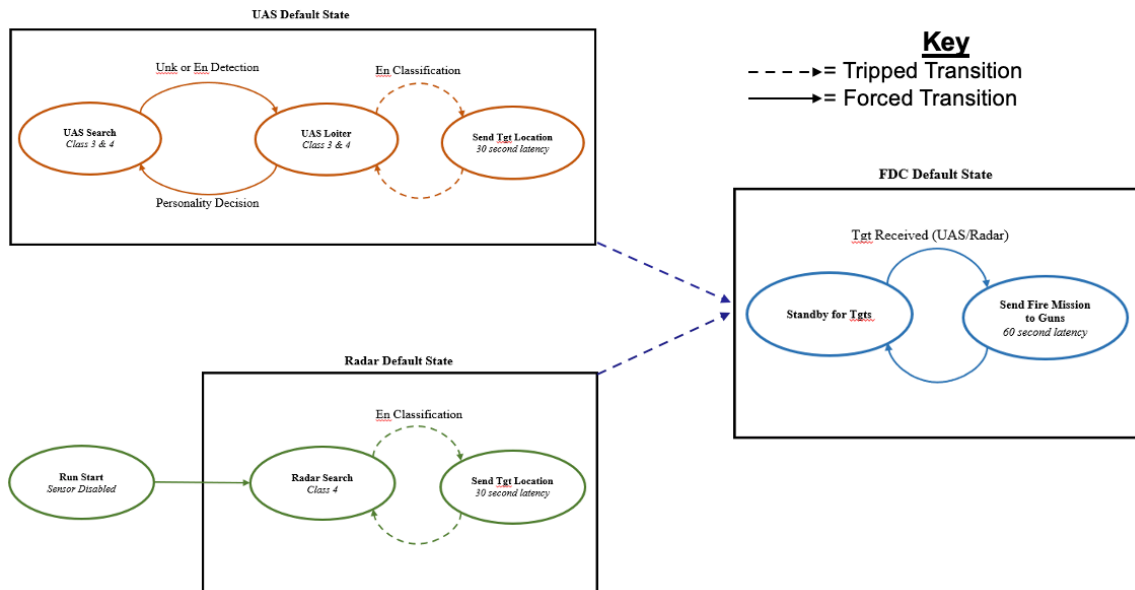


Figure 12. UAS, Counterbattery Radar, and FDC Simulation-State Diagrams

5. Fires Agents

Although Red and Blue fires platforms differ in capability, each follows a common logical pattern. The following sections document the closed-loop state transitions for Blue and Red firing agents.

a. *Blue Firing Agents*

The simulation-state diagram for the Blue firing agent squads is shown in Figure 13. For readability, firing agent squads will hereby be referred to as guns. The discussion that follows describes each state, transition, and analogous real-world event.

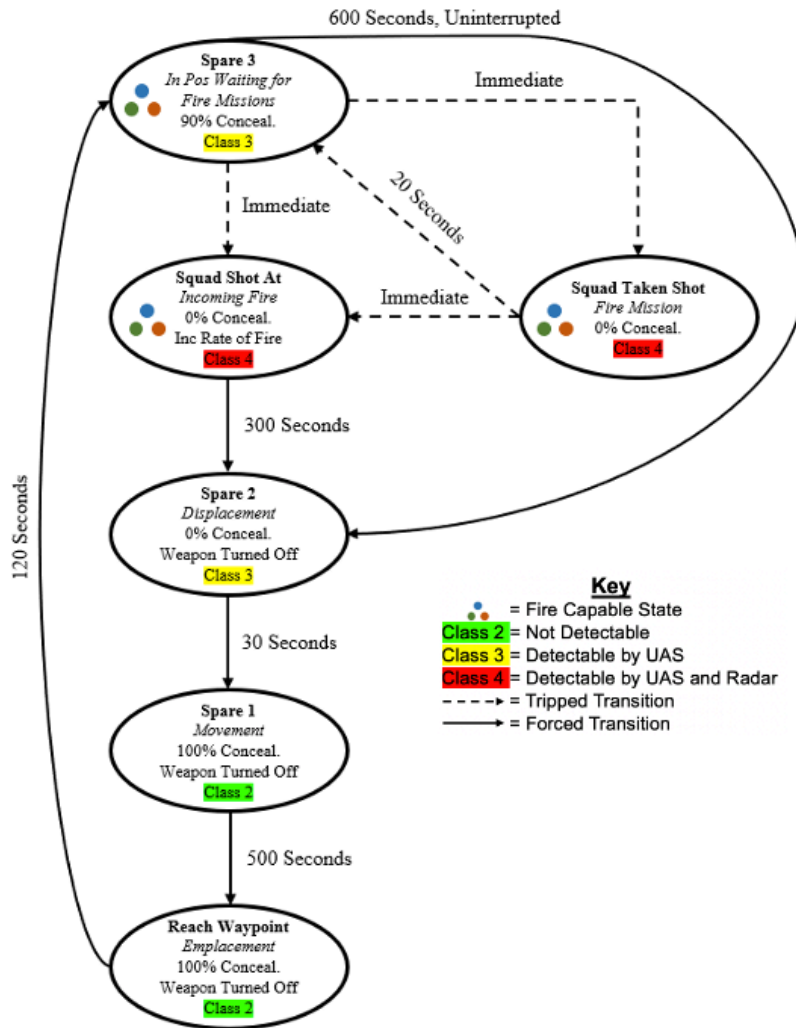


Figure 13. Blue Firing Agent Squad Simulation-State Diagram

At the beginning of the model run, Blue guns begin in the Spare 3 state. This state simulates the guns being emplaced, FIRECAP, and awaiting fire missions. In Spare 3, the guns are Class 3 (only detectable by UAS) and possess some level of concealment. From Spare 3, three key events can happen.

First, if the guns receive a fire mission, they will execute the mission by transitioning to the Squad Taken Shot state. The guns will become susceptible to counterbattery radar (Class 4). If no counterbattery fires are received, the guns will transition back to Spare 3 after 20 seconds, which is approximately the time of flight for a projectile at the ranges under evaluation.

Second, if at any point the guns receive incoming fires, they will immediately transition into the Squad Shot At state. The rate of fire will be increased in an effort to gain fires superiority. After a set amount of time, the guns will conduct transition into Spare 2 state in order to displace.

Finally, if the guns receive no fire mission or incoming fire within a certain amount of time in Spare 3, then a survivability move is conducted by transitioning into the displacement Spare 2 state.

Regardless of how the guns reached the transition to the displacement Spare 2 state, they will eventually begin to displace. After a certain amount of time displacing, guns will transition into Spare 1, or the movement state. At this time, the guns become 100% concealed and are reduced to Class 2, meaning that they are undetectable to any acquisition effort. In this state, the guns are moving to their next position with a high preponderance to reach the next waypoint. Upon reaching the next position, the guns transition into the Reach Waypoint state, which begins the emplacement.

While emplacing, the guns are Class 2 and not detectable by any acquisition effort. Due to the air-denied environment and the high value of fires assets to the tactical situation, the modeler assumes that a fire mission will be conducted only after a targeted unit is fully emplaced. Realistically, the earlier a unit receives fires in its emplacement phase, the faster it can displace out of incoming fire. Conversely, if a unit is permitted to become fully emplaced prior to being fired upon, it is significantly more difficult to displace quickly. Given the risk incurred by unmasking by firing, it is advantageous to wait for a unit to become fully emplaced before an attack. It is for this reason that guns remain Class 2 during emplacements.

Once the emplacement is complete, the guns transition back to Spare 3, and are FIRECAP and awaiting fire missions. For each independent fire agent squad, this closed-loop process repeats itself for the duration of the simulation.

In a counterbattery scenario with targets often acquired by counterbattery radar, it is important to note that missions are conducted against a point of origin rather than a visually detected and tracked target. MANA assumes that once detected, a targeted agent can be fired upon with fires automatically adjusted for position. This behavior is counter to the intended point of origin mission with minimal battle damage assessment. To coerce intended point of origin attack, the guns were built to receive fire mission location data as a snapshot-in-time location, which is displayed on an inorganic contact persistence map. The targets remain on this inorganic contact persistence map for five minutes. This forces the guns to fire upon the point-of-origin without tracking the target if it were to move during the conduct of the mission.

By this logic, a fire mission will be conducted if the guns are in a FIRECAP state and are not processing another mission. If the guns are not in a FIRECAP state, the mission will not be conducted, with one exception. If the guns receive a fire mission when they are not in a FIRECAP state but manage to transition into a FIRECAP state while the target resides on the inorganic contact persistence map, then the mission will be conducted.

b. Red Firing Agents

The majority of the logic presented for the Blue firing agent squads holds true for Red. The differences in logical state changes are due to the defensive posture of Red and the two different weapons systems employed by Red. The simulation state diagrams for Red cannon firing agent squads and Red MLRS firing agent squads are shown in Figure 14.

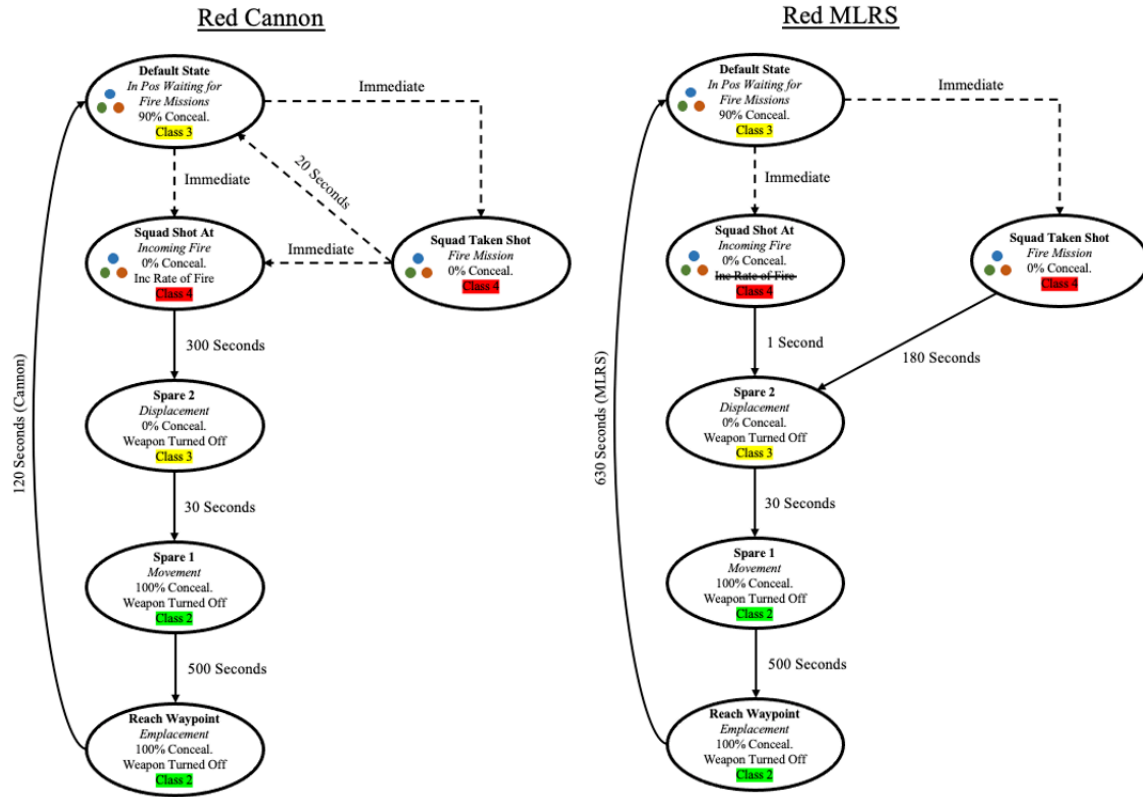


Figure 14. Red Cannon and MLRS Firing Agent Squads Simulation-State Diagrams

Regardless of weapon type, Red firing agents begin in the Default state, analogous to the Spare 3 state of Blue. Unlike Blue, Red does not maintain a direct transition arc from the Default (FIRECAP) state to the Spare 2 (displacement) state. This is because Red, in defensive positions, does not conduct survivability moves if no events occur after a certain amount of time. Except for this alteration, the Red cannons maintain a logical state change identical to the Blue firing agents.

Red MLRS do not have arcs from Squad Taken Shot to the Default or Squad Shot At states. This is due to the conventional employment of MLRS. Since the MLRS system expends a full pod of rockets in a single fire mission, the squad transitions into the Spare 2 (displacement) state at the conclusion of firing. A transition arc to Squad Shot At is unnecessary since all rocket ammunition is already expended after conducting a fire mission and the unit desires a rapid displacement before refitting. Lacking the capability

for subsequent attacks before a lengthy pod reload time, this transition is realistically necessary as a survivability move. If the squad enters the Squad Shot At state, it immediately transitions to the Spare 2 state. No increased rate of fire will occur due to the firing mechanics of pod-stored rocket fires.

IV. FACTORS AND EXPERIMENT METHODOLOGY

To identify the factors most important to Blue lethality and survivability, multiple experiments are conducted, each of which provides unique insights. This chapter discusses the location of each factor within the computer model and presents our experiment methodology.

A. FACTORS AND LEVELS EVALUATED

To answer the question of which factors most significantly influence lethality and survivability of cannon artillery in a Russian counterbattery scenario, Chapter II established seven broad factor categories to be evaluated in this thesis. These are

- Employment Method
- Time in Position
- Rate of Fire
- Camouflage and Concealment
- Emplacement and Displacement
- Range
- Caliber

These broad factors can generally be split into equipment and TTP based categories, as seen in Figure 15. Equipment based factors are those which are most influenced by the weapon systems employed on the battlefield. TTP based factors are those which are most influenced by unit standard operating procedure or decisions made by the commander. Generally, new or refined TTPs can be incorporated more quickly than changes to equipment.

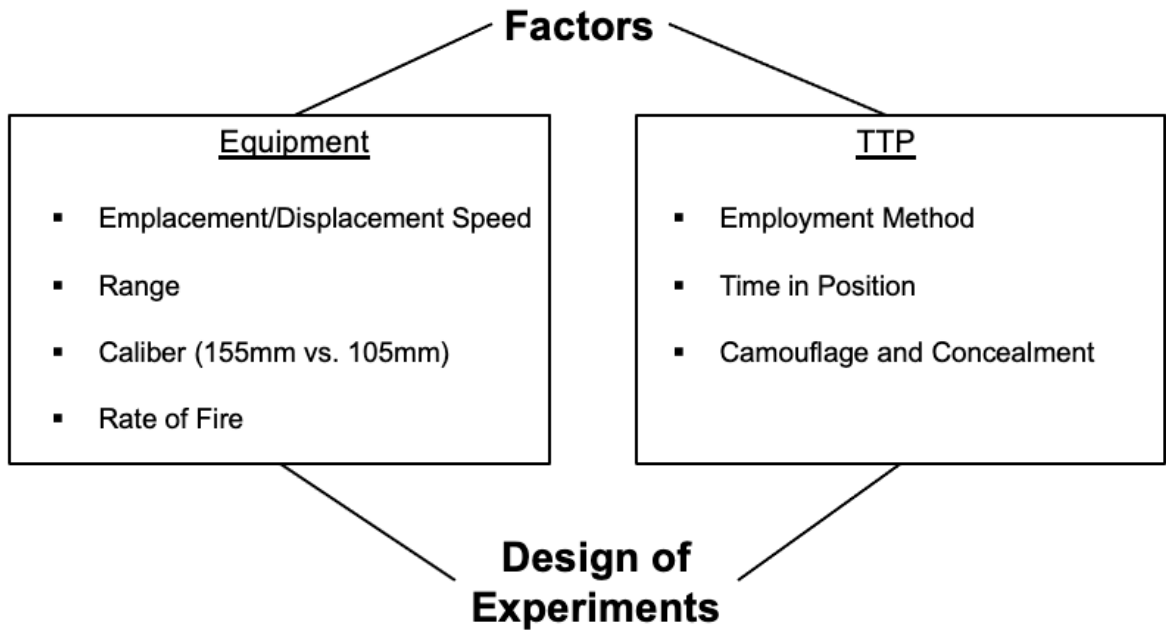


Figure 15. Broad Factor Families

Within the computer model, each broad factor is influenced by various inputs to the firing agent squad. The broad factors are segmented into more granular factors, each affecting a specific aspect of the firing agent. Using the previously presented simulation state diagram for the firing agent squads, each factor’s data input location is identified.

B. EQUIPMENT BASED FACTORS

The five broad equipment-based factors established are rate of fire, range, caliber, emplacement time, and displacement time. Figure 16 shows the specific location of each of the aspects of these broad factors.

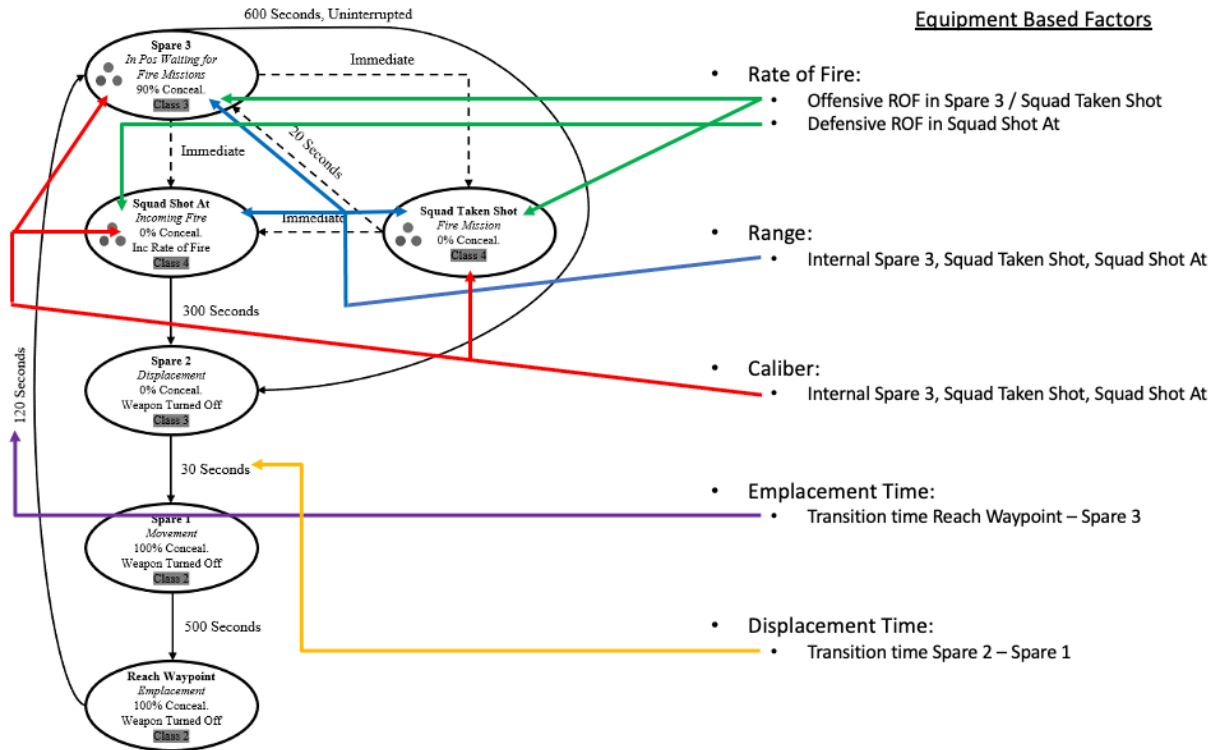


Figure 16. Equipment-Based Factor Simulation State Diagram Locations

Rate of fire is changed in each of the FIRECAP states. *Offensive rate of fire*, or the rate at which the weapons system fires projectiles during an offensive fire mission, is affected in the Spare 3 and Squad Taken Shot state. *Defensive rate of fire*, or the increased rate of fire at which the weapon system fires after receiving incoming projectiles, is affected in the Squad Shot At state.

Both *Range* and *Caliber* are varied in the FIRECAP states of Spare 3, Squad Taken Shot, and Squad Shot At states. *Emplacement time* is the time to transition from Reach Waypoint to Spare 3, and *displacement time* is the time to transition from Spare 2 to Spare 1.

C. TTP BASED FACTORS

The three broad TTP-based factors established are *time in position*, *camouflage*, and *employment method*. Figure 17 shows the specific location of each of the aspects of these broad factors.

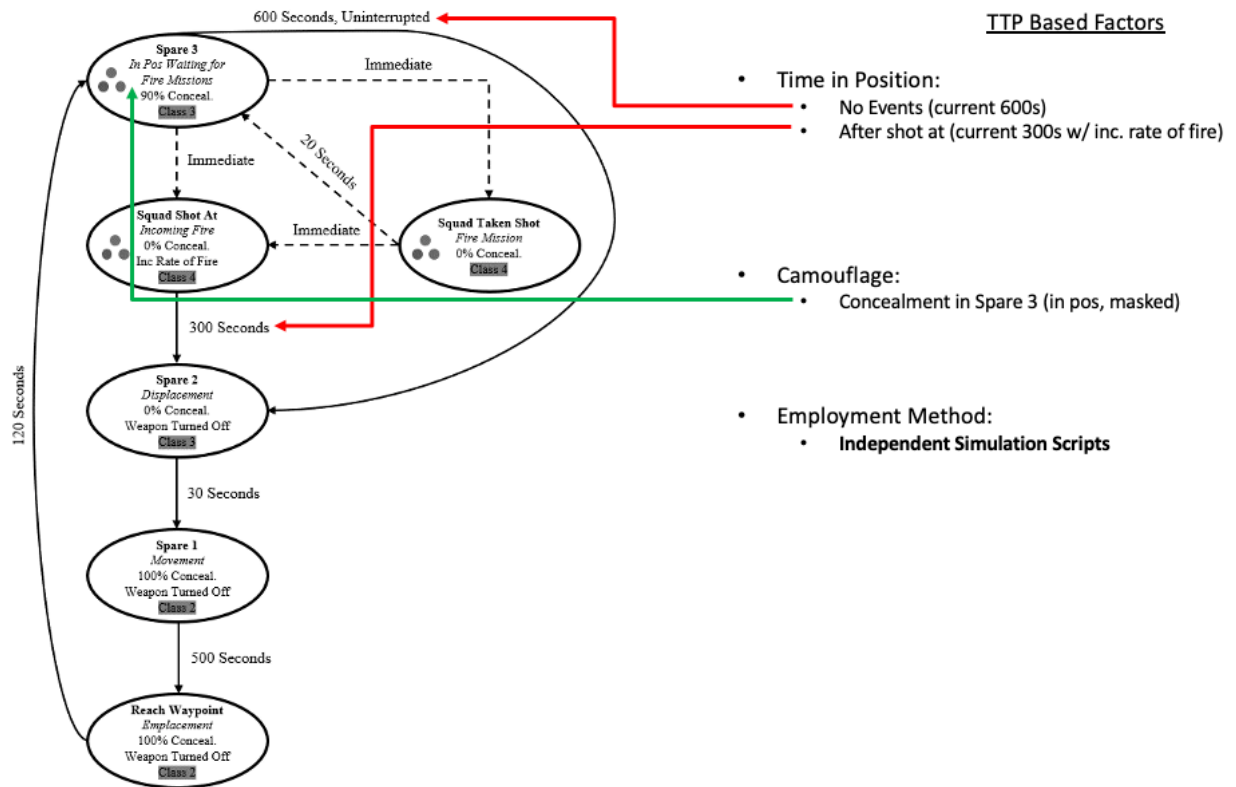


Figure 17. TTP-Based Factor Simulation State Diagram Locations

Time in position is affected in two distinct locations. First, the time until a survivability move is conducted occurs in the transition time between Spare 3 and Spare 2. This is the amount of time that a unit will remain FIRECAP before displacing if no actions occur. Second, the amount of time a unit remains in position after receiving incoming fires is identified as the transition time between Squad Shot At and Spare 2. If this is set to be zero seconds, a unit displaces immediately after receiving incoming fires. If this is set to five minutes, then the unit exchanges rounds with an increased rate of fire until beginning displacement after five minutes.

Camouflage, or the amount of concealment a unit has from UAS detection, is affected in Spare 3, the only state in which a unit is FIRECAP and masked.

The only factor that cannot be controlled by varying a data input to the simulation is *employment method*. MANA lacks the ability to dynamically distribute a unit while maintaining adequate control measures. In order to control the employment method factor by tactic, four separate scenarios were implemented in MANA.

As discussed in Chapter II, USMC artillery conventionally operates as consolidated, six-gun batteries where a battery FDC controls six geographically centralized howitzers. In split battery operations, one FDC controls two three-gun sections which are geographically separated. In distributed operations, one FDC controls six geographically separated howitzers. These three employment methods are currently practiced to differing extents. The modeler created one theoretical section employment method in which one FDC controls three two-gun sections which are geographically separated. Figure 18 provides a visual reference of these employment method constructs.

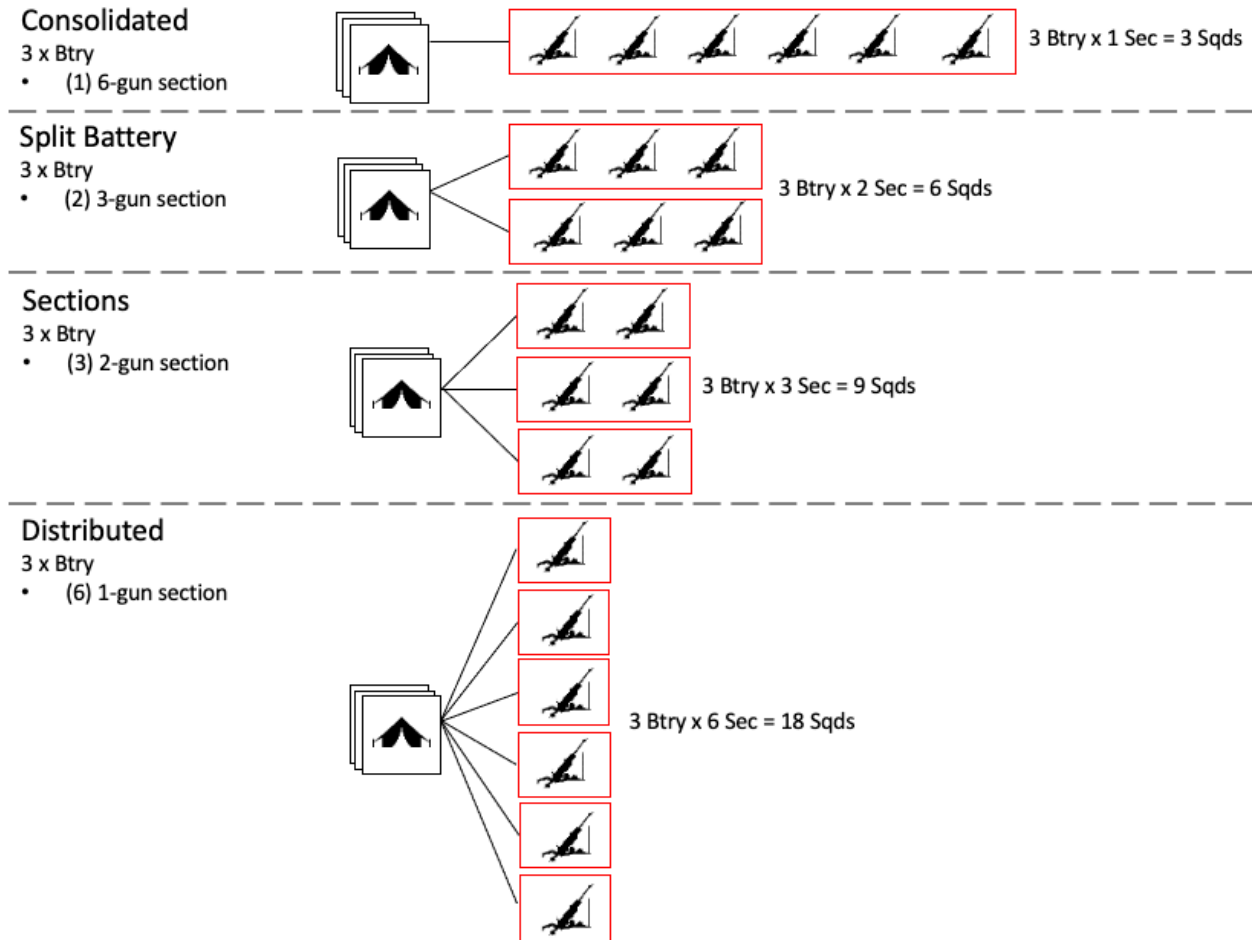


Figure 18. Employment Method Constructs

Regardless of employment method, Blue firing units progress toward the objective area. In order to deconflict movement, each firing squad is assigned a proportional lane to maneuver toward the objective area. As units become more dispersed, each respective firing squad lane becomes narrower. Each battery maintains an approximately equal lane width throughout each employment method, with the size of each firing section size dictating the lane width of the respective firing squad. Figure 19 provides a graphical representation of the force laydown throughout each of the four employment methods.

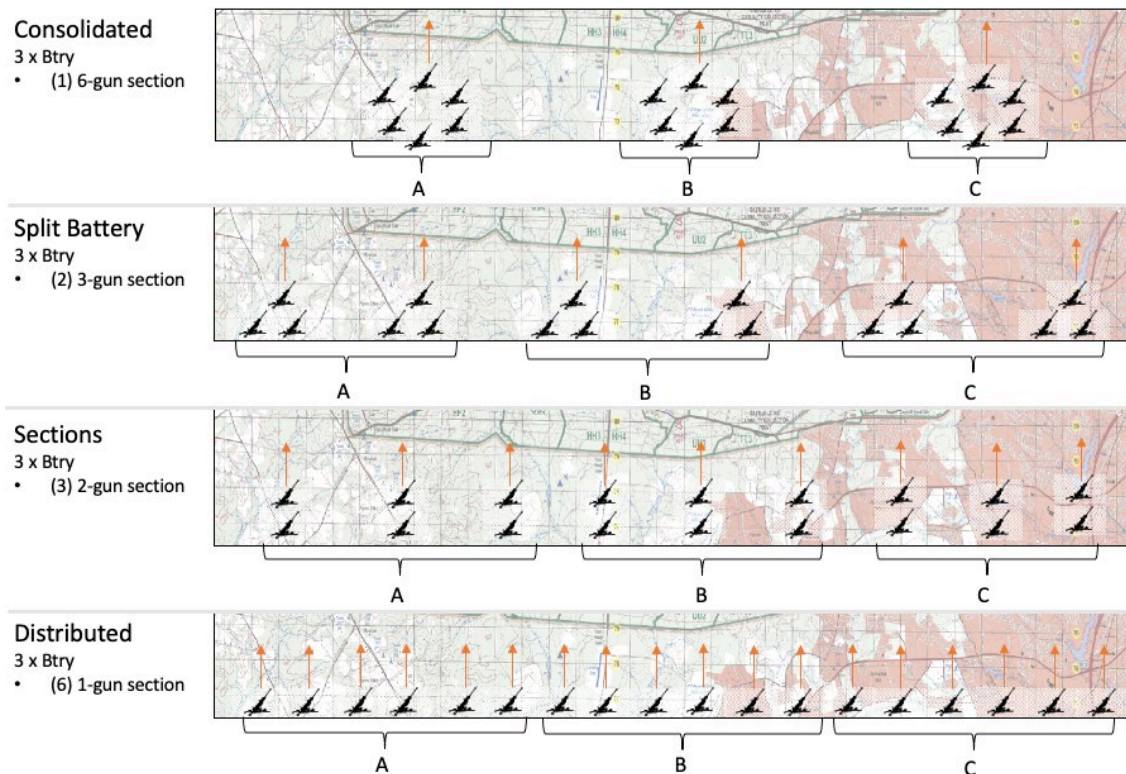


Figure 19. Employment Method Force Laydown and Movement

In order to vary the employment method factor across these four levels, four simulation scenarios were created. In each, the only difference is the number of blue firing squads, the number of agents comprising each squad, and the initial location and waypoints of each squad.

D. FACTORS UNIQUE TO RED

Red factors are not altered until the fourth experiment. All factors that are varied for Red are identified above with the exception of *armor* and conventional *force composition*.

The modeler assumes that armor integration will not be pursued for Blue given USMC expeditionary weight constraints. Red is under no such constraints and actively employs various armored artillery units.

The extent of armor effectiveness on the 2S19M2 self-propelled howitzer is unknown, and Janes offers the following:

The protection offered by the hull is unclear as it is understood to be based on the T-72. In its standard configuration the T-72A is built from rolled homogeneous armour that is further protected by Combination-K armour. This provides the vehicle with protection from earlier generation anti-tank rounds, but it is unclear whether this level of protection is offered to the vehicle. The turret is understood to protect only against small arms fire and primarily artillery fragmentation (Janes 2021).

Given the uncertainty surrounding the level of armor, the modeler assumed that the 2S19 turret is comprised of one inch, or 25mm, of armor with which Red cannon firing agents were built in MANA. This factor is changed in the FIRECAP states of Default State, Squad Taken Shot, and Squad Shot At (see Chapter III, Figure 14).

The conventional Red force built in MANA consists of two 2S19M2 batteries and one BM-21 ‘Grad’ MLRS battery. The modeler defines a unique Red factor as the composition of the force varying between this construct and one in which three 2S19M2 batteries and no MLRS comprise the force. This factor is changed through back-end mapping.

E. EXPERIMENT METHODOLOGY

An incremental experiment methodology is developed to build intuition and draw conclusions about the factors most influential to Blue lethality and survivability. Experiment one evaluates the range of possibilities if Blue and Red forces were to engage in battle as currently constructed. Experiment two examines the relative benefit of different Blue employment methods against the current Red force. Experiment three varies Blue factors to determine the most significant factors against the current Red force. Experiment four varies both Blue and Red factors to determine the most significant factors for success against variable and unknown Red force capabilities.

1. Experiment One: Fight Tonight—Base Case

In experiment one, a base case is established. In this experiment, Blue and Red are constructed with parameters to best approximate the current capabilities and tactics employed by USMC and Russian artillery. The results of this experiment lend insight into

the range of results that may be observed if these forces were to engage as currently equipped.

2. Experiment Two: Train Tomorrow—Blue Employment Method

Experiment two envisions the same Blue and Red capabilities, but varies the method in which Blue employs its forces. The most immediately influenced capability that the USMC can affect through wargaming and training is artillery employment. The results of this experiment lend insight into the relative impact that differing USMC artillery employment methods make in a counterbattery scenario against current USMC and Russian capabilities.

3. Experiment Three: Optimize the Force—Blue Factors

Holding Red forces constant, as in experiments one and two, experiment three varies all equipment-based and TTP-based factors for Blue. The results of this experiment lend insight into the most significant factors for optimal USMC configuration for lethality and survivability against the best approximation of the current Russian artillery force.

4. Experiment Four: Hedge the Construct—Blue and Red Factors, Robust Experiment

Experiments one, two, and three model various Blue constructs against a best-approximation Red force. Experiment four varies both Blue and Red factors. By varying Red factors through a carefully selected range of factor levels, true Russian capabilities are likely captured within the design space. The results of experiment four lend insight into the most robust USMC configuration to address a Russian artillery force of uncertain capability.

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V. DESIGN OF EXPERIMENTS

An efficient DOE strives to balance competing priorities of maximizing the quality of data to determine the relative importance of various factors and minimizing the computational work required. This chapter defines the factors explored in each experiment, establishes the levels between which these factors vary, discusses the manner in which each efficient DOE was constructed, and discusses the determination of adequate replications.

A. EXPERIMENT ONE: FIGHT TONIGHT—BASE CASE

In experiment one, both Blue and Red are built as a best approximation of current USMC and Russian capabilities and tactics. See Appendix B for a summary of current conventional USMC and Russian forces used to construct Blue and Red for the base case.

As no factors are varied, a DOE is not required for experiment one. The stochastic nature of MANA introduces variability across multiple simulation runs. The variance across replications serves as a benchmark for the range of expected results if the two conventional forces engage as currently constructed. The base case is run for 200 replications, and results are presented in Chapter VI.

B. EXPERIMENT TWO: TRAIN TOMORROW—BLUE EMPLOYMENT

Experiment two examines the relative differences in Blue lethality and survivability by varying the employment method used. The employment method, which is determined by four different MANA simulation scenarios, is the only factor varied. For each of the four employment methods, 200 replications were conducted.

Although results are presented in Chapter VI, the results were influential in determining the number of replications required for subsequent experiments and thus are discussed in this section.

A power analysis is conducted to determine the number of replications sufficient for each design point in subsequent experiments. After each employment method was run for 200 replications, histograms for Blue Casualties were plotted and the standard deviation

was estimated. The case with the largest standard deviation was selected to calculate the sample size required.

The calculation used to determine sufficient sample size is

$$n = \left(\frac{\sigma(Z_\alpha + Z_\beta)}{(\mu_0 - \mu') } \right)^2$$

where σ is the standard deviation estimate, Z_α is the z-score for the desired confidence interval capability, Z_β is the z-score for power, $\mu_0 - \mu'$ is the practical difference to be detected, and n is the sample size required.

Blue Casualties displayed the highest standard deviation of 3.22 in the Distributed case. With a desired 95% confidence interval ($Z_\alpha = 1.96$), power of 0.85 ($Z_\beta = 1.04$), and practical difference of Blue Casualty detection of one, the resulting minimum sample size was calculated (n) as 94. For convenience, this was rounded to 100. Therefore, for subsequent experiments, 100 replications per design point is used to achieve 95% confidence intervals and 85% power for detecting a difference of one Blue casualty. Figure 20 shows the graphical determination of sample size given a desired Blue Casualty detection resolution of one and 95% confidence intervals with a power of 0.85.

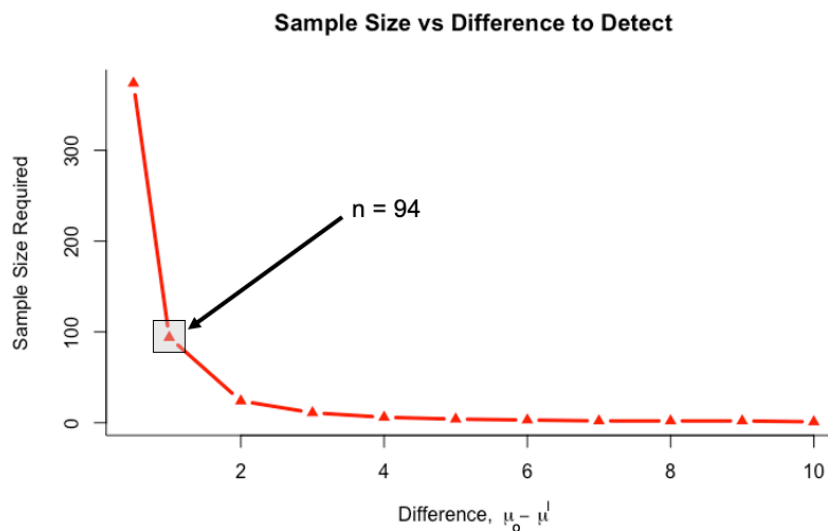


Figure 20. Power Analysis, Sample Size Determination

C. EXPERIMENT THREE: OPTIMIZE THE FORCE—BLUE FACTORS

In experiment three, Blue factors are varied against a best approximated Red force. Having identified the model data input corresponding to each factor and simulation scenario for each Employment Method level, a DOE is built to vary the factors over an interval of levels. Figure 21 displays a summary of Blue factors varied in experiment three.

Categorical						
Factor Num	Factor Name	Factor Type	Levels			Notes
1	Blue Employment	Categorical	Consolidated, SpltBtry, Sections, Distributed			(4) Separate Scenarios created, common situation, different employment method
2	Blue Caliber / Projectile Strength	Categorical (and continuous for armor penetration)	155mm, 105mm			105mm Range to Center 1/2 that of current 155mm Range to Center i.e 155 RtC currently 5, 50, 100, so 105mm RtC is 2.5, 25, 50 Armor Penetration 155mm Prob Penetration vary from 0.4 to 0.6 105mm Prob Penetration vary from 0.2 to 0.4

Discrete/Continuous						
Factor Num	Factor Name	Factor Type	Low	High	Units	Notes
3	Blue Time Until Survivability Move	Continuous	300 (5)	1200 (20)	sec (min)	Time gun squad will remain in position prior to conducting a survivability move (if no actions occur while in position)
4	Blue Displacement After Incoming	Discrete	0 (0)	300 (5)	sec (min)	Time gun squad will remain in position after receiving effective fire
5	Blue Offensive Rate of Fire (sustained)	Discrete	2 (4/100)	6 (10/100)	rds/min (rds/sec)	Rate of fire in Spare 3 (standard mission) 2 rds/min == 4/100 rds/sec, 6 rds/min == 10/100 rds/sec Levels by 1 (2, 3, 4, 5, 6)
6	Blue Defensive Rate of Fire (rapid)	Discrete	4 (7/100)	10 (17/100)	rds/min (rds/sec)	Rate of fire in Squad Shot At (defensive fires/increased rate) 4 rds/min == 7/100 rds/sec, 10 rds/min == 17/100 rds/sec Levels by 1 (4, 5, 6, 7, 8, 9, 10)
7	Blue Concealment/ Camouflage	Continuous	0	90	pct	Concealment when masked in position (affects UAS capability to identify)
8	Blue Emplacement Time	Continuous	30 (0.5)	480 (8)	sec (min)	Length of emplacement, time from Reach Waypoint to fallback to Spare 3
9	Blue Displacement Time	Continuous	30 (0.5)	480 (8)	sec (min)	Length of displacement, time from Spare 2 to fallback to Spare 1
10	Blue Max Range	Continuous	14000 (14)	30000 (30)	meters (km)	Maximum range of weapon system (30000 ~ ERM777A2, 14000 ~ range M119)

Figure 21. Experiment Three Factor and Level Summary

In total, 10 factors are identified for evaluation. These include two categorical, five continuous, and three discrete factors. Each categorical factor has a specific number of levels. The levels for Blue Employment Method are the four employment methods and is controlled by the four separate simulation scenarios. The Blue Caliber/Projectile Strength

factor includes the 155mm and 105mm projectile, each with respective kinetic strength and armor penetration probabilities. The discrete and continuous factors are varied over an appropriate range of factor levels. The Low and High columns establish the lower and upper bound of each continuous and discrete factor range. To construct an efficient DOE over all factors, component DOEs are constructed and crossed. Each component DOE has properties that make it a good choice for its purpose, and the final design yields the benefit of having used each component piece to accomplish a specific goal.

First, a full factorial is constructed over the categorical factors. This establishes a design point for each unique combination of categorical factor levels. The full factorial of categorical factors results in an eight-design point DOE, as seen in Figure 22.

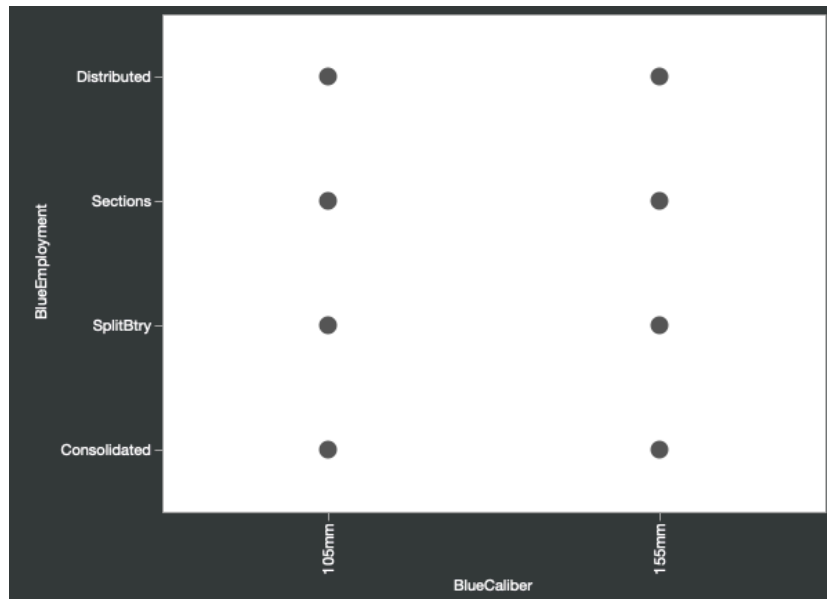


Figure 22. Categorical Factor Full Factorial Design

The discrete and continuous factors can be evaluated over a three-dimensional design space, visualized as a cube. The Resolution IV Fractional Factorial establishes the corner points, or most extreme points, of the cube. The Resolution IV Fractional Factorial only evaluates the maximum and minimum factor levels and guarantees that main effects are not aliased with two-way interactions. The Resolution IV Fractional Factorial results

in a 16-design-point DOE. Figure 23 shows how the Resolution IV Fractional Factorial establishes the corner points of the cube for three of the factors.

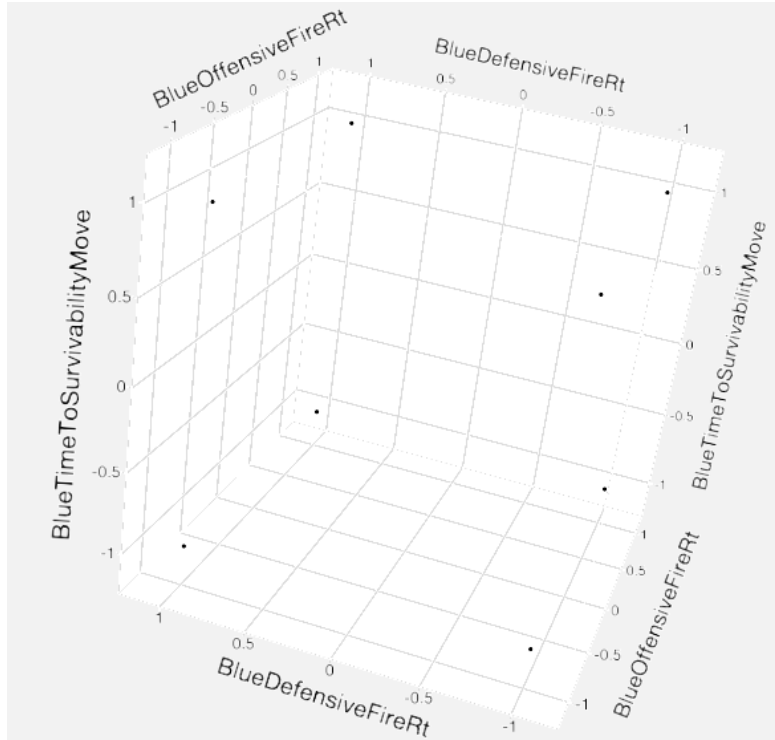


Figure 23. Discrete and Continuous Factor Scaled Resolution IV Fractional Factorial Design

Having established the corner points of the discrete and continuous cube in the Resolution IV Fractional Factorial, the cube is then filled in using a Nearly Orthogonal and Balanced (NOB) design. A design is called nearly orthogonal if the absolute maximum pairwise correlation between any two columns of the design matrix is less than 0.05 (Hernandez et al. 2012). This will ensure minimal multicollinearity affects for main effect terms. The balance property ensures that each level of each factor is (ideally) equally sampled. The NOB is an efficient, space-filling, and flexible design which can handle multiple factor types (Vieira et al. 2013). The NOBs in this research were calculated using a genetic algorithm (MacCalman et al. 2017). The constructed NOB results in a 25-design-point DOE. Figure 24 shows the interior space-filling achieved with the NOB.

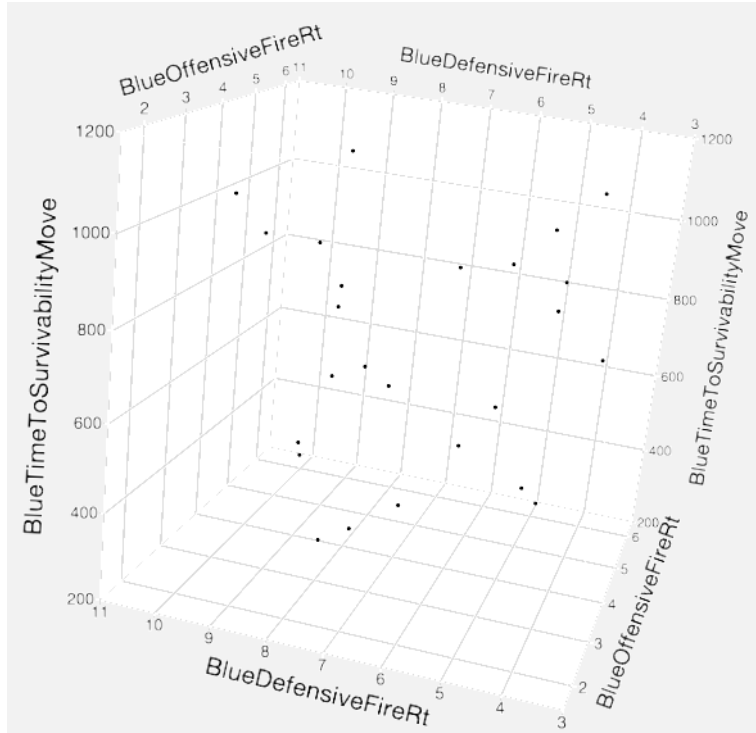


Figure 24. Discrete and Continuous Factor Nearly Orthogonal and Balanced Design

The 16 design point Resolution IV Fractional Factorial and 25 design point NOB are combined together to complete the discrete and continuous design space, resulting in a 41 design point DOE. Figure 25 shows the corner points established in the Resolution IV Fractional Factorial and the space filling points from the NOB for three factors.

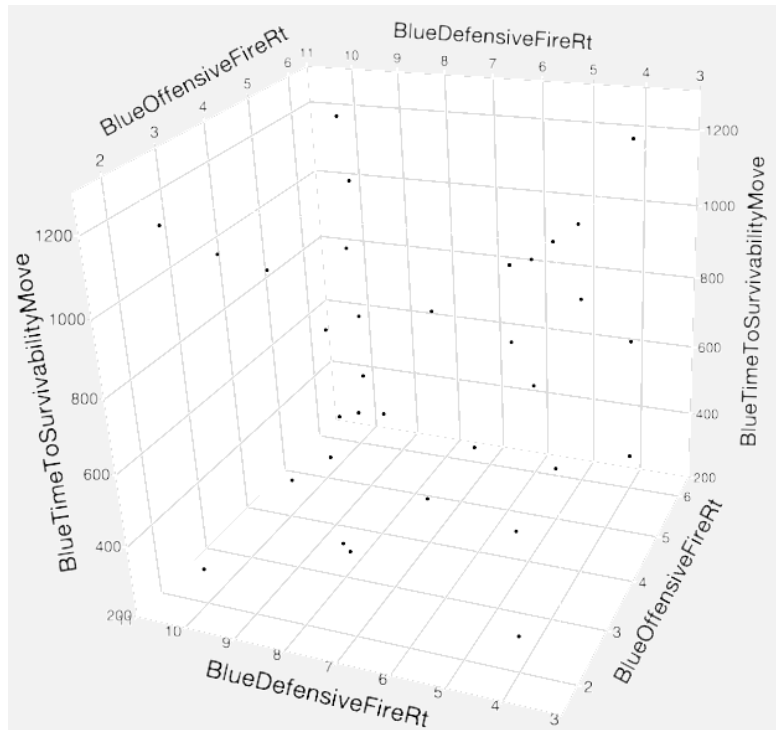


Figure 25. Discrete and Continuous Factor Res IV Full Factorial + NOB Design

Finally, the eight design point categorical full factorial DOE is crossed with the 41 design point NOB, resulting in a final 328 design point DOE for this experiment. Crossing the design over important categorical factors with the design for the discrete and continuous factors is desirable when computationally feasible because it allows every combination of the categorical factors to be run against exactly the same set of other factor variations. Figure 26 visualizes how the eight design point categorical full factorial crossed with the Resolution IV Fractional Factorial plus NOB creates a cube design space for each unique combination of categorical factors.

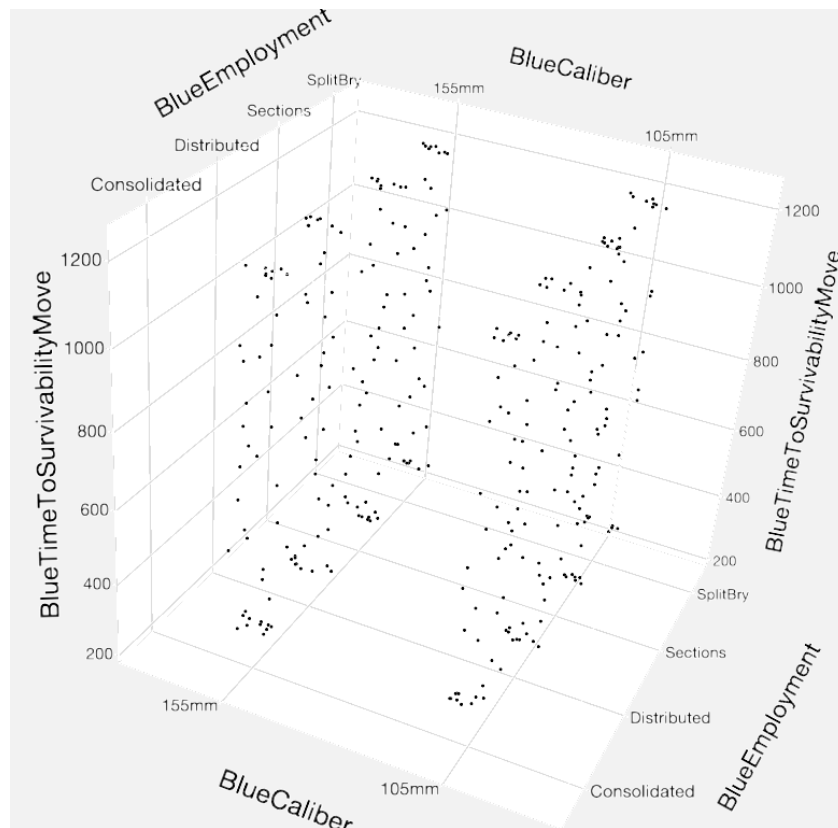


Figure 26. Full Factorial Crossed with (Res IV Fractional Factorial + NOB) Final Design

D. EXPERIMENT FOUR: HEDGE THE CONSTRUCT—BLUE AND RED FACTORS, ROBUST EXPERIMENT

In experiment four, both Blue and Red factors are varied. By varying factors on both sides, robust solutions can be attained. A robust solution for Blue is one in which the Blue construct is “not overly sensitive to small changes in the [Red] inputs” (Sanchez et al. 2020). By varying Red factors over carefully selected levels, true Russian capabilities are likely captured at some point in the design space. The intent of the robust experiment is to determine an optimal Blue construct that is resilient to variations in Red factors.

Figure 27 displays a summary of the two Blue and one Red categorical factors varied in experiment four. Factors one and two are identical to those in experiment three. Factor three, or Red MLRS, evaluates two levels. The first level imagines a composite Red force consisting of two cannon batteries and one MLRS battery, as previously assumed in

experiments one through three. The second level imagines a pure Red force consisting of three identical cannon batteries and no MLRS battery.

<i>Categorical</i>				
Factor Num	Factor Name	Factor Type	Levels	Notes
1	Blue Employment	Categorical	Consolidated, SpltBtry, Sections, Distributed	(4) Separate Scenarios created, common situation, different employment method
2	Blue Caliber / Projectile Strength	Categorical (and continuous for armor penetration)	155mm, 105mm	105mm Range to Center 1/2 that of current 155mm Range to Center i.e 155 RtC currently 5, 50, 100, so 105mm RtC is 2.5, 25, 50 Armor Penetration 155mm Prob Penetration vary from 0.4 to 0.6 105mm Prob Penetration vary from 0.2 to 0.4
3	Red MLRS (Y/N?)	Categorical	MLRS, No MLRS	If Yes, Red constructed with (2) cannon batteries and (1) MLRS battery If No, Red constructed with (3) cannon batteries and (0) MLRS battery

Figure 27. Experiment Four Categorical Factors and Levels Summary

Figure 28 displays a summary of the eight Blue and eight Red discrete and continuous factors varied in experiment four. Blue and Red vary the same factors in seven of eight respective cases, albeit with different factor levels unique to each side. The factor unique to Blue is Time to Survivability Move. Red does not consider this factor as it maintains defensive positions with no survivability moves conducted. The factor unique to Red is Armor Thickness. Blue does not consider this factor as Blue does not currently possess armor and will likely not pursue armored equipment due to deployable weight limitations.

Discrete/Continuous						
Factor Num	Factor Name	Factor Type	Low	High	Units	Notes
4	Blue Time Until Survivability Move	Continuous	300 (5)	1200 (20)	sec (min)	Time gun squad will remain in position prior to conducting a survivability move (if no actions occur while in position)
5	Blue Displacement After Incoming	Continuous	0 (0)	300 (5)	sec (min)	Time gun squad will remain in position after receiving effective fire
6	Blue Offensive Rate of Fire (sustained)	Discrete	2 (4/100)	6 (10/100)	rds/min (rds/sec)	Rate of fire in Spare 3 (standard mission) 2 rds/min == 4/100 rds/sec, 6 rds/min == 10/100 rds/sec Levels by 1 (2, 3, 4, 5, 6)
7	Blue Defensive Rate of Fire (rapid)	Discrete	4 (7/100)	10 (17/100)	rds/min (rds/sec)	Rate of fire in Squad Shot At (defensive fires/increased rate) 4 rds/min == 7/100 rds/sec, 10 rds/min == 17/100 rds/sec Levels by 1 (4, 5, 6, 7, 8, 9, 10)
8	Blue Concealment/ Camouflage	Continuous	0	90	pct	Concealment when masked in position (affects UAS capability to identify)
9	Blue Emplacement Time	Continuous	30 (0.5)	480 (8)	sec (min)	Length of emplacement, time from Reach Waypoint to fallback to Spare 3
10	Blue Displacement Time	Continuous	30 (0.5)	480 (8)	sec (min)	Length of displacement, time from Spare 2 to fallback to Spare 1
11	Blue Max Range	Continuous	14000 (14)	30000 (30)	meters (km)	Maximum range of weapon system (30000 ~ ERM777A2, 14000 ~ range M119)
12	Red Armor Thickness	Continuous	0	30	mm	Armor thickness of Red cannon squads
13	Red Displacement After Incoming	Continuous	1 (0)	300 (5)	sec (min)	Time gun squad will remain in position after receiving effective fire
14	Red Offensive Rate of Fire (sustained)	Discrete	2 (4/100)	10 (17/100)	rds/min (rds/sec)	Rate of fire in Default State (standard mission) 2 rds/min == 4/100 rds/sec, 10 rds/min == 17/100 rds/sec Levels by 1 (2, 3, 4, ..., 17)
15	Red Defensive Rate of Fire (rapid)	Discrete	4 (7/100)	12 (21/100)	rds/min (rds/sec)	Rate of fire in Squad Shot At (defensive fires/increased rate) 4 rds/min == 7/100 rds/sec, 12 rds/min == 21/100 rds/sec Levels by 1 (4, 5, 6, ..., 21)
16	Red Concealment/ Camouflage	Continuous	0	90	pct	Concealment when masked in position (affects UAS capability to identify)
17	Red Emplacement Time	Continuous	30 (0.5)	480 (8)	sec (min)	Length of emplacement, time from Reach Waypoint to fallback to Default State
18	Red Displacement Time	Continuous	30 (0.5)	480 (8)	sec (min)	Length of displacement, time from Spare 2 to fallback to Spare 1
19	Red Max Range	Continuous	14000 (14)	30000 (30)	meters (km)	Maximum range of weapon system (30000 ~ ERM777A2, 14000 ~ range M119)

Figure 28. Experiment Four Discrete and Continuous Factors and Levels Summary

The DOE for experiment four is constructed in the same manner as experiment three with one additional step. Sub-DOEs are constructed for both Red and Blue by crossing the categorical full factorial with the combination of the discrete and continuous NOB and Resolution III fractional factorial. After Blue and Red sub-DOEs are constructed, the sub-DOEs are crossed. The final DOE for experiment four consists of 13,456 design points, significantly more than the 328 design points obtained in experiment three.

E. IMPORTANCE OF EFFICIENT DESIGN OF EXPERIMENTS

The importance of efficient space-filling design of experiments cannot be overstated. As an example, the experiment four DOE obtained using efficient designs with good space-filling properties results in 13,456 design points. Assuming 180 processors available on a cluster computer, 20 second replication run times, and 100 replications per design point, experiment four can be completed in 1.7 days. If a full factorial of all factors were constructed, evaluating discrete and continuous factors at only three levels (low, mid, and high), the full factorial design would result in 688,747,536 design points. Under the same cluster computer, replication run time, and replications per design point assumptions, this theorized full factorial would take over 242 years to run.

In the above example, one might be led to believe that more explanatory information is captured in the exhaustive full factorial design. This is not necessarily the case. The theorized full factorial evaluates discrete and continuous factors at only three levels, whereas the efficient DOE evaluates throughout the factor level space. This is the principal benefit of the space-filling properties of the NOB. Although the full factorial's high number of design points enables better estimation of second order effects, the more efficient space-filling design allows for the possibility for estimating effects higher than second order (as it is not limited to three levels per factor) and detecting change points (Cioppa and Lucas 2007).

By implementing efficient designs of experiment, computational time is reduced, and high order effect analysis is possible. In totality, this thesis evaluated 13,788 design points over the course of the four experiments, for a total of over 1.3 million simulated artillery engagements. The total run time for this thesis was less than 48 hours.

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VI. ANALYSIS

This chapter presents analysis for each of the four experiments developed in Chapters IV and V. The sequential experiment methodology progressively builds intuition into the research objectives of this study, informed by identifying factor significance for lethality and survivability. As equipment and TTP based factors are identified as significant, findings lead to the development of a TTP decision tree to assist commanders in selecting the most advantageous tactics for success in a counterbattery fight. The chapter concludes with a discussion about robust Blue artillery constructs against both a hybrid and cannon-pure Red force construct.

A. EXPERIMENT ONE: FIGHT TONIGHT—BASE CASE

In experiment one, Blue and Red are constructed with equipment attributes mirroring current respective USMC and Russian capabilities and conventional employment methods. The experiment establishes a baseline for the range of possibilities that may be seen if the two forces were to engage as currently equipped and deployed. No factors are changed in experiment one, and the simulation is run for 200 independent replications.

1. Experiment One Analysis

This thesis defines a casualty as a destroyed artillery piece. As seen in Figure 29, Blue forces often exhibit higher casualties than Red. The median Blue casualties are 15, or 83% of Blue artillery pieces, while Red sustains median casualties of six, or 33% of Red artillery pieces. Given the shape and modality of the histograms for Blue and Red casualties, it is observed that Red is frequently dominant in terms of lethality and survivability. It is also striking how much natural variability there is, as Blue losses range from six to 18 artillery pieces and Red's from zero to 13.

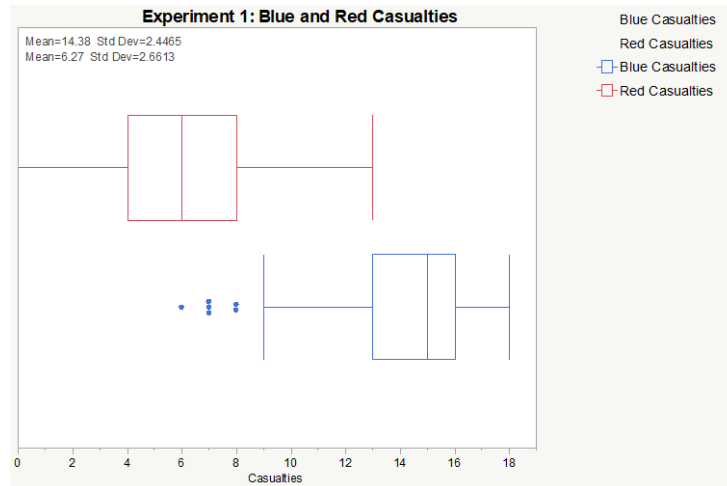


Figure 29. Base Case Casualties

This thesis assumes that attriting Red artillery pieces to half the original force level is favorable for Blue to continue its seizure of the expeditionary airfield. For a time-based perspective, the time at which 50% of the Red artillery force is killed is evaluated. In experiment one, Blue was successful at achieving at least 50% Red attrition only 38 times, or 19% of all simulations. In other words, Blue failed to shape the battlefield for success in 81% of all replications. Figure 30 shows that in these 38 cases, it took Blue between 65 and 158 minutes to achieve this goal, with a mean time of 108 minutes. While this metric is an interesting data point in experiment one, it becomes more significant in subsequent experiments.

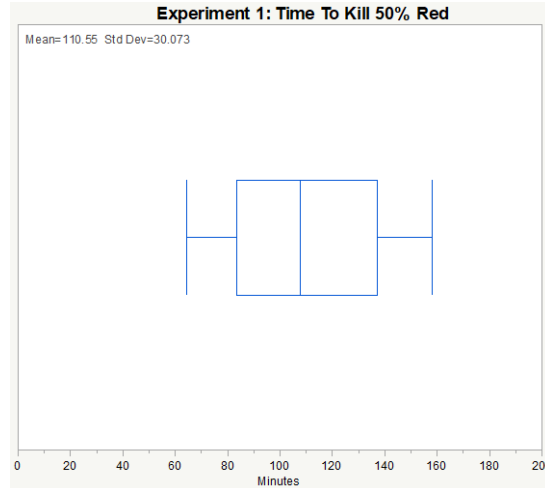


Figure 30. Base Case Time to Kill 50% Red Artillery

Although the flow of logistics is outside of the scope of this study, the amount of ammunition expended by Blue is analyzed to ensure that conceptual equipment and employment constructs are within feasible support bounds. Figure 31 shows the range of total Battalion ammunition expenditures across the 200 base case replications. Although variability remains high, the upmost outlier is below 1,000 rounds, and ammunition expenditure is not outside of feasible bounds. This metric becomes more comparatively powerful in subsequent experiments.

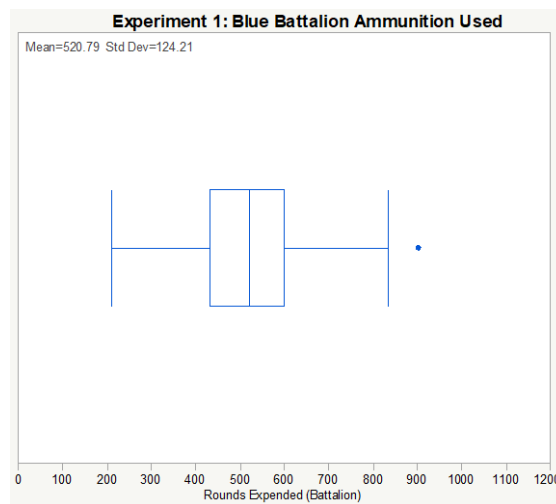


Figure 31. Base Case Blue Battalion Ammunition Used

2. Experiment One Insights

The base case established in experiment one serves as a comparative benchmark for subsequent experiments. The primary insight drawn from experiment one is that, assuming that the simulation is representative of USMC and Russian capabilities and employment, current USMC cannon artillery would sustain high casualties compared to Russian forces and fail to set conditions for success if the forces were to engage in battle as currently constructed. Experiment two builds from this conclusion and evaluates the effect of altering only one factor in the pursuit of tactical superiority.

B. EXPERIMENT TWO: TRAIN TOMORROW—BLUE EMPLOYMENT METHOD

Experiment two maintains the equipment capabilities of current USMC and Russian forces, but alters the employment method of Blue. Unlike developing, testing, and fielding new equipment, the Marine Corps can train to different employment methods immediately. This experiment evaluates the comparative results of these potential training priorities.

1. Experiment Two Analysis

The four employment options, from most concentrated to most dispersed, are consolidated, split battery, section, and distributed. Each employment method simulation is run for 200 independent replications.

Figure 32 displays the casualty boxplots for Blue and Red by various Blue employment methods. A clear trend emerges for both Blue and Red casualties. As the Blue force becomes more dispersed, Blue casualties become lower and Red casualties rise. This is indicative of an increase in both Blue survivability and lethality.

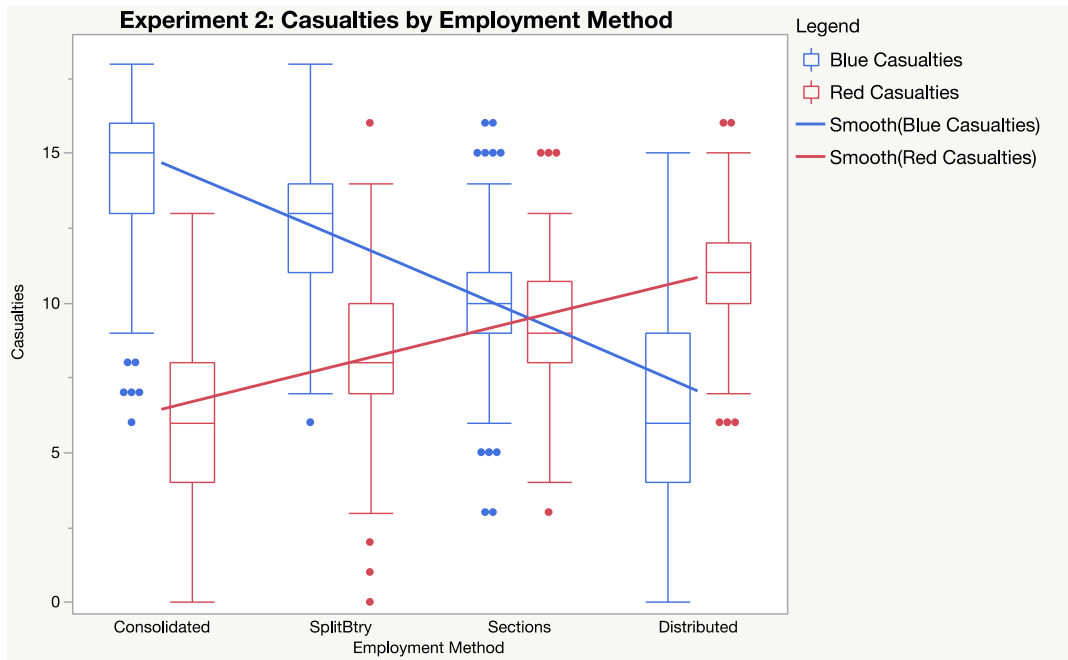


Figure 32. Blue and Red Casualties by Blue Employment Method

With increased dispersion, Blue cannons are less susceptible to catastrophic Red massing of fires. As Blue increases survivability through dispersion, the average lifetime of each Blue artillery piece increases. The survival of more Blue firing pieces equates to more assets available to fire, and tempo (ability to inflict Red casualties rapidly) and momentum for Blue is increased.

Near parity in casualty medians is achieved in the section employment method, and Blue gains an advantage in the distributed case. It is important to note that while Blue appears to have an advantage in median casualties in the distributed case, Blue and Red variability remains high.

A Kruskal-Wallis test at the 0.05 significance level results in a P-value less than 0.0001 and confirms that Blue and Red casualty means are not the same for all employment methods (Devore 2014, p. 671). A post-hoc Tukey's procedure produces P-values less than 0.0001 between all employment methods, which supports the assertion that no employment methods share a common mean Red or Blue casualty count (Devore 2014, p. 420).

As dispersion increases, more cases are observed in which at least 50% of Red forces are killed. This is due to the increase in Blue lethality and survivability, and Figure 33 shows the percentage of replications in which Blue reaches this goal.

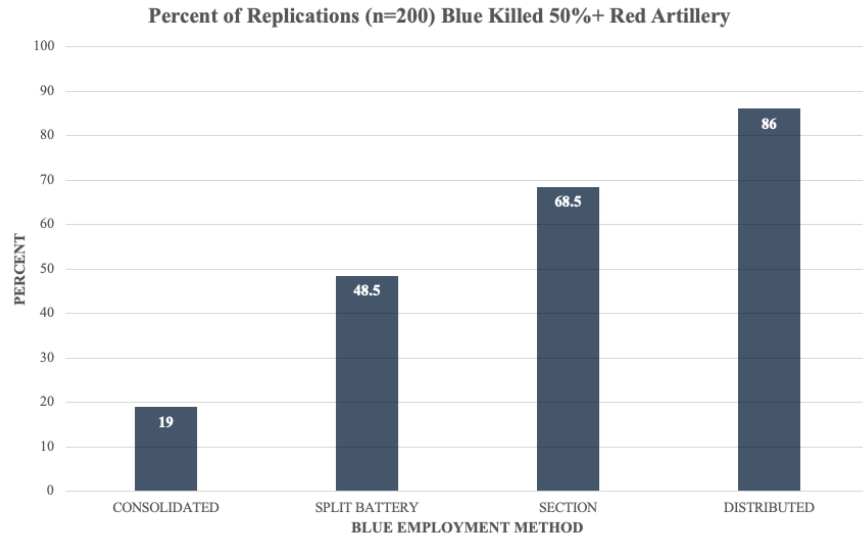


Figure 33. Percentage of Replications in which Blue Kills >50% Red Artillery

Figure 34 shows the boxplots of the time to destroy 50% of Red artillery pieces by employment method. Although the number of replications for which Blue achieves this goal changes based on employment method, the trend is that more Blue dispersion results in a faster time to kill 50% of Red artillery when this goal is met. The slight median increase from consolidated to split battery employment is small, not statistically significant, and is likely due to chance. A Kruskal-Wallis test at the 0.05 significance level results in a P-value less than 0.0001 and confirms time to kill 50% Red artillery medians are not the same for all employment methods (Devore 2014, p. 671).

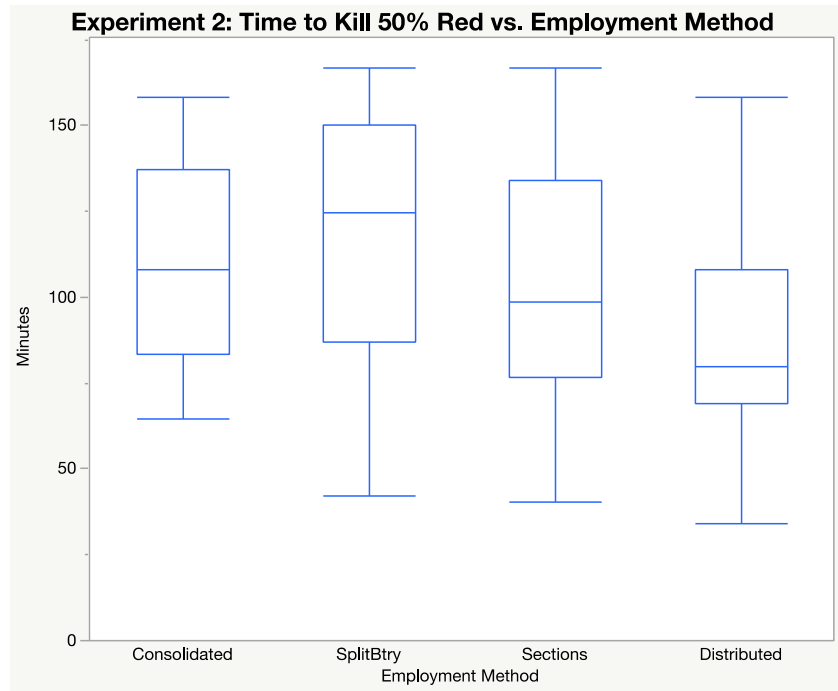


Figure 34. Time to Kill 50% Red Artillery by Employment Method

With a demonstrated relationship between dispersion and survivability, there is an expectation that the quantity of rounds expended by the Blue Battalion increases. Figure 35 shows this increase. However, the increase in rounds expended is not outside of the range of feasible battalion support, even at the upmost outlier in the distributed case. Again, a Kruskal-Wallis test at the 0.05 significance level results in a P-value less than 0.0001 and confirms ammunition expenditure means are not the same for all employment methods (Devore 2014, p. 671).

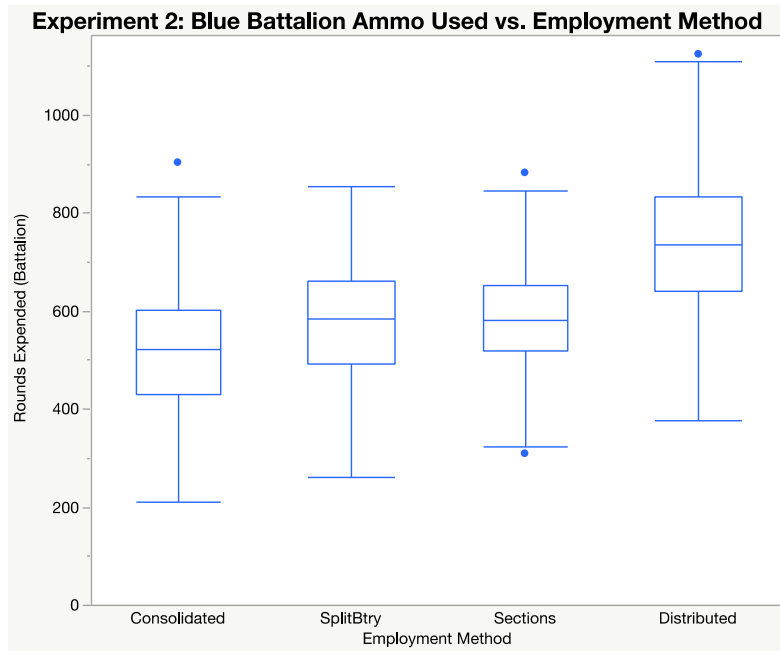


Figure 35. Blue Battalion Ammunition Used by Employment Method

2. Experiment Two Insights

By altering the method by which USMC artillery is employed, a tactical advantage can be gained by Blue while maintaining the current equipment set. By increasing dispersion, Blue gains an increase in both lethality and survivability. The resulting increase in Blue tempo enables Blue to attrit Red below 50% force levels faster, all while maintaining battalion round expenditure within the feasible range of organic ammunition capacity or battalion support.

C. EXPERIMENT THREE: OPTIMIZE THE FORCE—BLUE FACTORS

Experiment three maintains the equipment capabilities of current Red forces, but varies a set of Blue factors. The DOE for experiment three has 328 design points, with 100 replications per design point. For each design point, the 100-replication data is summarized by the mean of Blue and Red casualties.

Figure 36 shows a scatterplot of Blue and Red casualty means for each unique Blue configuration (100 replications each). The blue box shows runs in which Blue sustained less than 50% casualties while inflicting over 50% casualties on Red. The red box shows

the inverse case in which Red inflicted more than 50% casualties on Blue while losing less than 50% Red. Blue and Red casualties are negatively correlated with a correlation of -0.5162 . There are clearly many more cases in which the outcome of the battle was favorable to Red. The intent of the remainder of this analysis for experiment three is to determine which Blue factors are most critical to achieving conditions that lower Blue casualties and increase Red casualties, visualized approximately as the area within the favorable blue box.

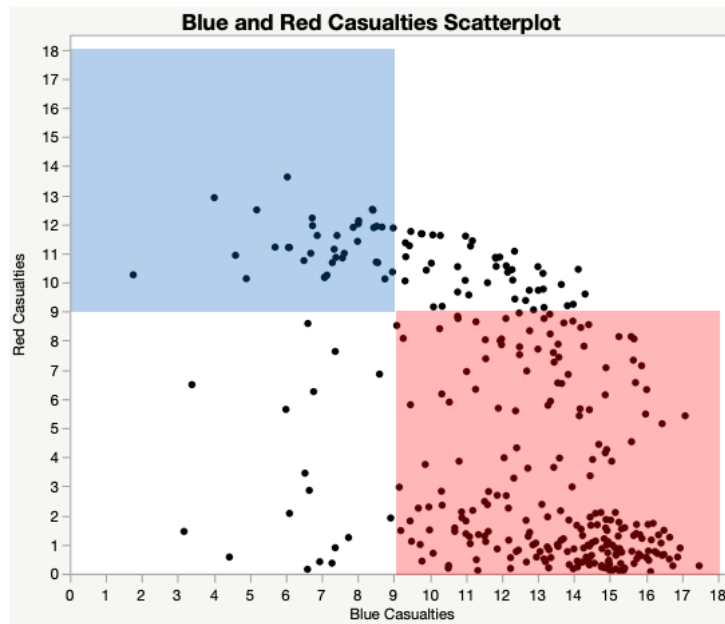


Figure 36. Blue and Red Casualty Scatterplot

Figure 37 shows the histograms of Blue and Red casualties across all 328 summarized design points. Blue casualties are markedly higher than Red with a histogram peak around 15. However, Blue casualties exhibit a long left tail, suggesting that there are solutions in which Blue casualties are much lower. Conversely, the Red casualty histogram has a prominent peak around one but has a long right tail with a prominent dip between the two modes. This dip is indicative of an influential factor or interaction with a subset of Blue factors.

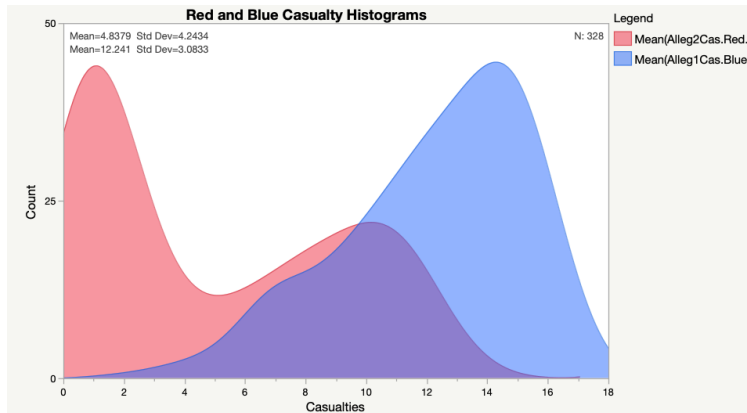


Figure 37. Red and Blue Casualty Histograms

1. Blue Lethality Partition Tree

To identify which factors most influence Red casualties, a partition tree is created using Red casualties as the response, as seen in Figure 38. After seven splits, an R-squared value of 0.91 is obtained, as seen in the yellow box. An R-squared value of this magnitude achieved from a stochastic, mission-level model is powerful, and suggests that 91% of Red casualties in the simulation can be explained within the seven splits.

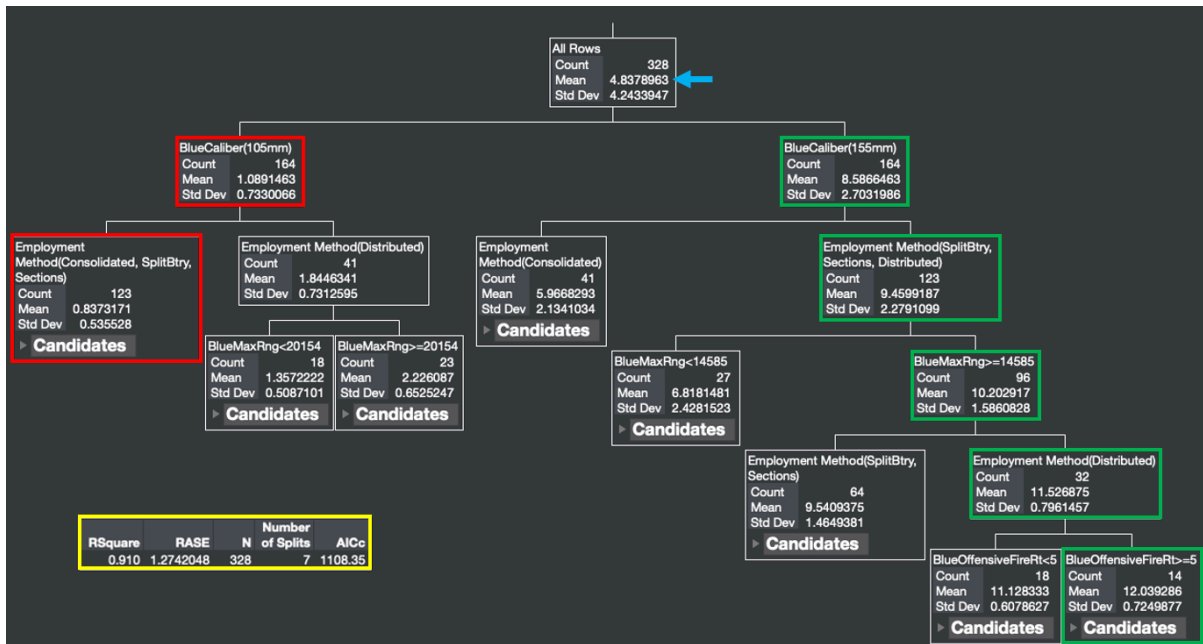


Figure 38. Blue Lethality Partition Tree

As the Red casualty mean corresponds with the histogram inner-mode dip (see the blue arrow), it can be reasonably assumed that the first split in the tree will determine what causes the separation between the two modes. The first split is Blue caliber, with Blue 155mm dramatically raising Red casualties. The scenarios in which Blue used 105mm howitzers resulted in mean Red casualties of 1.09 and a small standard deviation of 0.73, as seen in the top red box. This shows that Blue caliber is the dominant factor in determining Red casualties, or Blue lethality.

Continuing down the right most side of the partition tree, the factors for increased Blue lethality are identified in green boxes. Among these are a more distributed employment method (dispersed being ideal), a maximum range above 14,685 meters, and an offensive rate of fire greater than or equal to five rounds per minute.

Figure 39 shows the column contributions for each of the factors. Again, it is noted that Blue caliber is the dominant factor in blue lethality, contributing over 86% explanatory power in the regression tree.

Term	Portion
BlueCaliber	0.8607
Employment Method	0.0916
BlueMaxRng	0.0465
BlueOffensiveFireRt	0.0012
BlueDefensiveFireRt	0.0000
BlueTimeToSurvivabilityMove	0.0000
BlueDisplaceAfterIncoming	0.0000
BlueConcealment	0.0000
BlueEmplaceTime	0.0000
BlueDisplaceTime	0.0000

Figure 39. Blue Lethality Partition Tree Column Contributions

Figure 40 shows a histogram for Red casualties after controlling for Blue caliber. This shows that Blue is at a decisive disadvantage when employing 105mm cannons as its lethality is significantly reduced with the smaller projectile. The two distinct and separate histograms show that the inner-mode dip point initially detected in Figure 37 is due to the subsets of Blue caliber design point simulations.

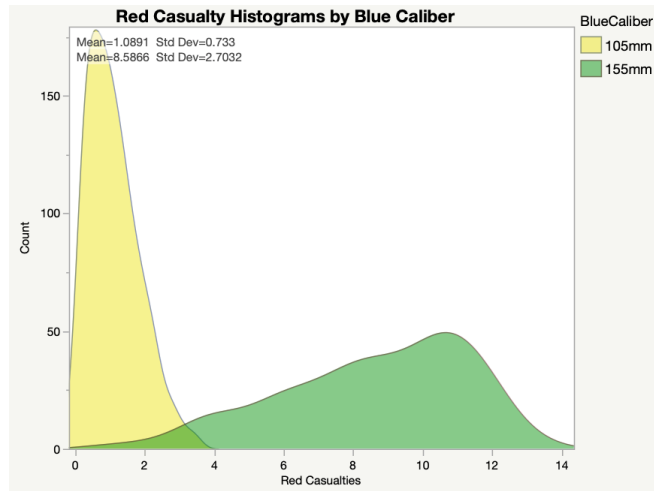


Figure 40. Red Casualty Histograms by Blue Caliber

2. Blue Survivability Partition Tree

Blue survivability is analyzed by creating a regression tree with Blue casualties as the response, as seen in Figure 41. After nine splits, an R-squared value of 0.642 is obtained, as seen in the yellow box. This R-squared value is lower than that obtained for Blue lethality, suggesting that a greater number of factors and interactions influence Blue survivability.

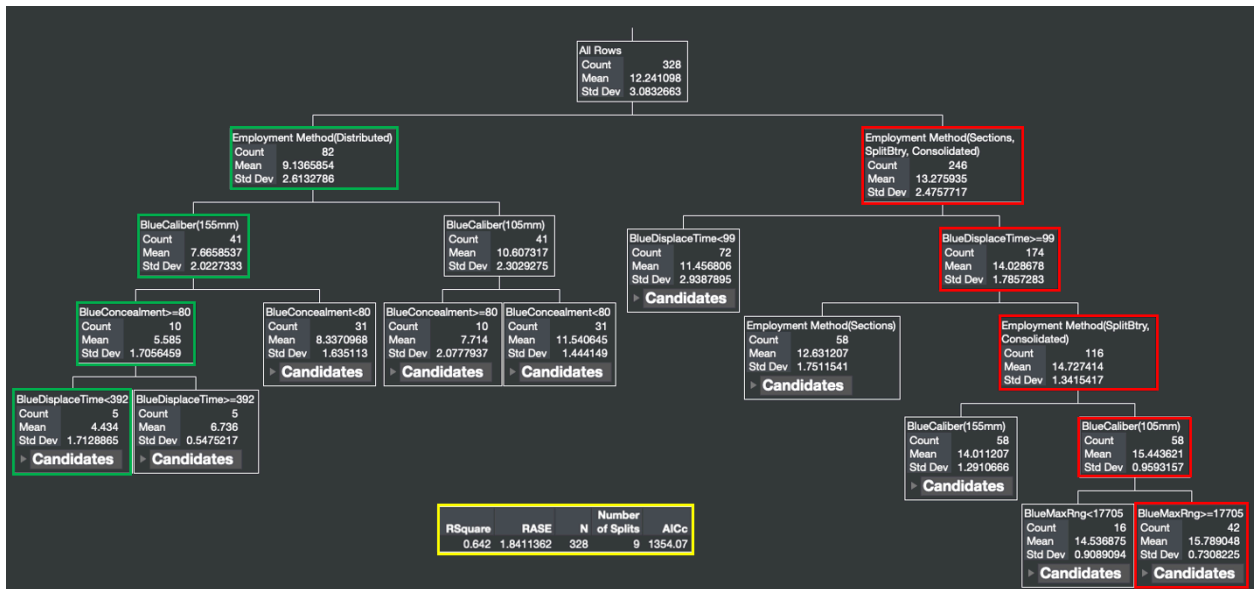


Figure 41. Blue Survivability Partition Tree

The first and most significant split relates to Blue employment method. Reinforcing the findings of experiment two, the distributed employment method results in a reduced number of casualties for Blue. The second most important split for increasing Blue survivability is a selection of 155mm Blue caliber. This suggests that Blue survivability is correlated with Blue lethality. By increasing lethality through a more powerful round (caliber), Blue is able to destroy Red forces faster, thus gaining a tempo advantage.

Along the red branch of the tree, which constitutes the worst conditions for Blue survivability, it is seen that Blue caliber does not appear until the fourth split. The nodes above Blue caliber are employment method and displacement time. If Blue is not able to disperse forces in the dispersed employment method, it is important for Blue to have the capability to displace quickly (within 99 seconds), prior to counterbattery rounds impacting the position.

Figure 42 shows the column contributions to the Blue survivability partition tree. Employment method is vitally important, accounting for over 60% of the explanatory power. Although displacement time only accounts for 18% of the column contributions, it is critical to have a fast displacement time if dispersion of forces cannot be practiced. The 12% contribution for Blue caliber suggests that the capability to destroy Red forces is important for gaining a survivability tempo advantage, perhaps best captured in the adage that ‘the [third] best defense is a good offense.’

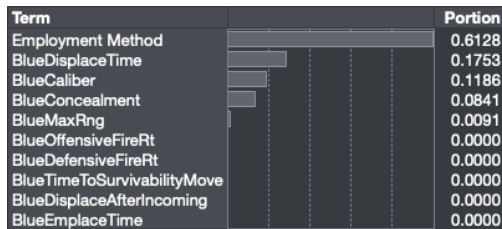


Figure 42. Blue Survivability Partition Tree Column Contributions

3. Partition Tree Dominant Factors

Caliber and employment method are dominant for lethality and survivability, respectively. Figure 43 shows a similar plot to that obtained in experiment two, but now

displayed by caliber in addition to employment method. It is clear that if Blue uses 105mm cannons, lethality is not effectively increased, even when more dispersed. However, when Blue uses 155mm cannons and disperses forces, lethality and survivability both increase dramatically.

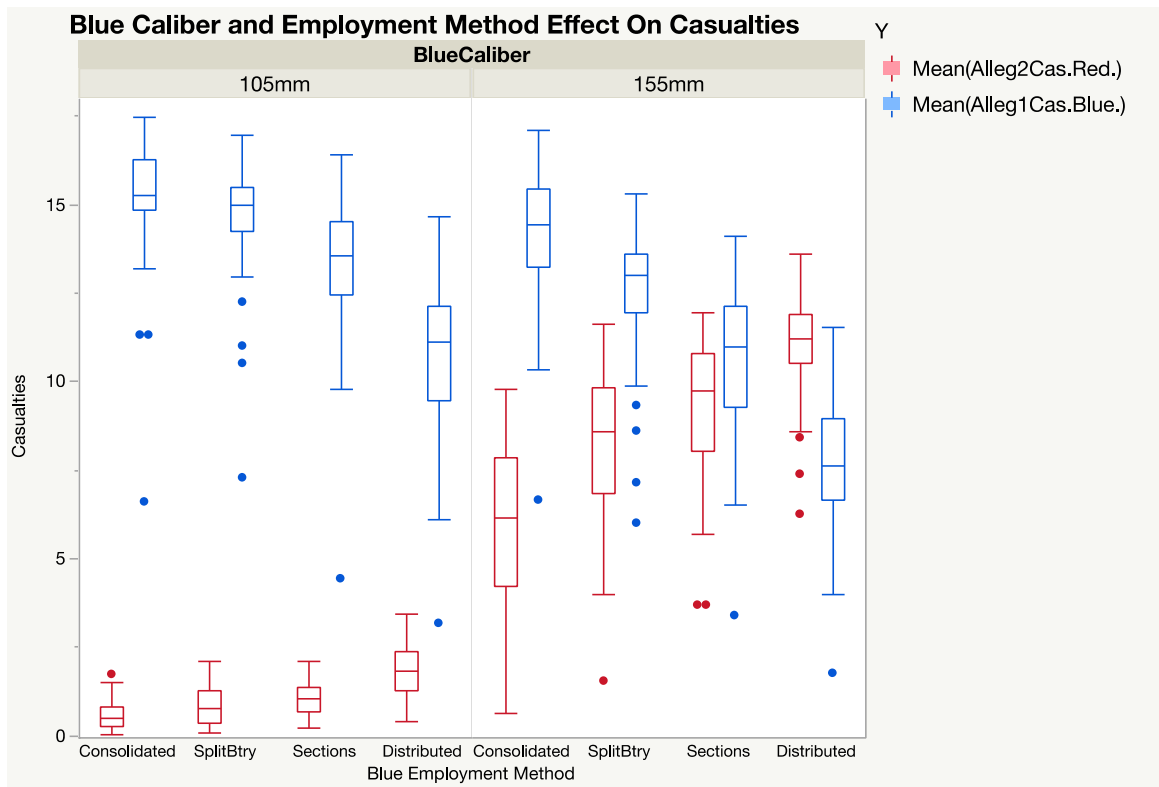


Figure 43. Blue and Red Casualties by Blue Caliber and Employment Method

Referring back to Figure 36, the majority of observations were favorable to Red. After identifying the factors of Blue employment method and caliber as critical to Blue lethality and survivability, the scatterplot is reconstructed, this time displayed by these influential factors, as seen in Figure 44, where Blue and Red boxes represent respective advantages.

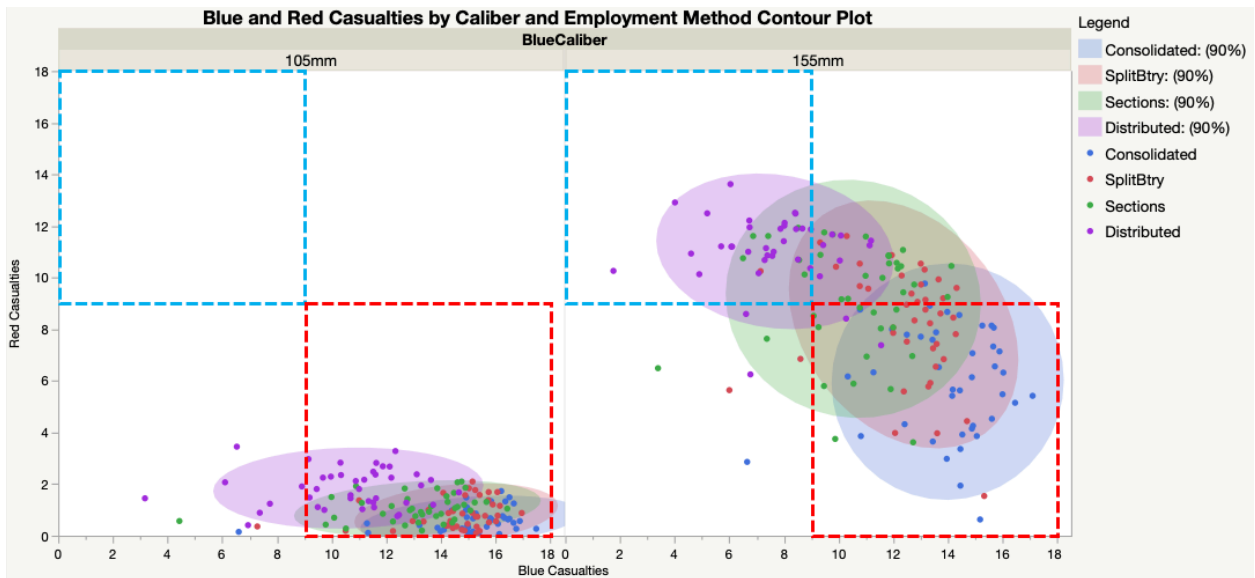


Figure 44. Casualty Clusters by Blue Caliber and Employment Method

Regardless of employment method, a Blue construct with 105mm cannons always results in low Red casualties and mid to high Blue casualties, with the majority of outcomes residing in the unfavorable, red box. However, when constructed with 155mm cannons, the distribution of outcomes is more pronounced and varied for both Blue and Red casualties. Clusters are constructed around different employment methods, with each cluster containing at least 90% of the representative employment method. Although there is significant overlap, it is clear that more dispersion corresponds with fewer Blue casualties and more Red casualties, with the most prominent points in the favorable blue box being 155mm howitzers employed in distributed or section methods.

4. Blue Lethality Linear Regression

A stepwise linear regression metamodel is built using Red casualties (Blue lethality) as the response. Figure 45 provides a summary of important aspects of the Blue lethality model. A full third order model is considered. Using the p-value threshold of 0.01 as the stopping rule, the model is manually stepped until diminishing returns were observed, achieving an adjusted R-squared value of 0.926 (outlined in yellow box). Adjusted R-squared injects a penalty for the number of predictors used in the construction of the model to discourage overfitting. The Residual by Predicted plot appears to produce

an approximate mean residual of zero, but variance is not constant. Therefore, this model does not meet all regression assumptions. However, a great deal (nearly 93%) of variation in the simulation is captured and explained in this metamodel. Moreover, we are using the metamodel not for prediction, but as a readily interpretable approximation to the simulation as a means for understanding (Kleijnen et al. 2005). The author determined that use of a transformation, higher order terms, or different regression method would complicate interpretation while providing little benefit. Therefore, although the model fit is not perfect, the model is considered reasonable and useful for the purpose of this analysis, given that the goal is understanding and not prediction

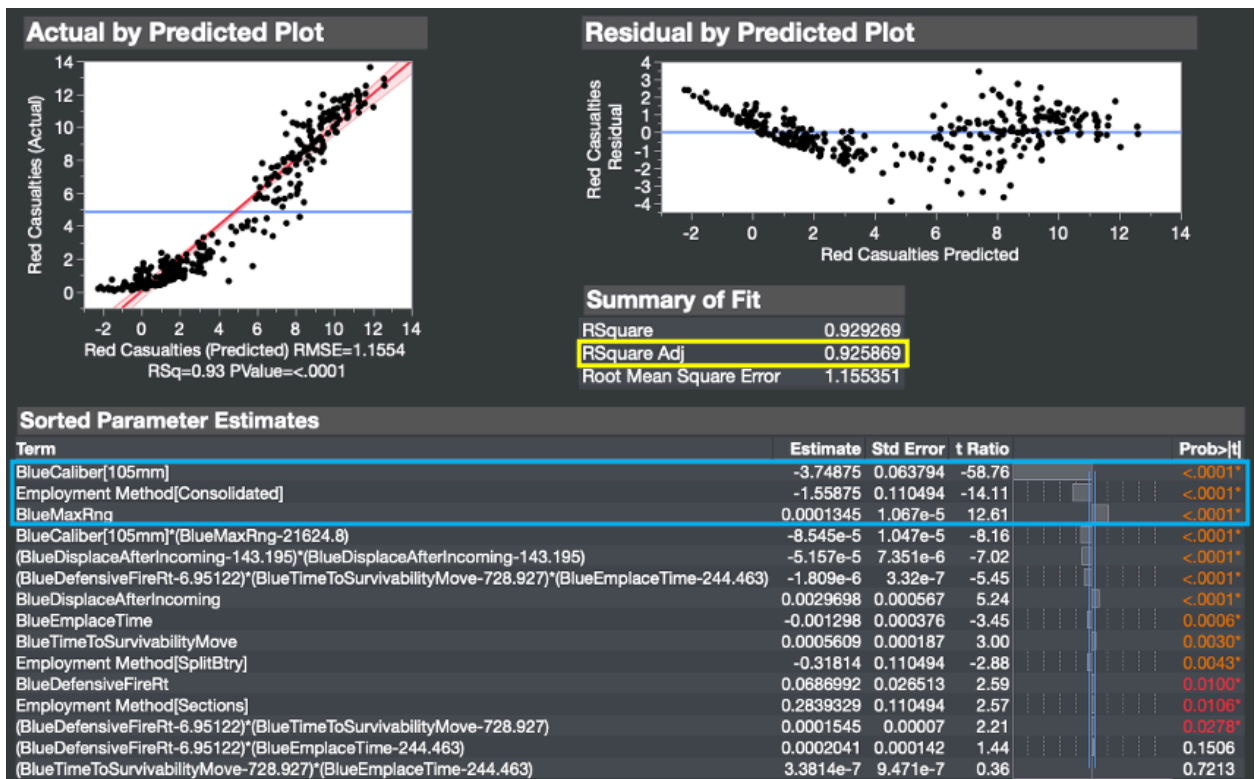


Figure 45. Blue Lethality Linear Regression Model

The sorted parameter estimates display the most significant predictors and interactions in the model, sorted by the absolute value of the t-ratio (magnitude of significance). The three most meaningful predictors for Blue lethality are caliber, employment method, and maximum range (outlined in blue box). The horizontal bar on

the right side of the sorted parameter estimates window offers a visual depiction of the magnitude of significance. The direction of the horizontal bar shows the directionality of the effect on the response (a bar to the left decreases the response, and a bar to the right increases the response). Here, we see that caliber is the dominant factor and is overwhelmingly influential in Blue lethality. The estimate, or coefficient, signifies the extent to which the expected value of the response is affected by the predictor when all other predictors are held constant. For example, the categorical predictor of caliber can take on a value of either 155mm or 105mm. In this model, not including interactions, we see that if Blue uses 105mm cannons, then 3.75 fewer Red casualties (on average) are produced compared to a situation in which Blue uses 155mm cannons. The second most important predictor is consolidated employment method, specifically showing that operating in a consolidated method contributes negatively to Blue lethality. The third most influential predictor is maximum range. As this predictor is continuous, the coefficient (0.0001345) is interpreted as the average main-effect-by-itself increase to Red casualties for every meter of additional range capability. This coefficient means that Blue can produce 0.1345 more Red casualties for every 1000m of additional range, or one additional Red casualty for every 7435m of additional range.

5. Blue Survivability Linear Regression

For Blue survivability, a stepwise linear regression model is built using Blue casualties as the response. Figure 46 provides a summary of important aspects of the Blue survivability model. All possible three-way interactions are considered. Using the p-value threshold of 0.01 as the stopping rule, the model is manually stepped until diminishing returns were observed, achieving an adjusted R-squared value of 0.867 (outlined in yellow box).

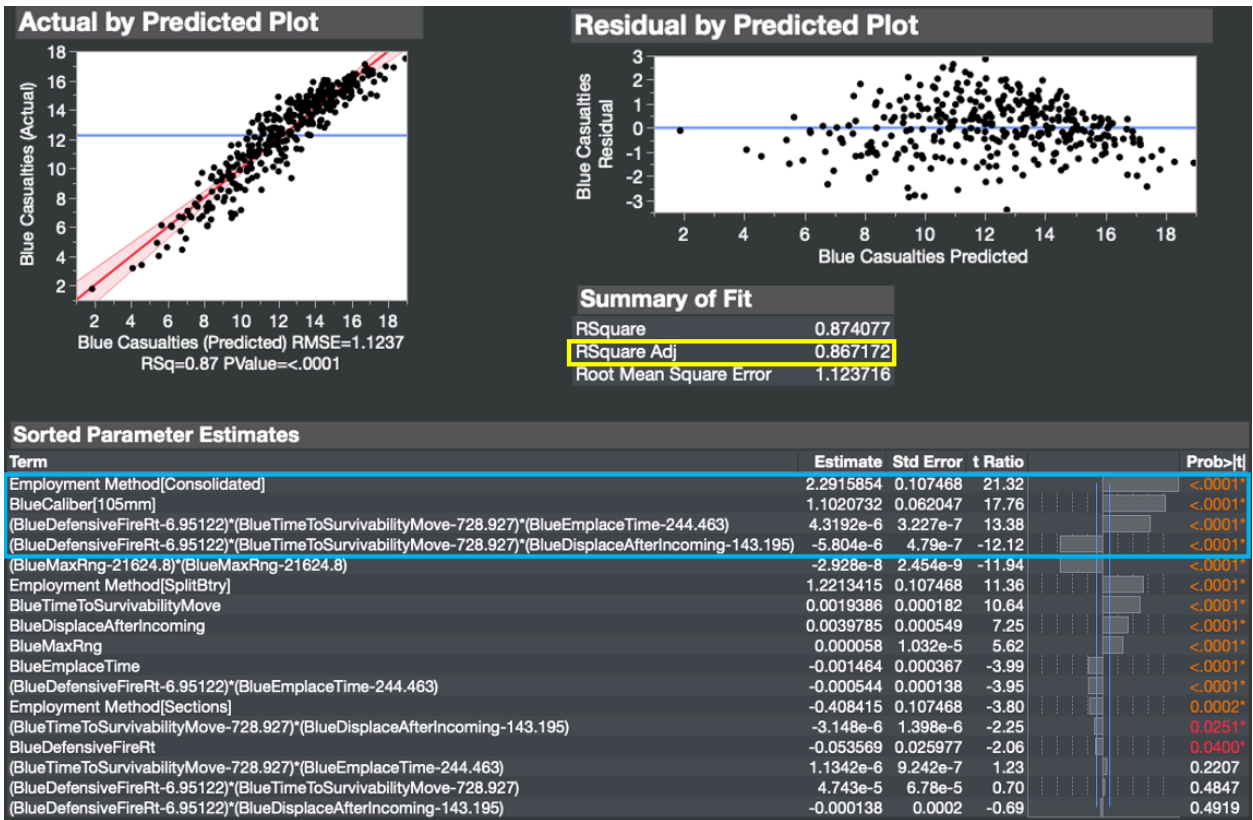


Figure 46. Blue Survivability Linear Regression Model

The most significant predictors for Blue survivability (outlined in blue box) are employment method, caliber, and two three-way interactions. The sorted parameter estimate window does not suggest that any one factor is dominant, but rather that multiple factors are significant for Blue survivability. This is reinforced by the lower adjusted R-squared value as compared to the Blue lethality model.

Similar to the findings in the Blue survivability partition tree, employment method and caliber are the two most significant factors for Blue survivability. Specifically, consolidated employment method should be avoided entirely, as should split battery (appearing as the sixth most important factor). Blue caliber is the second most significant, and it is critical that 155mm be used by Blue to reduce the number of Blue casualties.

The largest benefit of fitting a linear regression model is the consideration and inclusion of two and three-way interactions. The second third and fourth most influential predictors in this model are both three-way interactions involving continuous factors:

defensive fire, time to conduct a survivability move, and time to emplace or time to displace after incoming fire. The simplest interpretation of a three-way interaction is that the interaction between any two factors is dependent on the third. Similarly, a two-way interaction is one in which one variable is dependent on the other. Although three-way interactions and the relationship to the response creates a four-dimensional surface, the effects of each component of the three-way interaction can be plotted carefully to extract insights.

Figure 47 shows the first three-way interaction that appears in the Blue survivability model (third most important predictor). This interaction is comprised of defensive rate of fire, time to survivability move, and emplacement time. The relationship between Blue casualties and the continuous values of these three factors is visualized by reducing defensive rate of fire into two categories ([4-8) rounds per minute and [8-10] rounds per minute), and emplacement time into three categories ([30-135) seconds, [135-374) seconds, and [374-480] seconds). With Blue casualties represented on the Y axis, the direction and magnitude of the slope describes the three-way interaction. For example, on the left-most plot (defensive rate of fire between four and eight rounds per minute), the most positive slope is the blue line, which represents an emplacement time between 30 and 135 seconds. The interpretation is that when defensive rates of fire are low and a unit can be emplaced quickly, the time to survivability move should be kept low. In this situation, Blue casualties grow proportional to the time until a survivability move is conducted.

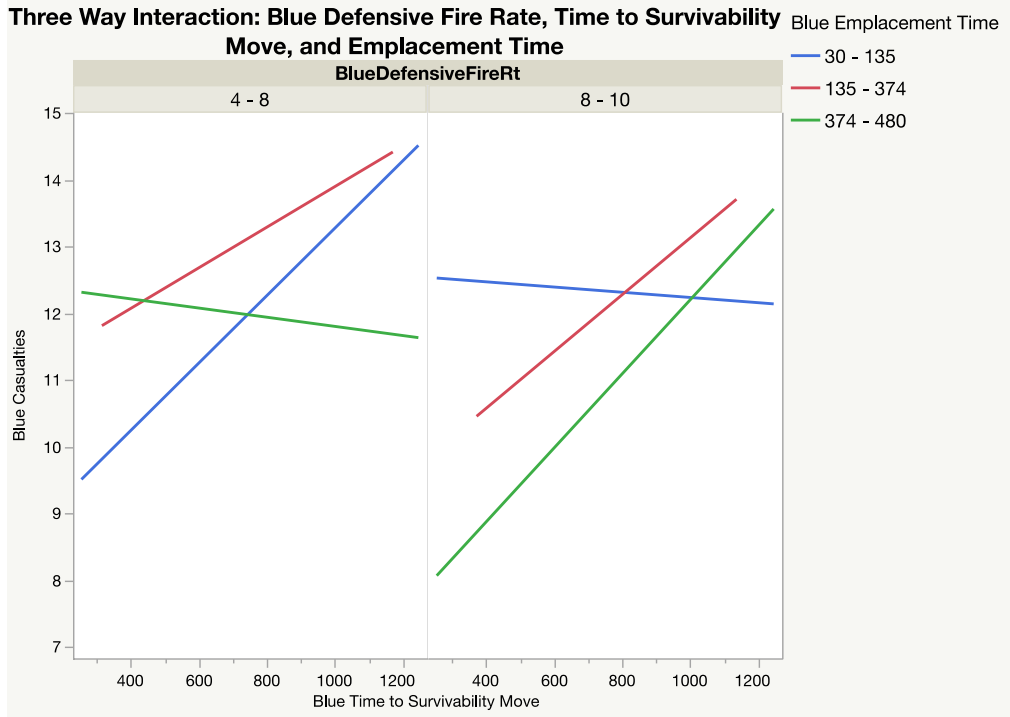


Figure 47. Three-Way Interaction One: Defensive Rate of Fire, Time to Survivability Move, Emplacement Time

The most significant observation in Figure 47 is the change of slope directionality of the blue and green lines from the left plot to the right plot. When defensive rates of fire are low (left plot), and emplacement times are low (blue line), survivability moves should occur with more frequency in order to reduce Blue casualties. This situation allows the quickly emplaceable units to move positions often and reduce the probability of being detected and fired upon, negating the disadvantage of a low defensive rate of fire. However, when defensive rates of fire are low (left plot) and emplacement times are high (green line), then it is advantageous to lengthen the amount of time until a survivability move is conducted. The slope is negative, which means that it is more advantageous to stay FIRECAP (responsive) awaiting missions rather than moving frequently and losing time available to fire due to a long emplacement time.

However, the same relationship is not true when Blue possesses a high defensive rate of fire (right plot). The slopes of the blue and green lines are opposite in directionality compared to low defensive rate of fire. Looking at the green line (long emplacement time)

specifically, a narrative interpretation is that when defensive rate of fire is high, it is more advantageous to remain FIRECAP for a short period of time before conducting a survivability move. While this may be beneficial to survivability (long emplacement times and frequent moves render the agent undetectable for long amounts of time), it likely does not contribute significantly to Blue lethality (non-FIRECAP units are unable to remove Red from the battlefield). A more practical case is the inversed slope of fast emplacement (blue line) units in high defensive rate of fire (right plot) situations. Here, a unit is able to emplace quickly but casualties are decreased when waiting in position for longer. This is because remaining in position offers more opportunities to be detected and fired upon, thereby allowing the unit to take advantage of a fast defensive rate of fire. After counterfiring, the unit is able to move to a new position and emplace quickly. Although an ‘offensive’ and ‘defensive’ rate of fire is more controlled in simulation than real world engagements, this is a testament to the importance of high rate of fire capability.

Figure 48 summarizes this interaction with the TTP decision of time until a survivability move is as a result of unit capabilities of defensive rate of fire and emplacement time.

		Time to Survivability Move Actions to Decrease Blue Casualties	
		Low Defensive ROF (4-8 rpm)	High Defensive ROF (8-10 rpm)
Low Emplacement Time (30-135 sec)		↓ Time to Survivability Move (more frequent moves)	↑ Time to Survivability Move (less frequent moves)
High Emplacement Time (375-480 sec)		↑ Time to Survivability Move (less frequent moves)	↓ Time to Survivability Move (more frequent moves)

Figure 48. Three-Way Interaction One: Decision Summary

Figure 49 shows the second three-way interaction that appears in the Blue survivability model (fourth most important predictor). This interaction is comprised of defensive rate of fire, time to survivability move, and displacement time after receiving incoming fire. Displacement time after receiving incoming fire is synonymous with the amount of time a unit remains in position returning fire (counterfire).

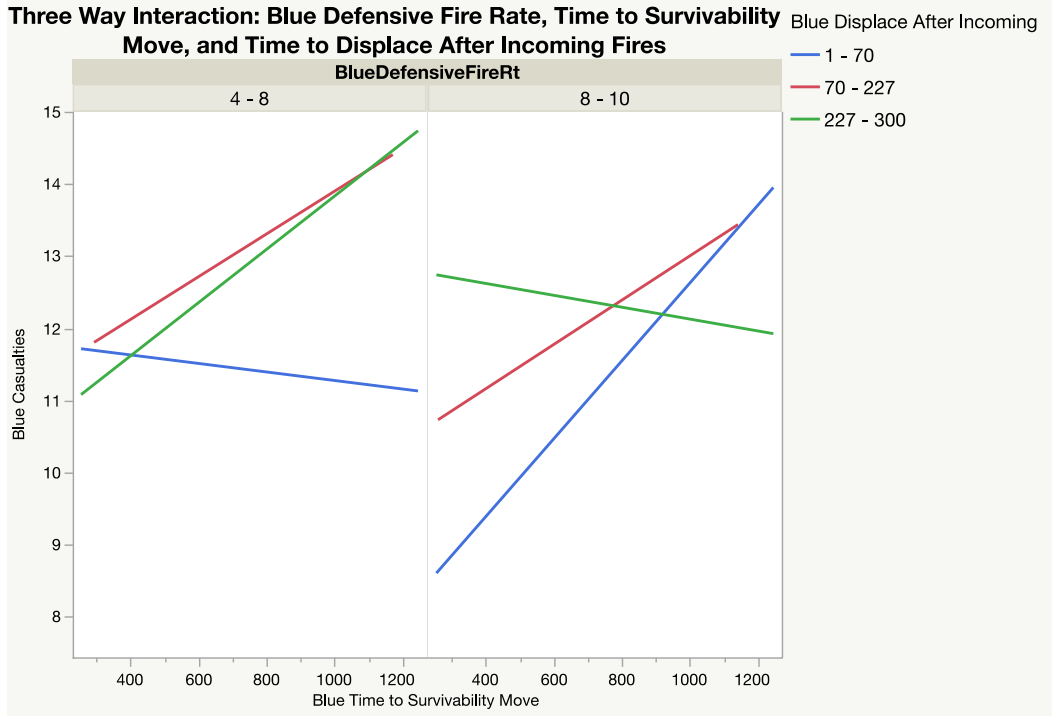


Figure 49. Three-Way Interaction Two: Defensive Rate of Fire, Time to Survivability Move, Displacement After Incoming

Similar to the first interaction, the most significant observation in Figure 49 is the change of slope directionality between the blue and green lines. When defensive rates of fire are low (left plot), and time to return fire after incoming are low (blue line), time until a survivability move should be increased in order to reduce Blue casualties. The interpretation is that if a unit has a low defensive rate of fire and elects to displace quickly after receiving incoming fire, it is advantageous to conduct survivability moves less frequently. This tactic presents the opportunity for a unit to conduct more offensive fire missions with a move most often triggered by the receipt of fires. The opposite is true for

units with a low defensive rate of fire (left plot) and long time to remain in position and return fire (green line). In this situation, a unit with a longer time to remain in position and return fire is better served to reduce the amount of time to a survivability move. If a unit has a low defensive rate of fire and elects to remain in position returning fire for a long amount of time, it is better to decrease the time until a survivability move is conducted. The purpose of this tactic is to continue to move forward and close distance through short survivability move windows while an identical friendly unit continually draws counterfire through a longer counterfire window. By having one Blue unit draw Red fires, sister units are able to take advantage of a higher offensive rate of fire in support.

The inverse relationship is true for the case in which a unit has a high defensive rate of fire (right plot). In this case, a unit with a low time to displacement after incoming fire (blue line) reduces Blue casualties the most when time to survivability move is low. A unit that practices movement quickly after receiving fire is best served by conducting survivability moves frequently. This creates more opportunities for the unit to be fired upon, thereby taking advantage of a fast defensive rate of fire prior to a quick displacement. Conversely, when a unit remains in positions returning fire for a long amount of time (green line), it is advantageous to increase the amount of time until a survivability move. This increases the probability that a unit will be detected and fired upon, thereby enabling the unit to take advantage of an increased defensive rate of fire for a long amount of time. This tactic is in line with gaining fires superiority through kinetic exchange.

Figure 50 summarizes this interaction with the TTP decision of time until a survivability move is as a result of unit capabilities of defensive rate of fire and time to displacement after incoming fires.

Time to Survivability Move Actions to Decrease Blue Casualties		
	Low Defensive ROF (4-8 rpm)	High Defensive ROF (8-10 rpm)
Low Displacement after Incoming Time (1-70 sec)	↓ Time to Survivability Move (more frequent moves)	↑ Time to Survivability Move (less frequent moves)
High Displacement after Incoming Time (227-300 sec)	↑ Time to Survivability Move (less frequent moves)	↓ Time to Survivability Move (more frequent moves)

Figure 50. Three-Way Interaction Two: Decision Summary

6. Experiment Three Insights

Blue lethality is most influenced by the dominant factor of caliber. Using a 155mm caliber howitzer contributes significantly to a more lethal USMC artillery force, to the point that 105mm caliber cannons should not be considered as a viable howitzer caliber for a counterfire engagement with current Russian forces.

Blue survivability is not as clear cut as Blue lethality, as there is no single dominating factor for decreasing Blue casualties. Instead, a range of prioritized factors is considered. First, employment method is critically important to Blue survivability. Reinforcing the findings in experiment two, the Blue force is significantly disadvantaged in survivability when consolidated. Second, the Blue force is at an advantage in survivability when using a 155mm howitzer, supporting the concurrent priority of Blue lethality. Finally, the interactions between defensive rate of fire, time to survivability move, and emplacement time or displacement time after incoming fires are significant in providing insights to TTPs derived from unit capabilities. A flow chart of unit capabilities and resulting TTP decisions for reduction of Blue casualties is presented in Figure 51.

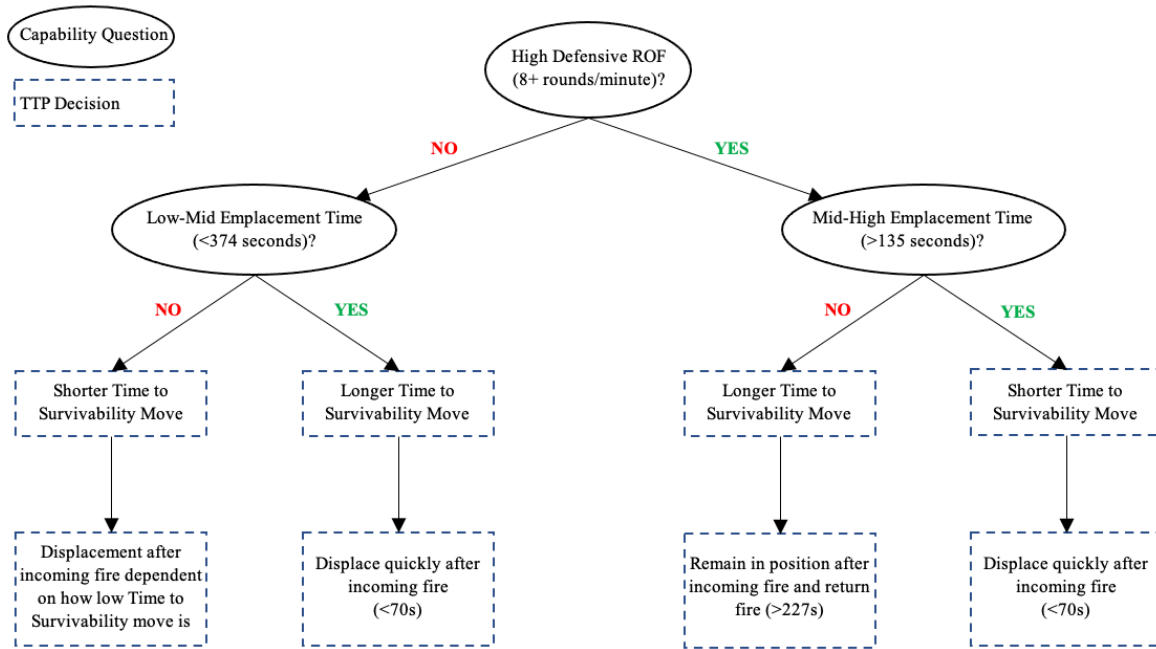


Figure 51. TTP Decision Tree

D. EXPERIMENT FOUR: HEDGE THE CONSTRUCT—BLUE & RED FACTORS, ROBUST ANALYSIS

In the context of this thesis, the end state is a Blue artillery construct that performs well in terms of lethality and survivability against a Red force. Experiments one, two, and three evaluated various Blue constructs against a consistent, best-approximation Red force. Altering controllable Blue factors allowed for analysis on relative performance across the Blue factor space. Experiment four “unlocks” the previously consistent Red force by explicitly varying Red force factors, akin to testing a wide range of potential Red artillery configurations. If Blue factors are considered to be controllable decision factors, the Red factors can be considered to be uncontrollable factors. By introducing uncontrollable factors, insights into Blue factor importance can be gained not only to increase performance, but also to ensure that performance is relatively consistent across a wide range of Red capabilities and tactics.

1. Intent of Robust Design and Analysis

A robust design is a “system optimization and improvement process that springs from the view that a system should not be evaluated on the basis of mean performance alone” (Sanchez and Sanchez 2020, p. 6-25). Robust analysis enables the construction of a system of processes which “exhibit an acceptable mean performance” while remaining “relatively insensitive to uncontrollable sources of variation present in the system’s environment” (Sanchez and Sanchez 2020, p. 6-25).

Within this context, improving mean performance for Blue lethality and survivability means increasing Red casualties and reducing Blue casualties, respectively. A Blue artillery configuration is ‘robust’ when it reduces variability (from uncontrolled Red noise factors) while still performing at or near the goals of achieving few Blue casualties and many Red casualties, on average.

One can imagine a three-dimensional fitness landscape where height represents performance. A robust configuration for the Blue force is one which resides on a high, flat plateau, as opposed to on top of a higher, “optimal” configuration that resides on top of a fragile “pointy” peak. The “optimal” peak configuration would be subject to failure given even a small amount of change from assumed conditions that are, in fact, uncertain. The robust configuration, residing on the plateau, would be resilient to variation and continue to produce good results.

Approaching analysis from a robust perspective enables recommendations for future force design and employment that are not merely based on mean performance, but also consider uncertainty and variability with respect to future Russian operating capabilities and tactics.

2. Loss Function

A loss function penalizes the distance away from a target value for a particular metric, multiplied by a scalar that can be used as a cost conversion. The quadratic loss function, with distance from target squared, so as to be in the same units as variance, is given by

$$loss(y_x) = c(y_x - \tau)^2$$

where ‘c’ is a penalty/cost constant, tau (τ) is the target value and y_x is the response for each x design point.

In the experiment four design, each unique Blue design point (232 total) is run for 100 replications over 58 unique Red configurations for a total of 5800 replications per Blue design point. Each run includes variability due to the stochastic nature of MANA as well as the change in Red factor settings. By collapsing the 5800 data points by unique Blue design point, summary statistics for the mean and standard deviation of each design point is obtained over the entire noise space. The expected loss function imposes penalties for both variability and mean value distance from the target with the following equation:

$$E[loss(y_x)] = c \left[(\sigma_{y_x})^2 + (\mu_{y_x} - \tau)^2 \right]$$

In this study, the two response metrics are Blue lethality and Blue survivability. Lethality is measured in the number of Red casualties inflicted by Blue and survivability is measured by the number of Blue casualties sustained. With the intent to determine favorable Blue constructs, natural responses (y_x) and target values (tau) for these metrics are:

- Blue Lethality: y_x = Red Casualties, tau = 18 (maximum number of Red casualties possible)
- Blue Survivability: y_x = Blue Casualties, tau = 0 (minimum number of Blue casualties possible)

After collapsing data, two expected loss columns for lethality and survivability are added using the expected loss equation with appropriate values for tau. A scatterplot is created by plotting Blue lethality loss (Red casualty loss) by Blue survivability loss (Blue casualty loss), seen in Figure 52. With the intent to minimize loss for both metrics, a Pareto frontier is identified along the points closest to the origin that are dominant for minimizing Blue and Red loss. Each point in the Pareto frontier represents a unique Blue artillery

construct. The point closest to the origin, highlighted in green, represents the Blue construct that minimizes loss for balanced priorities of lethality and survivability.

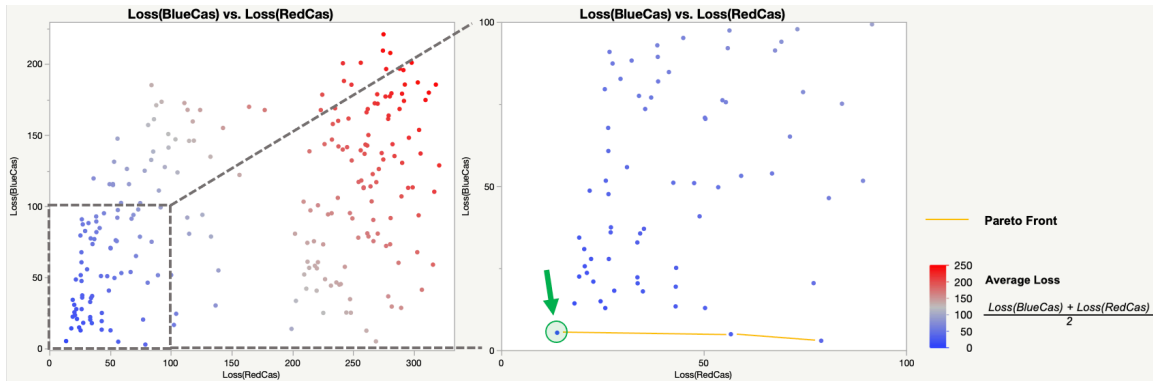


Figure 52. Minimum Loss Pareto Frontier

The preferable design point (green) along the Pareto frontier represents a Blue force construct with the following characteristics:

- **Employment:** Distributed
- **Caliber:** 155mm
- **Offensive ROF:** 6 rounds/minute
- **Defensive ROF:** 4 rounds/minute
- **Time to Survivability Move:** 300 seconds
- **Time in Position after Incoming:** 1 second
- **Concealment:** 90 percent
- **Emplacement Time:** 30 seconds
- **Displacement Time:** 30 seconds
- **Max Range:** 30,000 meters

While this design point construct is closest to the origin, it represents only one point on the Pareto frontier. Some of the parameters in the above construct may be infeasible or mutually contradicting to achieve. To evaluate which factors are most important in the robust case, partition trees and regression models are built to provide more in-depth insight.

3. Partition Trees

Partition trees are created for Blue casualty loss (survivability), Red casualty loss (lethality), and average loss (balance of survivability and lethality). In each partition tree, the goal is to minimize the overall loss by splitting and progressing down the left side of the tree.

a. Blue Casualty Loss

Figure 53 shows the partition tree for Blue casualty loss. After eight splits, an R squared value of 0.749 is attained. In order to reduce Blue casualties consistently, Blue should disperse forces, use a 155mm caliber weapon system, and prioritize concealment.

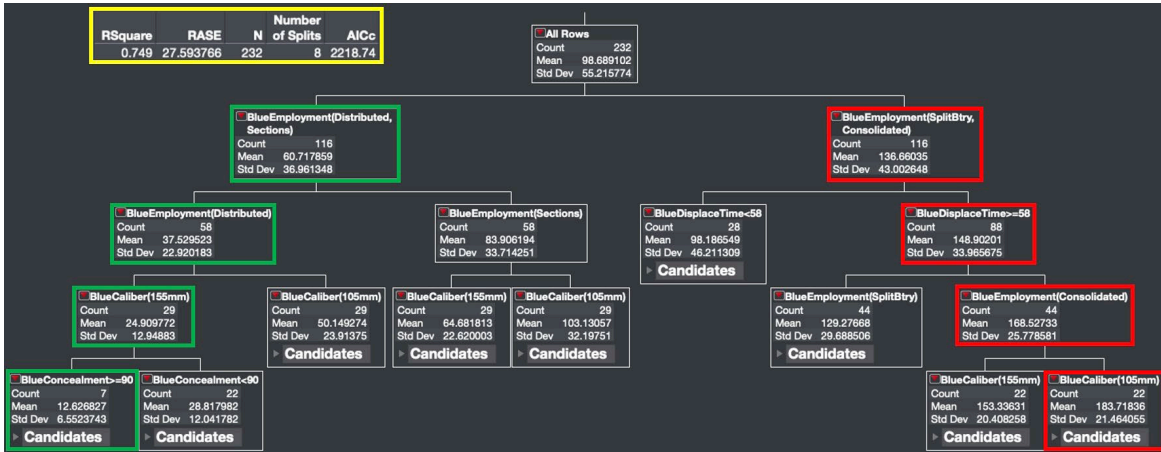


Figure 53. Blue Casualty Loss (Blue Survivability) Partition Tree

b. Red Casualty Loss

Figure 54 shows the partition tree for Red casualty loss. After only five splits, a high R squared value of 0.922 is attained. To consistently produce high Red casualties,

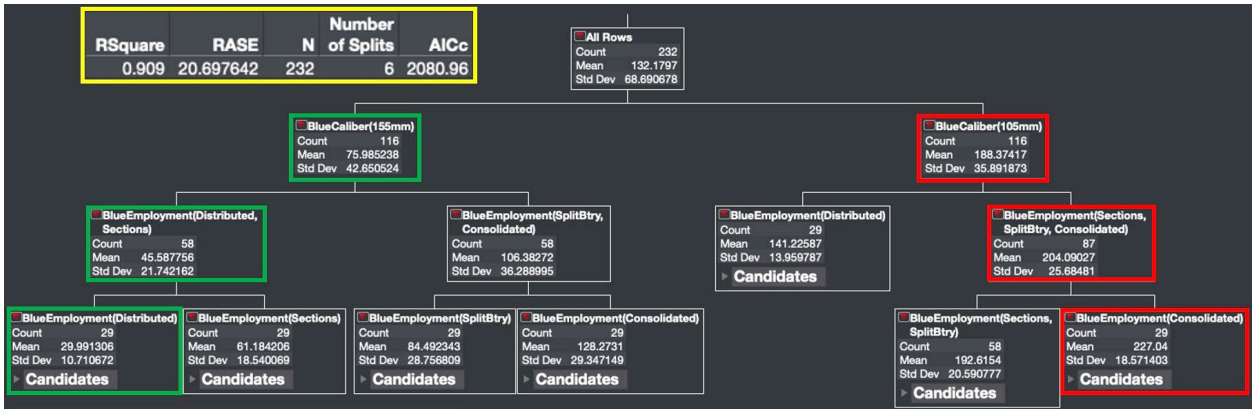


Figure 55. Average Loss (Balanced Priority) Partition Tree

Figure 56 shows the column contributions for the above partition tree. Caliber was found to be dominant for Blue lethality in experiment three. When both Blue lethality and survivability are considered equally and variability is reduced, caliber is also the predominant factor, followed by employment method.

Term	Number of Splits	SS	Portion
BlueCaliber	1	732613.763	0.7396
BlueEmployment	5	257951.745	0.2604
BlueOffensiveFireRt	0	0	0.0000
BlueDefensiveFireRt	0	0	0.0000
BlueTimeToSurvivability/Move	0	0	0.0000
BlueDisplaceAfterIncoming	0	0	0.0000
BlueConcealment	0	0	0.0000
BlueEmplaceTime	0	0	0.0000
BlueDisplaceTime	0	0	0.0000
BlueMaxRng	0	0	0.0000

Figure 56. Average Loss (Balanced Priority) Partition Tree Column Contributions

4. Metamodels

Next, main-effects only models are fit to the mean and variance of Blue casualties first, followed by Red casualties. All predictors are included. In these cases, the addition of interaction terms are not statistically significant and are not included in the models. With only main effects, the direct comparison of the prediction profilers for mean and variance

will allow us to determine which factors drive expected performance towards the target value while also reducing variability.

a. Blue Casualties

A metamodel is constructed by evaluating all main effects against the responses of Blue casualty mean and variance. Figure 57 shows the resulting prediction profiler after the model is constructed. Blue casualty variability plots are shown within the magenta outlines and mean Blue casualty plots are outlined in yellow.

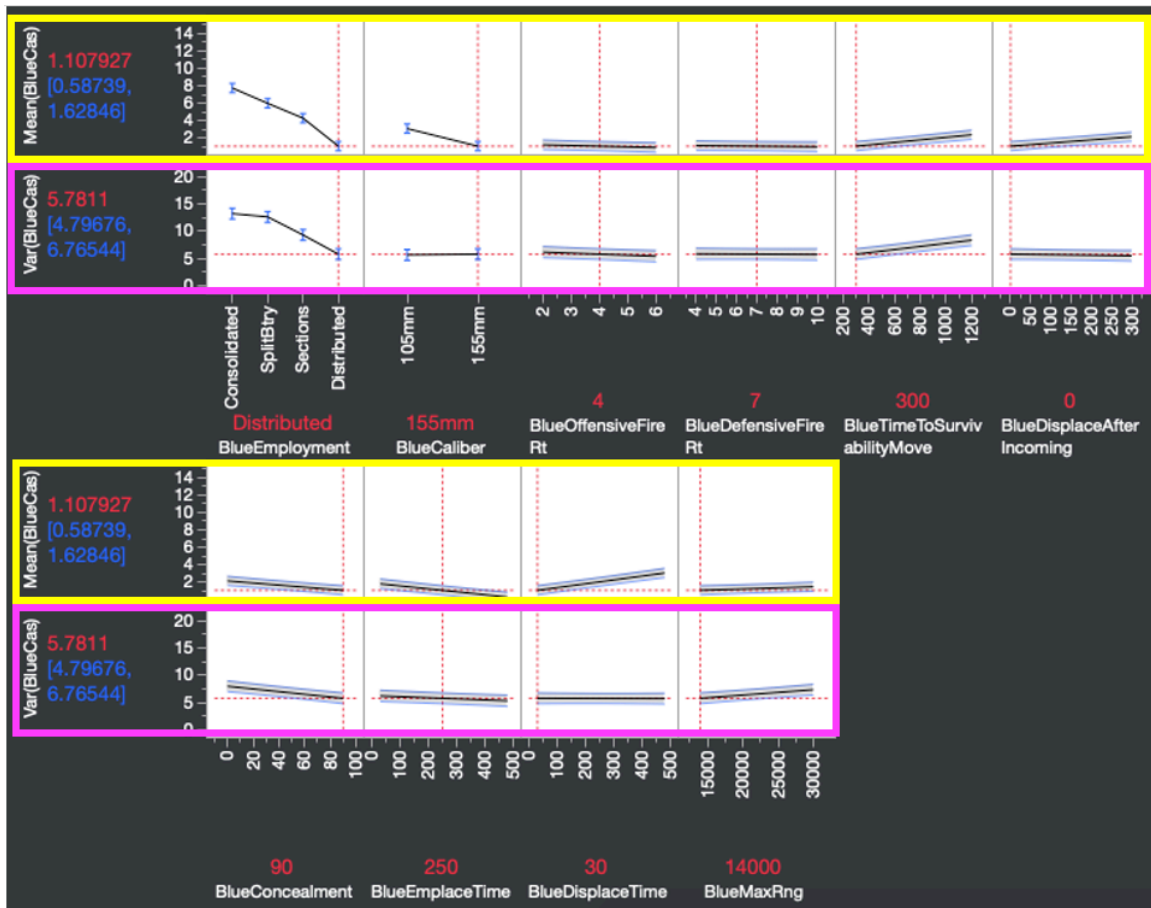


Figure 57. Blue Casualty (Blue Survivability) Robust Metamodel Prediction Profiler

A neutral slope means that the factor has negligible effect on the response. Any positive or negative slope indicates that the factor does affect the response, with the

magnitude of the slope indicating the significance of the factor. In this case, employment method has a series of steep negative slopes and influences both variability and mean Blue casualties greatly.

The first goal is to identify the factors important for reducing variability (outlined in magenta). A slider is dynamically moved to the category or numerical value which imparts lower (or least) variability. Main effects which most impact variability for Blue casualties are employment method, time to survivability move, concealment, and max range.

Once variability is reduced, the mean casualty plots are adjusted to minimize Blue casualties sustained. In this model, there are no instances in which variability and mean are negatively correlated (opposing slope directionality). The sliders for caliber, time to displacement after incoming, and displacement time are adjusted intuitively to reduce mean Blue casualties. Factors not adjusted were offensive and defensive rate of fire and emplacement time. Offensive and defensive rates of fire were not adjusted as these main effects are inconsequential to variability and mean Blue casualties. Emplacement time was not adjusted as the model suggests that a long emplacement time reduces Blue casualties—while this may be true for the model itself (a unit is not detectable during emplacement, and therefore cannot be killed), it is not practicable for real world implementation.

Ultimately, a Blue construct that is robust to a wide range of Red constructs and sustains low casualties has the following characteristics:

- Distributed employment
- 155mm caliber
- Conducts survivability moves frequently
- Displaces immediately after receiving incoming fire
- Maintains high concealment
- Has a fast displacement time

- Has a short maximum range

It is important to note that this robust configuration is informed only by the Blue survivability metric. Some of the above characteristics will differ with respect to robust analysis on Blue lethality, presented next.

b. Red Casualties

The same metamodel construction process as above is repeated for Red casualty mean and variance. Figure 58 shows the resulting prediction profiler after the model is constructed.

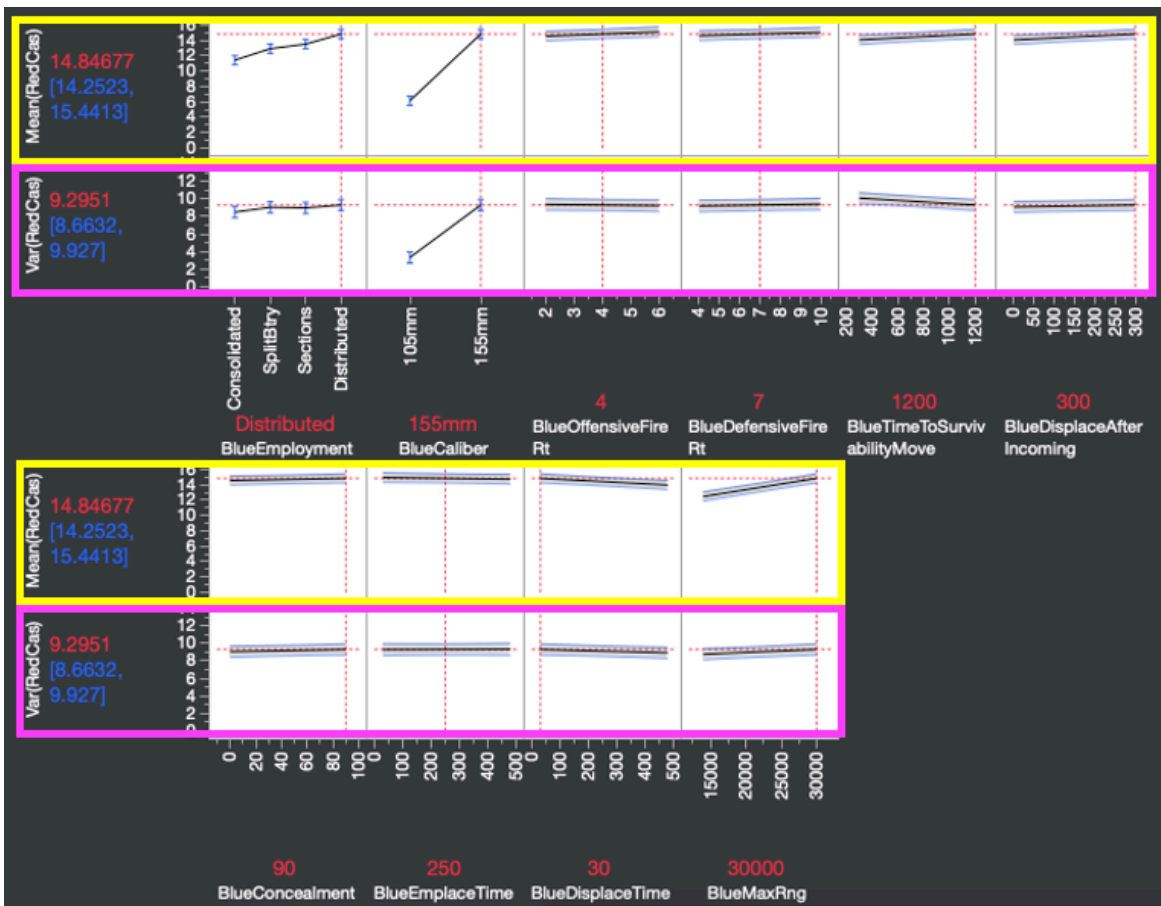


Figure 58. Red Casualty (Blue Lethality) Robust Metamodel Prediction Profiler

As Red casualties are a measure of Blue lethality, the mean Red casualty target is maximized after reducing variance. Many factors do not influence variability. Caliber is the most influential factor to variability, followed by employment method. The remainder of the factors are negligible to variability. After minimizing variance, Red casualties are increased with the prediction profiler sliders.

A Blue construct that is robust to a wide range of Red constructs and produces high Red casualties has the following characteristics:

- Distributed employment
- 155mm caliber
- Conducts survivability moves infrequently
- Remains in position after incoming, returning effective defensive counterfire
- Maintains high concealment
- Has a fast displacement time
- Has a long maximum range

Employment method, caliber, concealment, and displacement time extremes agree with the findings in the Blue casualty robust configuration. Similarly, Blue offensive and defensive rates of fire and emplacement time are not significant to either variance or mean Red casualties. However, three factors conflict with the findings from the Blue casualty model. In the Red casualty model, time to survivability move, displacement after incoming, and maximum range are maximized. In the Blue casualty model, these factors were minimized. It is for these factors specifically that a balance is required.

c. Opposing Factor Finding Reconciliation

Considering both Blue lethality and survivability robust models, a higher maximum range contributed to slightly more variance in both cases. However, a contradiction exists

when minimizing Blue casualties and maximizing Red casualties. By minimizing range, Blue casualties are lowered. By maximizing range, Red casualties are raised. To compare the relative responses with respect to range, a model of all main effects was created with Blue and Red mean casualties as the responses. After applying consensus conclusions found above, the Blue max range prediction profiler was compared, seen in Figure 59.

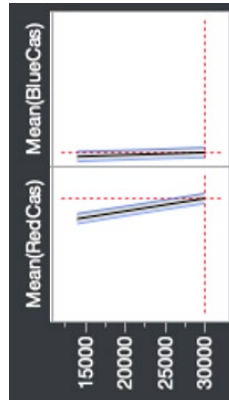


Figure 59. Maximum Range Prediction Profiler for Blue and Red Casualties

The absolute value of the magnitude of the slopes indicates that while extending maximum range is slightly detrimental to sustaining more Blue casualties, it is more beneficial to inflicting a higher quantity of Red casualties. Therefore, a higher maximum range is slightly more beneficial to Blue. Due to the modeling logic, a low maximum range would cause units to continue to bound forward by executing survivability moves, whereas a high maximum range would allow the unit to execute both offensive and defensive fires. The translation from the modeling environment to a real-world counterbattery engagement would be that it is beneficial for Blue to possess longer range capability but initially prioritize closing distance as quickly as possible.

The two other conflicting factors of time until survivability move and displacement after incoming are most effectively analyzed by tracing the capability TPP decision tree previously presented in Figure 51 (presented redundantly below as Figure 60) from the bottom branch terminations up to the start node and setting them dynamically in the prediction profiler. All findings were in keeping with the decision tree. Rather than

suggesting a prescriptive time until survivability move and displacement after incoming time, the analyst suggests that these TTP based factors are best determined by utilizing the decision tree, beginning with capabilities.

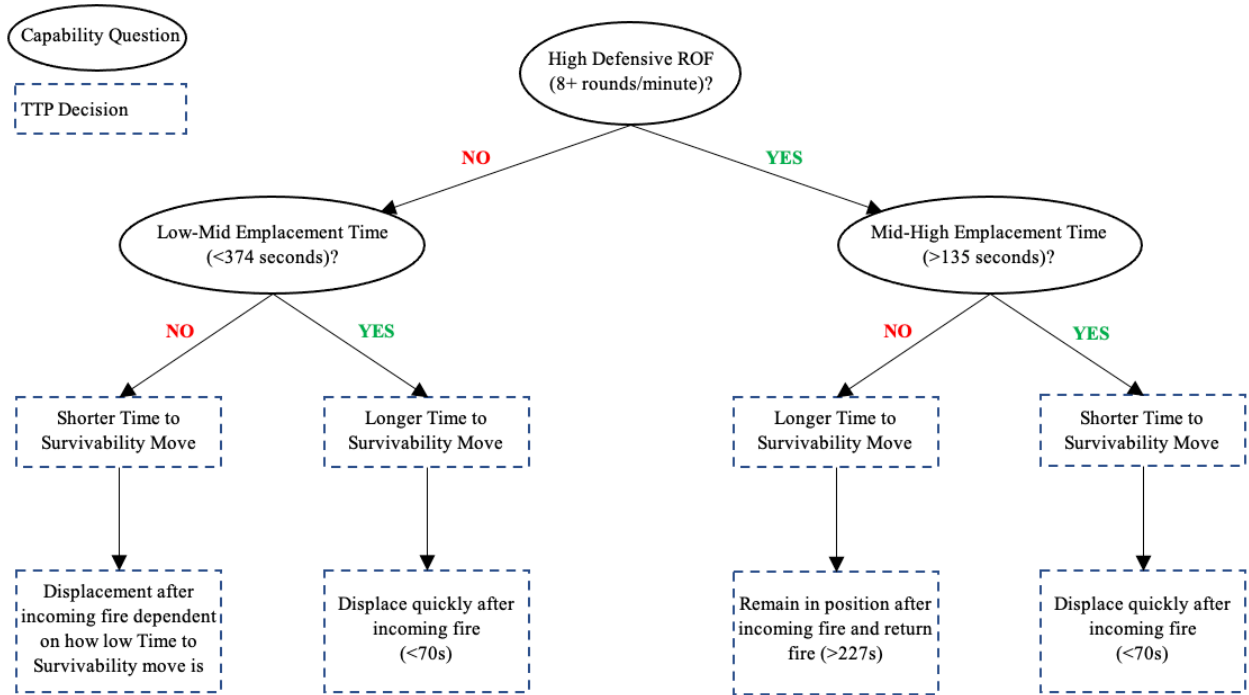


Figure 60. TTP Decision Tree (repeated from Figure 51)

5. Experiment Four Insights

The factors which contribute the most to variability are employment method, time to survivability move, concealment, max range, and caliber. Variability is reduced predominantly by distributing forces and employing 155mm weapon systems. After variability is reduced, the target goals of minimizing Blue casualties and maximizing Red casualties presents sets of both concurrent and conflicting force design and employment decisions.

A Blue force which prioritizes survivability is best suited to be fast and nimble, characterized by frequent survivability moves, quick displacement times, and immediate displacement after receiving incoming fires.

A Blue force which prioritizes lethality is most effective when it conducts survivability moves infrequently and elects to remain in position after receiving incoming fires, returning effective defensive counterfire.

An effective artillery force must balance these priorities. After comparative robust analysis, the tactics employed by the artillery force is determined to be dependent on their capabilities. These decisions are best informed by the decision tree presented in Figures 51 and 60. This tree was derived from experiment three and reinforced by findings in experiment four. Additionally, the employed weapon system should have maximum range capability of at least 17,000 meters.

E. SIGNIFICANCE OF RED FORCE DESIGN: HYBRID VERSUS CANNON-PURE

The methodology for robust analysis presented above was repeated from the Red perspective, treating Red factors as controllable and Blue factors as uncontrollable. A linear regression model was constructed for Blue casualties, or Red lethality. The most influential factor for Red lethality was the employment of a hybrid force (two cannon batteries and one MLRS battery) versus a cannon pure force (three cannon batteries and no MLRS batteries). Red is observed to be more lethal when employing a cannon-pure construct. This can be seen in the sorted parameter estimates for Red lethality from the Red perspective in Figure 61.

Term	Estimate	Std Error	t Ratio	Prob> t
RedMLRS[No]	2.0613065	0.122668	16.80	<.0001*
RedMaxRng	0.0001461	1.926e-5	7.58	<.0001*
RedDisplaceAfterIncoming	0.0069404	0.001032	6.73	<.0001*
RedConcealment	0.011392	0.003417	3.33	0.0017*
RedEmplaceTime	-0.001758	0.000685	-2.57	0.0135*
RedDisplaceTime	-0.001666	0.000685	-2.43	0.0188*
RedOffensiveFireRt	0.0807672	0.037398	2.16	0.0358*
RedDefensiveFireRt	0.0345788	0.03746	0.92	0.3606
RedArmor	0.0008158	0.010243	0.08	0.9369

Figure 61. Factor Significance for Red Lethality (Blue Casualties)

Evaluating across all Red and Blue factor levels and controlling for Red force design, Red produces a mean of 11 Blue casualties when employed in a cannon pure force

design and a mean of six Blue casualties when employed as a hybrid, cannon-MLRS mix. Variability in Blue casualties is largest in the hybrid case, seen in Figure 62.

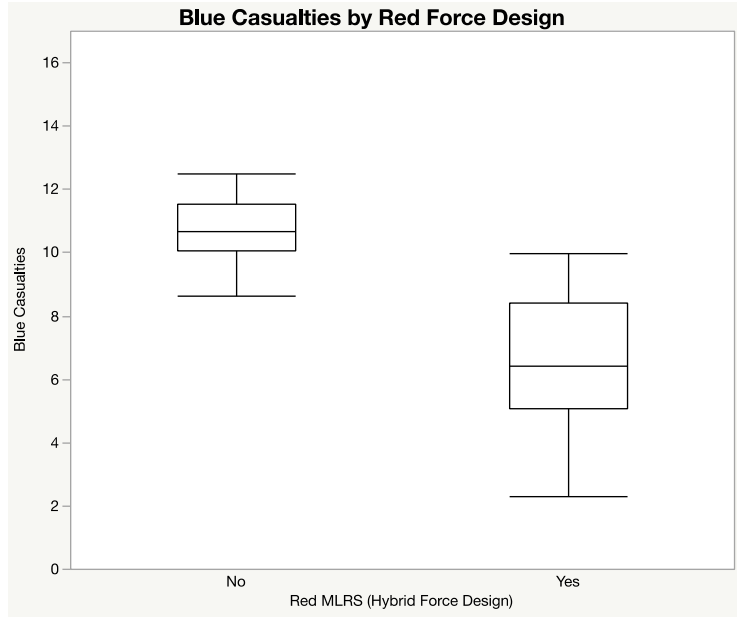


Figure 62. Blue Casualties by Red Force Design (Hybrid versus Cannon Pure)

With the knowledge that the Red force design is significant in terms of Red lethality, Blue tactics are analyzed in two cases: Red hybrid force design and Red cannon pure force design.

From the insights from all experiments, the author designates six theoretical Blue cannon constructs. The base case used a Blue force approximating current USMC capabilities, derived from training and readiness standards and current equipment capabilities. Experiment two retained all parameters of the best-approximation force but changed employment method. The first four theoretical constructs represent the best-approximation of the current USMC artillery force across the four distinct employment options (all factor levels other than employment method are held constant).

Experiment four insights lead to robust Blue cannon constructs. Two opposing tactics emerged, which were:

- **Nimble:** Characterized by frequent survivability moves, quick displacement times, and immediate displacement after receiving incoming fires
- **Staying:** Characterized by infrequent survivability moves and remaining in position after receiving incoming fires, returning effective defensive counterfire.

As a result of three-way factor interactions, these two tactics are changed in the time to survivability move and time to displace after incoming factors.

Figure 63 shows these six theoretical Blue cannon constructs and their associated factor levels.

		Employment Method	Caliber	Offensive Rate of Fire	Defensive Rate of Fire	Time to Survivability Move	Time to Displace After Incoming	Concealment	Emplacement Time	Displacement Time	Maximum Range
		<i>Categorical</i>	<i>Millimeters</i>	<i>Rounds per Minute</i>	<i>Rounds per Minute</i>	<i>Seconds</i>	<i>Seconds</i>	<i>Percent</i>	<i>Seconds</i>	<i>Seconds</i>	<i>Meters</i>
Best-Approximate Current USMC Capabilities	1	Current Construct Consolidated	155	3	4	600	300	90	360	180	24700
	2	Current Construct Split Battery	155	3	4	600	300	90	360	180	24700
	3	Current Construct Sections	155	3	4	600	300	90	360	180	24700
	4	Current Construct Distributed	155	3	4	600	300	90	360	180	24700
Proposed Future USMC Constructs	5	Robust Nimble	155	4	7	480	0	90	300	120	24700
	6	Robust Staying	155	4	7	1200	300	90	300	120	24700

Factor level unchanged over constructs

Figure 63. Theoretical Blue Cannon Construct Factor Levels

After controlling for Red force design (cannon-pure and hybrid), the parameters for each factor were input in the prediction profiler. Mean Red and Blue casualties and 95% confidence intervals were attained and are presented in Figure 64.

		Red Cannon Pure [3] Cannon, [0] MLRS		Red Hybrid [2] Cannon, [1] MLRS		
		Blue Casualties	Red Casualties	Blue Casualties	Red Casualties	
Best-Approximation Current USMC Capabilities	1	Current Construct Consolidated	7.71 [7.28, 8.15]	8.63 [8.17, 9.10]	12.19 [11.65, 12.73]	10.28 [9.64, 10.93]
	2	Current Construct Split Battery	5.93 [5.49, 6.37]	9.85 [9.40, 10.30]	10.47 [9.93, 10.93]	12.04 [11.39, 12.69]
	3	Current Construct Sections	4.61 [4.17, 5.05]	10.30 [9.84, 10.76]	8.42 [7.88, 8.96]	12.78 [12.14, 13.43]
	4	Current Construct Distributed	2.12 [1.69, 2.56]	11.41 [10.95, 11.87]	4.51 [3.97, 5.05]	14.31 [13.67, 14.96]
Proposed Future USMC Constructs	5	Robust Nimble	0.64 [0.23, 1.05]	11.03 [10.60, 11.46]	3.09 [2.58, 3.60]	13.93 [13.33, 14.57]
	6	Robust Staying	2.73 [2.29, 3.16]	12.44 [11.98, 12.89]	5.24 [4.71, 5.77]	15.29 [14.66, 15.93]

Figure 64. Theoretical Blue Cannon Construct Mean Performance with 95% Confidence Intervals

Under current construct capabilities (1-4), performance progressively increases for Blue as employment method becomes more segmented, supporting the findings in experiments two through four. For proposed future constructs, the robust nimble construct (5) has the best Blue survivability performance, and the robust staying construct (6) exhibits the best results for Blue lethality.

Figure 65 visualizes the relative performance of the six theoretical Blue artillery constructs in both cannon-pure and hybrid Red force design scenarios. Mean Red and Blue casualty points are designated by the cross-point, with 95% confidence intervals for casualties sustained by Red (vertical) and Blue (horizontal) constituting the dimensions of the surrounding box.

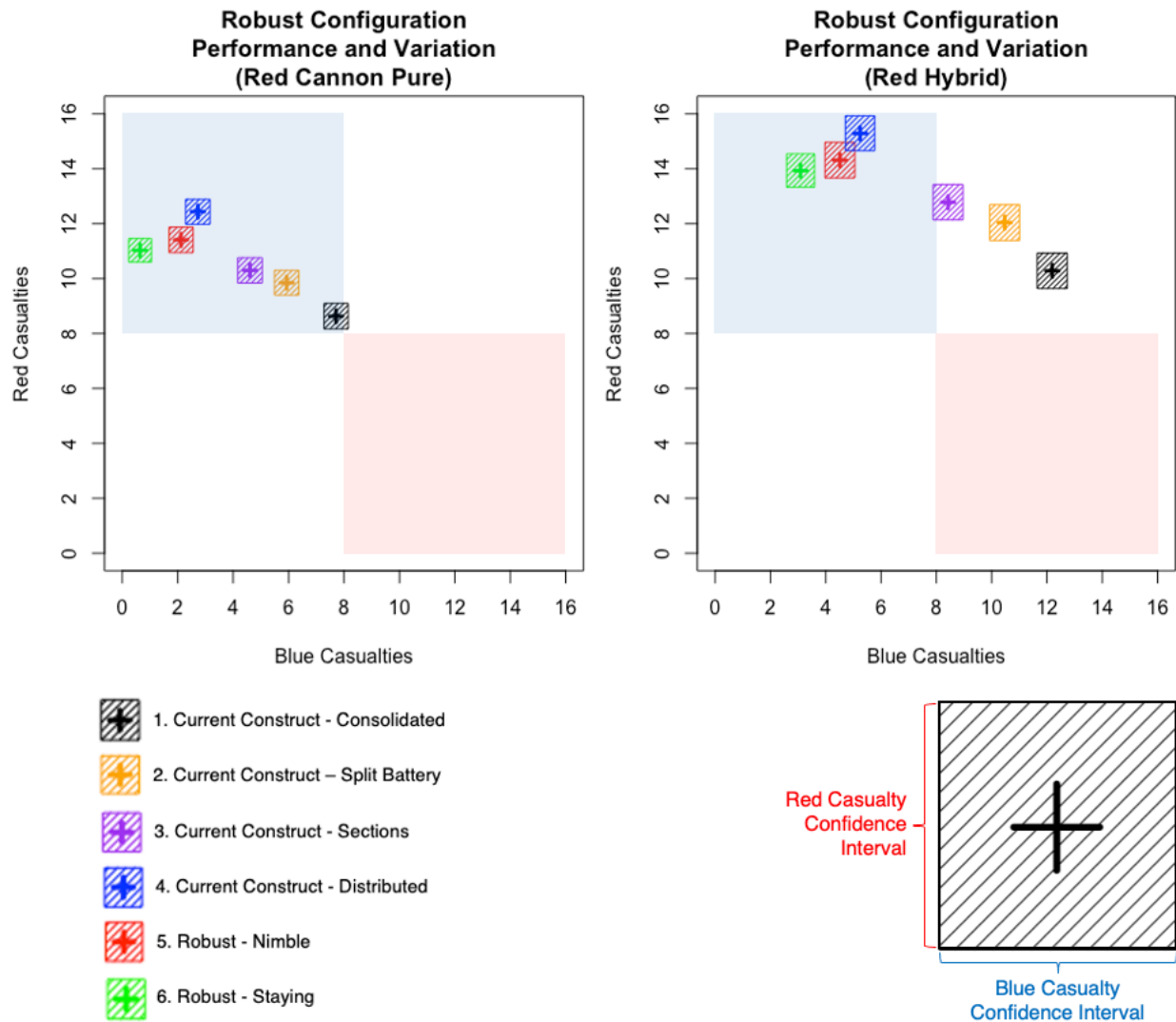


Figure 65. Comparison of Theoretical Blue Cannon Constructs by Red Force Design

The specific location and size of variation is a function of the range of factor levels over which Red and Blue were varied in this study. As each factor range was constructed widely to encompass capability extremes, the mean performance cannot be interpreted to be predictive. Therefore, relative location and size of variation is more significant than specific location and size of variation for drawing insight.

Observing the cluster of Blue constructs as a whole and comparing location between the two Red force designs, it is apparent that when Red uses a hybrid force with one MLRS battery, both Red and Blue are more lethal and produce more casualties (cluster

located mid-upper left for Red cannon pure, shifted upper center for Red hybrid). Red is able to produce more Blue casualties due to large area mass rocket salvos. Blue is able to produce more Red casualties due to the unarmored characteristics of the MLRS.

The dimensions and area of the variation boxes is larger in the Red hybrid force design case. This is likely the result of the simulation time in which the MLRS battery was destroyed by Blue. If destroyed early, the MLRS battery is unable to conduct mass rocket fires. Conversely, if the MLRS battery is not destroyed early in the simulation, mass fires are able to swing tactical tempo favorable to Red.

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VII. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes findings from experiments one through four, draws conclusions about factor significance for cannon artillery lethality and survivability, and presents recommendations for immediate consideration. The chapter concludes with a discussion on future work to further this study in the analytic, wargaming, and experimentation communities of interest.

A. SUMMARY OF EXPERIMENT FINDINGS

Experiment One: *Fight Tonight* served as the base case and imagines a counterbattery fight occurring between USMC and Russian forces as currently equipped and employed. The findings are that the current USMC construct is not postured for success in a counterbattery engagement with Russian forces.

Experiment Two: *Train Tomorrow* evaluated the efficacy of altering the most rapidly affectable factor of employment method. As Blue artillery units became more segmented and dispersed, Blue inflicts more Red casualties and sustains fewer Blue casualties, showing that dispersion increases Blue lethality and survivability. Each level of additional dispersion results in both a faster time to kill at least 50 percent of the Red artillery force and more observations in which Blue achieves this goal, leading to the conclusion that dispersion increases tempo significantly. Although logistics is outside of the scope of this study, total projectile expenditure was analyzed and found to be within feasible bounds for all employment methods considered.

Experiment Three: *Optimize the Force* considered all controllable Blue factors to determine which are most important to USMC lethality and survivability. Caliber is the dominant factor for lethality, and a 155mm weapon system was found to be critical for inflicting the maximum amount of Red casualties. While there is no single dominating factor for Blue survivability, employment method and caliber are the most influential factors for minimizing Blue casualties. Unique three-way interactions emerged, leading to a capability based TTP decision tree. The ultimate conclusions from experiment three are

that it is critical that a USMC artillery battalion employ 155mm weapon systems, disperse as much as possible, and employ tactics based on the operational capabilities of the unit.

Experiment Four: *Hedge the Construct* considered controllable Blue factors and uncontrollable Red factors to determine the most significant factors for USMC performance over a range of unknown or future Russian capabilities and tactics. The methodology used in experiment four enabled the analysis of robust Blue constructs that consistently perform well while remaining resilient across a wide range of Red constructs. Keeping with the findings of experiments one and two, caliber and employment method remain critically important. Maximum range was determined to be the third most important factor for lethality and a threshold of greater than 17,000 meters was established. The remainder of the factors are meaningful in their interactions with each-other and ideal levels are determined by unit capabilities and the priorities of the commander. A Blue force that prioritizes survivability should be nimble, displacing and emplacing quickly, and changing positions frequently; whereas a Blue force that prioritizes lethality should have a staying mentality, remaining in position returning defensive fire if fired upon and changing positions infrequently. These TTP decisions are mutually exclusive, and the author assumes that the commander desires to balance these priorities. The TTP decision tree derived in experiment three was validated in experiment four and was determined to be appropriate in determining TTPs predicated on the operational capabilities of the employed unit.

The most influential factor for Red lethality was found to be the inclusion of an MLRS battery in a hybrid force design. When controlling for this factor, it was found that when Red includes an MLRS battery, the number of casualties for both Red and Blue increases.

B. RECOMMENDATIONS

The findings of this study are that the equipment currently fielded by USMC artillery battalions is largely in line with the most significant factors for lethality and survivability. However, significant changes to current TTPs are necessary for force

protection and mission success. The author presents four recommendations for immediate consideration within the artillery community of interest.

1. **Caliber and Range**

- *Finding:* M777A2 currently meets all equipment-based significant factor thresholds for success in a counterbattery scenario.
- *Discussion:* The M777A2 is a 155mm caliber weapon system and possesses a maximum range above the 17,000-meter threshold. This study finds that the current USMC artillery equipment set, specifically the M777A2, is sufficient in significant factor equipment capabilities of caliber and range.
- *Recommendation:* Funding for artillery research and development is not critical for cannon artillery at this time and should remain allocated for rocket modernization.

2. **Employment Method**

- *Finding:* Employment method is a critical factor for Blue survivability and lethality with increased dispersion and segmentation of units important for improved performance in both metrics.
- *Discussion:* Current USMC artillery battalion TTPs are diametrically opposed to the findings of this study, principally in employment method. USMC artillery batteries are currently conventionally employed as consolidated, battery sized units. While operating in a consolidated method reduces C2 complexities and increases local security defensive posturing, the risk to mission and risk to force is greatly elevated in a counterbattery scenario against a formidable opponent such as Russia.
- *Recommendation:* USMC artillery battalions immediately begin training employment methods that maximize segmentation of firing units. Command and control at the battalion and battery level, local security

resilience, and operational endurance of individual firing elements should be field tested and improved accordingly. This effort should be informed by, and inform, rocket artillery employment in the context of EABO.

3. Tactics

- *Finding*: Interactions between remaining factors present unique TTP force design decisions.
- *Discussion*: Defensive rate of fire, emplacement time, time to survivability move, and time in position after receiving incoming are not dominantly significant but are meaningful in relation to each other. Simply, the two broad tactics are nimble or staying. Neither tactic has significant benefits to absolute performance over the other, but unit attributes should be consistent with the overall spirit of tactics employed. While a nimble force is attractive for survivability, the fast emplacement and displacement times and frequent survivability moves present a risk to force endurance. Ultimately, the tactics employed will be a function of commander priorities, unit capabilities, and situation. It is recommended that the commander's decisions be informed by unit capabilities, referencing the TTP decision tree.
- *Recommendation*: Units assess their current capabilities to determine the most effective tactics by referencing the TTP decision tree.

4. Russian Artillery Force Composition

- *Finding*: A Russian artillery force that includes an MLRS battery increases the casualties sustained by both sides compared to a cannon-pure Russian artillery force.
- *Discussion*: The Russian military is an artillery-centric force and prioritizes mass artillery fires. The modular and composite design of the BTG allows Russia to field either a cannon-pure or hybrid MLRS force,

depending on tactical objectives. Inclusion of an MLRS battery in the BTG brings the capability of mass area rocket salvo fires. The critical vulnerability of the Russian MLRS is its lack of armor protection. If a hybrid force with MLRS is fielded for a counterbattery engagement, both Blue and Red sustain more casualties.

- Recommendation: MLRS should be designated as a high-value target and prioritized for targeting. Early destruction of the soft-skin, unarmored (easily destructible) MLRS removes the threat of large area mass salvos (highly lethal).

C. FUTURE WORK

Both logistics and command and control were outside the scope of this study. Having determined that the current shortfalls in cannon artillery are held largely at the employment method level, the author presents two recommendations for future work.

1. Logistics

Logistics in support of artillery battalion operations were outside the scope of this thesis and research objectives. Although battalion ammunition expenditure was analyzed at the surface level to ensure feasibility, the logistics complexities associated with a distributed force was not analyzed. Further research is recommended for each level of possible employment method to determine supporting demands for distribution of supplies and medical support.

2. Command and Control Complexity

This study assumed perfect communications between all communication chains. Although dispersion was found to increase lethality and survivability, it naturally results in a more complex C2 structure. The potential increase in radio traffic has potential to create a negative effect to concealment, rendering transmitting units vulnerable to electronic detection, targeting, and destruction. Further research is recommended to determine the

appropriate C2 network for each employment method with particular focus on existing Digital Fire Control System capabilities.

D. THE MODELING & SIMULATION, WARGAMING, AND EXPERIMENTATION PARADIGM

The process of fielding new capabilities or redesigning a force is expensive in time and resources. An analytical paradigm between modeling and simulation, wargaming, and experimentation exists to reduce these costs and leverage the relative strengths of each.

Modeling and simulation attempt to approximate reality within scope and is thus only as powerful as the quality of quantitative data from experimentation and qualitative outcomes from wargaming. Experimentation produces real-world conclusions for feasibility and live fire data, but requires significant manpower and resources. Simulation reduces these costs through relatively inexpensive computer replication and statistical analysis. Wargaming aims to capture human decisions to ensure that appropriate and useful experiments are conducted.

A white paper on modeling and simulation, experimentation, and wargaming from the MITRE corporation concludes that “each of [modeling and simulation], experimentation and wargaming exist on a spectrum ranging from very basic applications to the highly complex. In many ways, these techniques are fundamentally intertwined and there are meaningful opportunities for reuse and cross-domain solutions within this space (Page 2016, p. 9). In *The Art of Wargaming*, author Peter Perla visualizes this three-way symbiotic relationship, adapted in Figure 66.

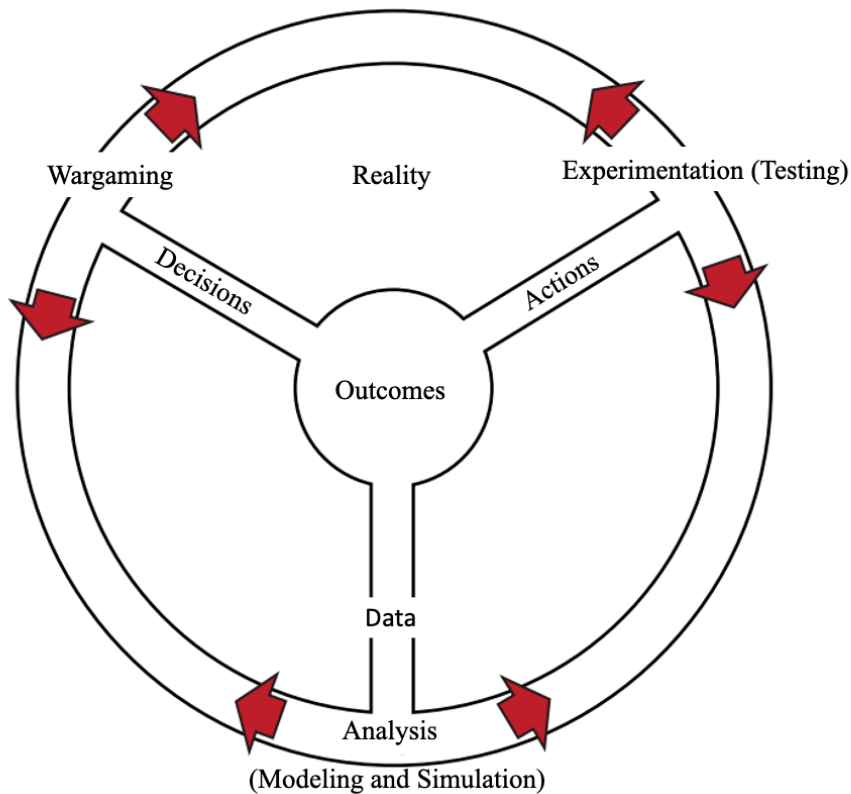


Figure 66. Modeling & Simulation, Wargaming, and Experimentation Paradigm. Adapted from *The Art of Wargaming* (Perla 2012)

The outputs and conclusions of each element in the design triad serve to inform concurrent and future iterations of the others. In the case of this thesis, conclusions are intended to inform both experimentation and wargaming. A method for broad analysis campaigns involving diverse analysis techniques such as simulations, wargames, and live exercises can be found in Lucas et al. 1997. The author recommends the following actions be taken to further this research:

- Operational cannon artillery units conduct internal wargaming to determine C2 architecture, logistics networks, and equipment requirements to support distributed operations. Operational cannon artillery units test distributed battalion artillery operations in a realistic training environment to assess feasibility, human factors, and weaknesses.

- The Marine Corps Warfighting Lab (MCWL) sponsor wargames at the operational level to determine the capability gaps associated with the reduction of cannon artillery, current cannon artillery constructs, and robust cannon constructs presented in this study. It is recommended that if the cannon artillery mission is to be assumed by another service (US Army), gaining responsibility service representation participate in wargaming.
- Outputs and conclusions from all above be routed appropriately for consideration for implementation in a higher-level modeling and simulation environment and scenario.

The underlying intent of this thesis is to provide data-driven bottom-up refinement during USMC force redesign efforts. Questions surrounding cannon artillery lethality and survivability in a peer fight began to emerge at the battalion level during the author's operational time at Battery B, 1st Battalion, 10th Marine Regiment. The author is hopeful that the findings in this study answer these questions and provide useful inputs for future cannon artillery modernization within the modeling and simulation, wargaming, and experimentation paradigm.

APPENDIX A. UAS SENSOR CAPABILITY

Both Red and Blue use one UAS modeled after the USMC RQ-21A Blackjack. While data on sensor performance is limited at the unclassified level, the researcher used a 2015 Operational Test and Evaluation report to estimate sensor performance. In initial testing, the RQ-21A was employed at a search height of 3000ft above ground level (AGL) and a sensor tilt angle of 45 degrees with the task of correctly classifying one-meter and three-meter objects (DOT&E 2015). At this flight altitude and sensor tilt, a target acquisition range of 4242 feet is achieved. A summary of successful classification percentages is shown in Figure 67.

Sensor	Environment	1-meter Object	3-meter Object
Electro-optical	Desert	41% (24, 60)	3-meter objects had 100 percent classification.
	Maritime	43% (24, 64)	
Infrared	Desert	48% (34, 63)	
	Maritime	11% (4, 25)	

Figure 67. Percent Correct Classification at Slant Range 4,242 Feet (with 80% Confidence Intervals). Source: DOT&E (2015).

This thesis assumes that the UAS will be employing the electro-optical sensor. As MANA assumes a foundational terrain of flat ground, the desert environment is used to extrapolate approximate sensor performance. Additionally, MANA assumes all agents are at ground level, and UAS movement is established as setting the agent to be unaffected by terrain. Therefore, assuming that the UAS is at 0ft AGL, a 45 deg sensor tilt at 4242ft AGL would be equivalent to 914.4m (3000ft) horizontally, and 914.4m is used as the range for 41% correct classification. A 100% correct classification probability is assumed when the UAS is directly overhead, or at range zero meters.

Assuming a linear relationship, the two data points of 100% correct classification at zero meters and 41% correct classification at 914.4 meters are used to fit a line for probability of correct classification by range, shown in Figure 68.

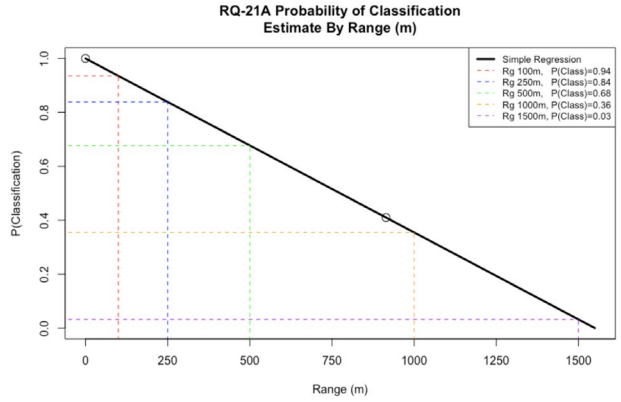


Figure 68. RQ-21A Blackjack Probability of Classification by Range

The study suggests that a 3-meter object has 100% correct classification under the experiment parameters (DOT&E 2015). This thesis assumes that all artillery targets are approximately 3-meter targets. Assuming that the probability of correct classification of 3-meter objects is 100% up to the tested range of 914.4 meters, the estimated regression line is appended and the resulting estimate for probability of correct classification is shown in Figure 69.

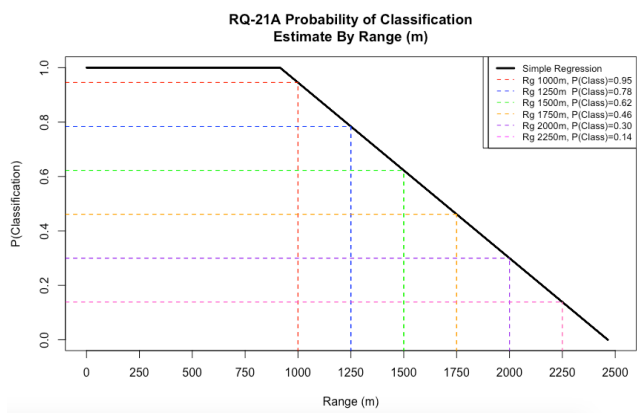


Figure 69. RQ-21A Blackjack Probability of Classification Distribution

Figure 70 displays the sensor parameters for the UAS agent in MANA. The sensor has a maximum range of 2500. Time between detection is stochastic, and the UAS has a

mean time between detection of 30 seconds. In the ‘Classify’ parameter section, probability of correct classification is set according to the probability distribution derived above.

Sensor Ranges (metres)

Detect

Range, R	2500						
Avg Time Between Detections (r<=R) (seconds)	30						

Classify

Range, R	915	1000	1250	1500	1750	2000	2500
Prob/Turn (r<=R)	1	0.95	0.78	0.62	0.46	0.3	0.14

Target Classes

Target Specific Classes

	3	4					
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Figure 70. Modeled UAS Sensor Parameters

Red and Blue UAS are capable of detecting Agent Classes 3 and 4. Agent Class 3 corresponds to artillery units which are emplaced and unmasked as well as artillery units which are displacing. Agent Class 4 corresponds to artillery units which are emplaced and unmasked (recently firing or being fired at). The only states in which a UAS cannot detect an artillery unit is when it is moving or emplacing.

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APPENDIX B. BASE CASE CONVENTIONAL FORCES

Figure 71 provides a brief comparative summary of Russian and USMC equipment capabilities.

	<p>Orlan-10 UAS</p> <ul style="list-style-type: none"> • Endurance: 16 hrs • Range: 120 km • Search Speed: 100 km/hr 		<p>RQ-21A Blackjack UAS</p> <ul style="list-style-type: none"> • Endurance: 16 hrs • Range: 92 km • Search Speed: 111 km/hr
	<p>1L219M Zoopark-1M</p> <ul style="list-style-type: none"> • Range: 23 km 		<p>AN/TPS-80 G/ATOR</p> <ul style="list-style-type: none"> • Range: 50 km
	<p>2S19M2 152mm Howitzer</p> <ul style="list-style-type: none"> • Self-Propelled, Armored • Max Range: 24.7 km • Emplacement: 30 sec • Max RoF: 10 rds / min 		<p>M777A2 155mm Howitzer</p> <ul style="list-style-type: none"> • Towed, Unprotected • Max Range: 24.7 km • Emplacement: 6 min • Max RoF: 4 rds / min
	<p>BM21 'Grad' 122mm MLRS</p> <ul style="list-style-type: none"> • Self-Propelled, Unprotected • Max Range: 20.75 km • Emplacement: 2.5 min • Max RoF: 36 rfts / 18 sec 		

Adapted from Janes (2021A), (2021B), DOT&E (2015), Defense Innovation Sweden (2019), United States Marine Corps (2013), Ministry of Defence of the Russian Federation (2018A).

Figure 71. Summary of Russian and USMC Conventional Equipment Modeled in Experiment One and Two.

1. Conventional Russian Equipment

Red is modeled as fires elements of a Russian BTG. Fires elements consist of two 2S19M2 152mm self-propelled artillery batteries and one 122mm BM21 'Grad' MLRS battery. Each firing battery has one organic FDC. Target acquisition platforms include one 1L219M Zoopark-1M counterbattery radar and one Orlan-10 UAS.

The Orlan-10 UAS is a Russian artillery regimental asset, capable of 16 hours of flight time, a range of 120 km, a maximum altitude of 5 km, and a cruising speed of 90–

150 km/h. After testing compatibility between three self-propelled howitzers batteries and one Orlan-10 in 2016, the Orlan-10 was adopted as the UAS of preference for Russian artillery operations (Janes 2020c).



Figure 72. Orlan-10 UAS. Source: Ministry of Defence of the Russian Federation (2018A).

The 1L219M Zoopark-1M counterbattery radar can detect multiple simultaneous artillery points of origin to a range of 23 km. Once a projectile is detected, its trajectory is computed and point of origin is identified. The Zoopark crew transmits the point of origin location to firing units to initiate a counterfire mission. The Zoopark can cover a sector of 90 degrees and is capable of scanning between sectors rapidly. The Zoopark is controlled by a crew of three and can be operated continuously for eight hours (Jane's 2020d).

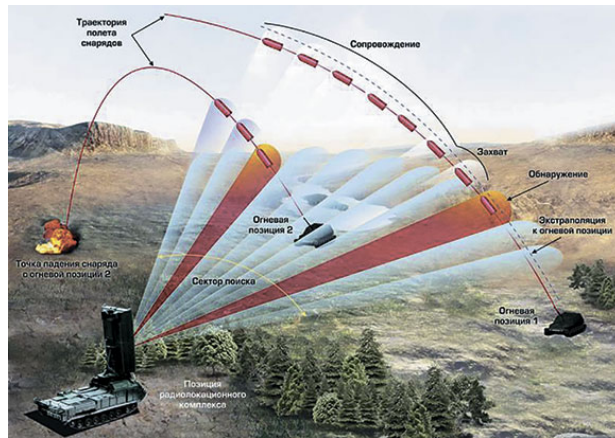


Figure 73. Zoopark-1m, 1L219M Counterbattery Radar. Source: Ministry of Defence of the Russian Federation (2018b).

The 2S19M2 152mm self-propelled howitzer has a maximum range of 24.7 km when firing conventional OF-45-HE-FRAG high explosive rounds. Maximum rate of fire is ten rounds per minute and a sustained rate of fire of four rounds per minute. Emplacement time of a 2S19M2 is noted as 30 seconds. The hull of the vehicle is based on the Russian T-72 tank and is outfitted with armor. While exact specifications on armor thickness are not available from unclassified intelligence sources, it is understood that the armor is primarily used as protection from artillery fragmentation as the primary anticipated threat for the 2S19M2 is artillery counterfire (Jane's 2021a).



Figure 74. 2S19M2 Self-Propelled Howitzer. Source: Janes (2021a)

The 122mm BM21 ‘Grad’ MLRS has a maximum range of 20,750m when firing the standard 9M22 rocket. As the BM21 is typically employed as a mass area fire weapon system, its entire rocket pod is expended in a single fire mission, with a salvo firing time of 36 rockets in 18 seconds. The BM21 can emplace in 2.5 minutes and displace in 30 seconds. A crew of five can reload the BM21 in eight minutes. The BM21 is unarmored (Jane’s 2021b).



Figure 75. BM-21 ‘Grad’ MLRS. Source: Janes (2021b).

2. Conventional USMC Equipment

Blue is modeled as a USMC M777A2 155mm cannon battalion. Each firing battery has one organic FDC. Target acquisition platforms include one AN/TPS-80 G/ATOR counterbattery radar and one RQ-21 Blackjack UAS.

The RQ-21A Blackjack UAS is of 16 hours of flight time, a range of 92 km, a maximum altitude of 5.79 km, and a cruising speed of 111 km/h (Jane’s 2020e). It is equipped with an electro-optical and infrared sensor for target detection (DOT&E 2015).



Figure 76. RQ-21A Blackjack UAS. Source: DOT&E (2015).

The AN/TPS-80 G/ATOR counterbattery radar can detect multiple simultaneous cannon points of origin to a range of 40 km and rocket points of origin to a range of 50 km. The G/ATOR can cover a sector of 90 degrees and is capable of scanning between sectors rapidly. The G/ATOR is controlled by a crew of four (Jane's 2021c).



Figure 77. AN/TPS-80 G/ATOR Counterbattery Radar. Source: Defense Innovation Sweden (2019)

The M777A2 155mm towed howitzer has a maximum range of 24.7 km when firing conventional high explosive rounds. Maximum published rate of fire is four rounds per minute and a sustained rate of fire of two rounds per minute. By current USMC Training and Readiness Standards, emplacement time is six minutes and displacement time is three minutes (USMC 2018). The M777A2 is towed by the M1094A2 MTVR and is unarmored.



Figure 78. M777A2, Towed by MTVR. Source: MCIPAC, USMC (2013).

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