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SIMULATION ANALYSIS OF USMC HIMARS EMPLOYMENT IN THE WESTERN PACIFIC

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THESIS

SIMULATION ANALYSIS OF USMC HIMARS EMPLOYMENT IN THE WESTERN PACIFIC

by

Caleb G. Crispell

June 2022

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13. ABSTRACT (maximum 200 words)

As a result of renewed focus on great power competition, the United States Marine Corps is currently undergoing a comprehensive force redesign. In accordance with the Commandant's Planning Guidance and Force Design 2030, this redesign includes an increase of 14 rocket artillery batteries while divesting 14 cannon artillery batteries. These changes necessitate study into tactics and capabilities for rocket artillery against a peer threat in the Indo-Pacific region. This thesis implements an efficient design of experiments to simulate over 1.6 million Taiwan invasions using a stochastic, agent-based combat model. Varying tactics and capabilities as input, the model returns measures of effectiveness to serve as the response in metamodels, which are then analyzed for critical factors, interactions, and change points. The analysis provides insight into the principal factors affecting lethality and survivability for ground-based rocket fires. The major findings from this study include the need for increasingly distributed artillery formations, highly mobile launchers that can emplace and displace quickly, and the inadequacy of the unitary warheads currently employed by HIMARS units. Solutions robust to adversary actions and simulation variability can inform wargames and future studies as the Marine Corps continues to adapt in preparation for potential peer conflict.

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SIMULATION ANALYSIS OF USMC HIMARS EMPLOYMENT IN THE WESTERN PACIFIC

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requirements for the degree of

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ABSTRACT

As a result of renewed focus on great power competition, the United States Marine Corps is currently undergoing a comprehensive force redesign. In accordance with the Commandant's Planning Guidance and Force Design 2030, this redesign includes an increase of 14 rocket artillery batteries while divesting 14 cannon artillery batteries. These changes necessitate study into tactics and capabilities for rocket artillery against a peer threat in the Indo-Pacific region. This thesis implements an efficient design of experiments to simulate over 1.6 million Taiwan invasions using a stochastic, agent-based combat model. Varying tactics and capabilities as input, the model returns measures of effectiveness to serve as the response in metamodels, which are then analyzed for critical factors, interactions, and change points. The analysis provides insight into the principal factors affecting lethality and survivability for ground-based rocket fires. The major findings from this study include the need for increasingly distributed artillery formations, highly mobile launchers that can emplace and displace quickly, and the inadequacy of the unitary warheads currently employed by HIMARS units. Solutions robust to adversary actions and simulation variability can inform wargames and future studies as the Marine Corps continues to adapt in preparation for potential peer conflict.

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ATACMS	Army Tactical Missile System
C2	Command and Control
CCP	Chinese Communist Party
CFF	Call for Fire
CPG	Commandant’s Planning Guidance
DOD	Department of Defense
DOE	Design of Experiments
DPICM	Dual-Purpose Improvised Conventional Munition
EABO	Expeditionary Advanced Base Operations
FD30	Force Design 2030
FDC	Fire Direction Center
FIRECAP	Fire Capable
FSCC	Fire Support Coordination Center
G/ATOR	Ground/Air Task Oriented Radar
GMLRS	Guided Multiple Rocket Launch System
HE	High Explosive
HIMARS	High Mobility Artillery Rocket System
IFV	Infantry Fighting Vehicle
MANA	Map Aware Non-Uniform Automata
MEB	Marine Expeditionary Brigade
MLRS	Multiple Launch Rocket System
MOE	Measure of Effectiveness
NMESIS	Navy Marine Corps Expeditionary Ship Interdiction System
NOB	Nearly Orthogonal and Balanced
NOLH	Nearly Orthogonal Latin Hypercube
PAA	Position Area for Artillery
PLA	People’s Liberation Army
PLAN	People’s Liberation Army Navy
PRC	People’s Republic of China
TTP	Tactics, Techniques, and Procedures

UAS	Unmanned Aerial System
USMC	United States Marine Corps

EXECUTIVE SUMMARY

To comply with the Department of Defense's (DOD) renewed emphasis on great power competition, the United States Marine Corps (USMC) is implementing sweeping force structure changes in accordance with *Force Design 2030* (USMC 2020). These include a substantial investment in rocket artillery with the goal of competing with the People's Republic of China (PRC) in the western Pacific. This investment is coupled with a divestment in conventional tube artillery batteries.

The prevalence of long-range precision fires in the future Marine Corps will be a vast departure from the typical construct of cannon artillery supporting infantry closing with the enemy. The artillery community is widening its scope beyond that traditional employment scenario. These changes present challenges to the USMC. In order to deter, and if necessary, defeat the PRC, the USMC must be knowledgeable and well-trained in the employment of rocket artillery to maximize lethality and survivability. Inherent differences between cannon and rocket artillery system capabilities will manifest themselves as different tactics needed for success. Due to limited organic expertise on rocket artillery in the service, research must be conducted into this area.

China has been designated as the United States' pacing threat due to their immense growth economically, politically, and militarily in the past two decades (Garamone 2021). Their claims over the South China Sea and Taiwan, coupled with aggressive rhetoric and imposing military exercises have brought them to the forefront of American military focus. This research specifically focuses on a Taiwan invasion scenario and simulates an engagement within this operation that has been adapted from the U.S. Army Training and Doctrine Command wargame "No Option is Excluded" (Sullivan 2021). In it, the People's Liberation Army makes a swift incursion into Taiwan, quickly maneuvering to seize critical infrastructure to allow for massing of combat power. The USMC responds by providing a High-Mobility Artillery Rocket System (HIMARS) battalion to support the defense of this critical infrastructure.

The primary research goal of this thesis is to determine which factors are critical to rocket artillery lethality and survivability in a defense-of-Taiwan scenario. This is done through implementation of an efficient design of experiments in a stochastic, agent-based simulation of the engagement described above using open source data. Progressively increasing in complexity, these experiments provide insight into which USMC (Blue) artillery tactics and capabilities are influential to maximizing lethality and survivability while remaining robust to variation in PLA (Red) tactical configurations. In all, over 1.6 million battles are simulated over the course of four experiments providing measures of effectiveness which then serve as the responses in metamodels. These metamodels are analyzed for critical factors, interactions, and change points.

Experiment one simulates an engagement between Red and Blue forces which are approximated by their current tactics and capabilities. This experiment provides a baseline for the variation in the simulation model and ensures the behavior in the model is functioning as designed. The findings from the experiment are that a wide range of outcomes is possible despite no changes to input data, and that the agents are behaving as intended.

Experiment two varies only Blue employment level with the goal of gaining insight into the impact of the most rapidly implementable factor in the study. The findings are clear that increased dispersion in Blue formations improves their lethality and survivability. The greatest single-step increase in survivability occurs when moving from a fully consolidated formation to a split battery construct.

Experiment three varies all Blue factors to determine the optimal configuration for maximizing lethality and survivability. The Blue factors studied are employment method, ammunition, defensive fires, time in position, emplacement time, and displacement time. The primary findings from experiment three are that dispersion remains critical, more numerous smaller-caliber dual-purpose improvised conventional munitions (DPICM) are more lethal than fewer larger, unitary warhead munitions, and that fast displacement improves both survivability and lethality. The following figure provides a visualization of the effect of displacement and ammunition on Blue lethality. This experiment identifies employment method as the most dominant factor on survivability and ammunition as the most impactful on lethality. Displacement time is highly impactful for both survivability and lethality.

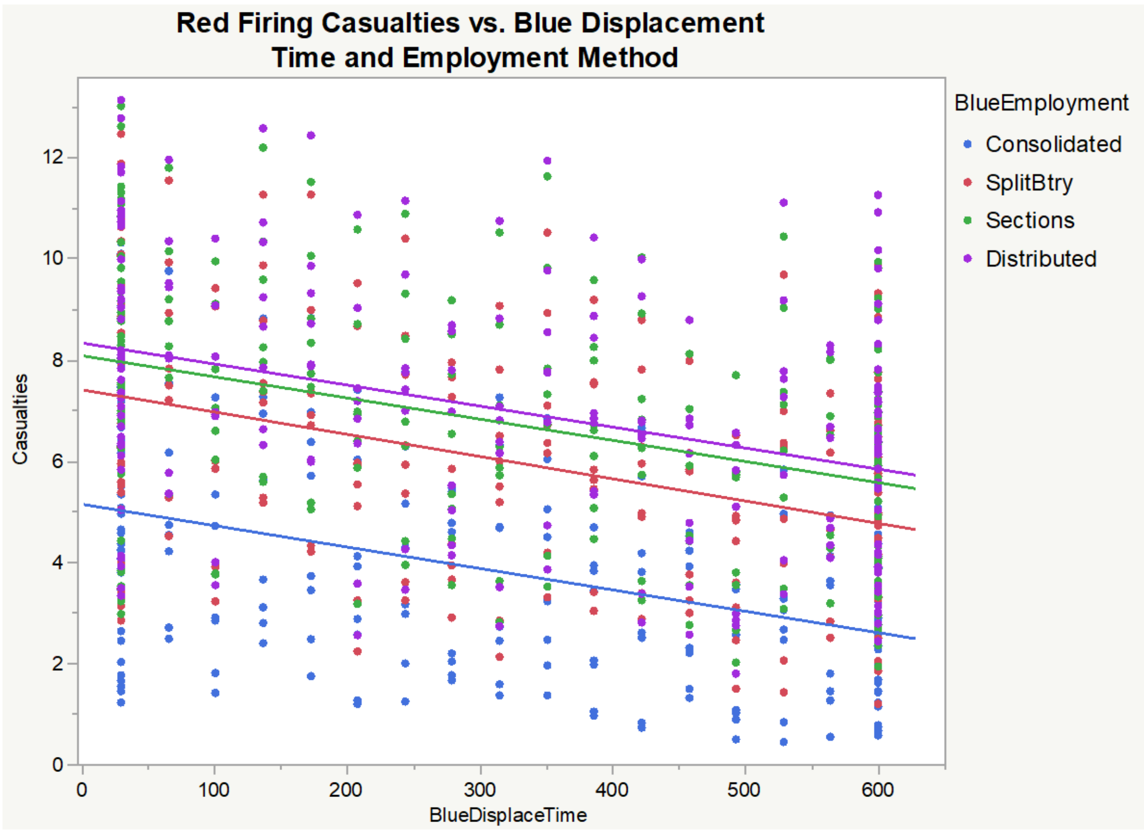

Figure ES1: Experiment Three: Effect of Blue Displacement Time and Ammunition on Red Maneuver Casualties

In experiment four, Blue and Red factors are varied to allow for the inclusion of uncontrollable variation in the form of enemy tactics and capabilities. This allows for an analysis of which Blue factors are resilient to changes in Red while maintaining high lethality and survivability. The analysis for this experiment includes a loss function analysis for Red and Blue casualties as well as metamodel analysis with the mean and standard deviation of casualties as the responses. The findings from experiment four are largely consistent with those from experiments two and three. Employment method and ammunition remain the most dominant factors, and fast displacement time has a consistent positive impact on lethality and survivability. One new finding is that while increasing dispersion eventually provides diminishing returns in terms of survivability, maximum dispersion greatly decreases the standard deviation of the number of Blue casualties. In other words within this model, a commander can minimize the uncertainty of a unit's survivability by operating in a fully distributed formation.

This experiment also identifies a tradeoff relating to the defensive fires factor. In experiment three, defensive fires is shown to be an ineffective tactic which limits survivability and lethality. Experiment four, however, demonstrates that while defensive fires limits lethality, it can have a positive impact on survivability. However, closer examination of this factor identifies that its decrement to lethality dominates its positive influence on survivability. Therefore, defensive fires are not recommended. A similar analysis is conducted on emplacement time, which experiment three and four identifies as having conflicting effects on survivability and lethality. Fast emplacement increases lethality but limits survivability. Again, the impact on lethality is more powerful than the impact on survivability, so units seeking a balance of both should strive for rapid emplacements.

In summary, the findings of this thesis provide strong support for implementing more distributed artillery formations and prioritizing rapid emplacement and displacement training. The emphasis on rapid displacement extends to the employment of defensive fires. This research does not support the employment of defensive fires for rocket artillery as its decrement to lethality is noteworthy. While DPICM is emphasized as a highly lethal munition, its employment carries significant civilian considerations. As this study's scope did not include command and control (C2) or logistics considerations, the author recommends that future work is done in these areas. Dispersed units will stress their capability to conduct C2 and logistics, and further studies can provide insights into the feasibility of implementing distributed operations.

References

Garamone J (2021) Official talks DOD policy role in Chinese pacing threat, integrated deterrence. U.S. Department of Defense. Accessed December 6, 2021, https://www.defense.gov/News/News-Stories/Article/Article/2641068/official-talks-dod-policy-role-in-chinese-pacing-threat-integrated-deterrence/.

Sullivan I (2021) No option is excluded: Using wargaming to envision a Chinese assault on Taiwan. All Partners Access Network. Accessed November 16, 2021, https://community.apan.org/wg/tradoc-g2/mad-scientist/m/articles-of-interest/380503.

United States Marine Corps (2020) *CMC38 Force Design 2030 Report Phase I and II* (Force Design 2030), Quantico, VA, https://www.hqmc.marines.mil/Portals/142/Docs/CMC38%20Force%20Design%202030%20Report%20Phase%20I%20and%20II.pdf?ver=2020-03-26-121328-460.

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I. INTRODUCTION

A. REEMERGENCE OF GREAT POWER COMPETITION

The Department of Defense (DOD) released the latest National Defense Strategy in 2018. In it, then-Secretary of Defense James Mattis describes the shifting priorities of the Department in response to changes in the global landscape. The military dominance that the United States has enjoyed over the last few decades is being threatened as multiple near peer competitors are seeking to overtake and replace the U.S. as the preeminent global power. Chief among these strategic competitors is China, which patiently continues to take methodical steps to increase its economic and military power around the globe. Secretary Mattis summarized the strategic shift succinctly, "Inter-state strategic competition, not terrorism, is now the primary concern in U.S. National Security" (Department of Defense [DOD] 2018).

1. Force Design and Modernization

In concert with the DOD, the Commandant of the Marine Corps, General David H. Berger, released his Planning Guidance in July 2019, outlining the strategic course for the service (United States Marine Corps [USMC] 2019). The Commandant's Planning Guidance (CPG) was written to serve as his commander's intent during his tenure as head of the service. In it, he identifies force design as his number one priority, concurring with his predecessor's assessment, "the current force is not designed, trained or equipped to support the naval force—operating in contested maritime areas, facilitating sea control, or executing distributed maritime operations" (USMC 2019, p. 1). This force design is centered around naval integration to ensure that the Navy-Marine Corps Team can maintain sea control and power projection in environments that are contested by the growing threat of our adversaries' long-range precision fires.

The Commandant details the specifics of the Marine Corps' force design in the publication *Force Design 2030* (FD30). He also provides an argument for the proposed changes. He argues,

> In light of unrelenting increases in the range, accuracy, and lethality of modern weapons; the rise of revisionist powers with the technical acumen and economic heft to integrate those weapons and other technologies for direct or indirect confrontation with the U.S., …, I am convinced that the defining attributes of our current force design are no longer what the nation requires of the Marine Corps. (USMC 2020, p. 2)

The rise of global powers such as China are forcing the Marine Corps to adapt its force considerably in order to maintain relevance in the coming decades. The changes, some of which are currently being implemented, are significant. Some of the most sweeping changes include a complete divestment in tanks, a divestment of 14 cannon artillery batteries, an increase in 14 rocket artillery batteries, a divestment of 8 total helicopter squadrons, and a total reduction of 12,000 Marines from the current Total Force. The USMC's progress on force design has been detailed in several updates. This thesis focuses on the Marine artillery force, specifically seeking to gain insight on how Marine artillery can maintain lethality and survivability in a challenging environment against a peer threat.

2. Purpose of the Marine Corps

In the past few decades, the USMC has strayed from its purpose as a maritime force. Out of necessity, the wars in the Middle East changed the way the service was employed. It has operated almost exclusively from and on the ground, and thus its relationship with the Navy has been limited. The enemy also influenced the employment of the USMC as they were not facing a peer threat. That is to say the enemy did not possess similar capabilities, and they employed themselves asymmetrically. U.S. forces could count on having air superiority, ground-based fires superiority, and general mobility around the battlespace. The enemy fought back with improvised explosive devices, suicide bombings, and only engaged when they held a tactical advantage. The U.S. faced a tough, adaptable enemy that used the rules of engagement to their advantage and possessed a significant advantage in knowledge of the terrain and populace. These were significant departures from the types of conflicts for which the USMC was originally created.

United States Code Title 10. Section 8063 provides the basis for the composition and functions of the service. The USMC exists "to provide fleet marine forces of combined arms, together with supporting air components, for service with the fleet in the seizure or defense of advanced naval bases and for the conduct of such land operations as may be essential to the prosecution of a naval campaign" (10 U.S.C. § 8063). On the future battlefield, the United States will not require the USMC to act as a second Army. Rather, the service will be relied upon as the expeditionary force-in-readiness, prepared to respond to crises around the globe in support of our naval forces. The USMC needs to be prepared to face any enemy, in any environment, and perform operations across the range of military operations. Successfully meeting this challenge will require significant restructuring of the force along with a paradigm shift in how we employ our forces.

3. China as a Pacing Threat

Historically, the United States has done a poor job at predicting future conflicts. In February 2011, Secretary of Defense Robert Gates summarizes this track record well in a speech to cadets at the United States Military Academy at West Point.

> When it comes to predicting the nature and location of our next military engagements, since Vietnam, our record has been perfect. We have never once gotten it right, from the Mayaguez to Grenada, Panama, Somalia, the Balkans, Haiti, Kuwait, Iraq and more—we had no idea a year before any of these missions that we would be so engaged. (Gates 2011)

This inability is largely unsurprising. War is an immensely complicated undertaking that is influenced by a broad range of factors. According to the RAND brief, *Peering into the Crystal Ball*, geopolitics, military trends, global economics, and space, nuclear and cyber advancements are all elements that play a role in determining the future of warfare (Cohen et al. 2020, p. 4-12). Knowing this, along with general human inability to predict the future, how should the U.S. shape its military to be prepared to fight and win in the next conflict? The answer is in the concept of a pacing threat.

A pacing threat is the adversary deemed most likely to overtake the United States in military, economic, technological, and/or political capability. The DOD's leadership has identified China as the United States' standalone pacing threat (Garamone 2021). Russia, North Korea, and Iran pose significant threats to stability and U.S. interests around the globe, but none of these countries have the rapid growth potential and increasing capabilities in all warfare domains that China is demonstrating. China's military and economic growth along with a clearly stated desire to unseat the United States as the preeminent superpower makes China a formidable adversary. They continue to expand their sphere of influence as they threaten the sovereignty of Taiwan and other neighboring countries.

The USMC's supposition behind the pacing threat is one of scalability. That is, a force that can deter and defeat China, can scale down to fight a lower-capability threat. Simply put, since no one can know who next enemy will be, the U.S. should prepare our forces for conflict with the most capable adversary we have. This approach is not without risk. Mark Cancian, a senior advisor in the International Security Program at the Center for Strategic and International Studies, observes that history is teeming with examples of this assumption leading to failure (Cancian 2020). A prime example is the Vietnam War. In the early years of the Cold War, the U.S. military was preparing itself for great power competition with the Soviet Union, only to find themselves in a counterinsurgency fight for which they were ill-equipped.

4. Marine Artillery Force Redesign

As mentioned, FD2030 presents sweeping changes to the Marine Corps artillery community, replacing the majority of cannon batteries with rockets. The geography of the western Pacific, the most likely place for a conflict with China, requires this adaptation. The limited range of cannon artillery reduces their usefulness in such an environment. In addition to their limited range, the majority of cannon artillery munitions are unguided, while the CPG highlights the importance of long-range precision fires in future conflicts. The USMC's current rocket platform, the High-Mobility Artillery Rocket System (HIMARS), provides this capability. A further benefit of rocket artillery is the ability to load launchers with anti-ship missiles. This allows ground-based Marine units to support the fleet by providing an anti-access area denial capability. In short, the artillery force is being restructured to facilitate continued fire support to ground forces while adding support to maritime forces in conflict against the pacing threat.

B. PURPOSE AND SCOPE

A recent Naval Postgraduate School thesis by Captain Caleb Kadrmas analyzed the critical factors for cannon artillery employment against a Russian artillery force in Eastern Europe (Kadrmas 2021). This study seeks to expand on that work by examining rocket artillery employment against a Chinese amphibious force assaulting Taiwan.

Due to the current relative lack of expertise in rocket employment in the Marine artillery community, there is a need for further study and analysis on this topic. Further, the added complexity of facing a peer threat in an environment such as the western Pacific creates a complex and difficult problem for the Marine Corps. This study aims to determine which factors are vital to USMC rocket artillery success against a Chinese threat, specifically in a defense-of-Taiwan scenario. The goal is that the insights garnered in this study can be applied to a range of potential future military operations in the western Pacific. The measures of effectiveness (MOEs) used to define success to are:

- Lethality: Number of adversary forces that survive the engagement and reach their objective. Less than 50% is deemed mission success.
- Survivability: Number of friendly artillery units that retain combat effectiveness throughout the scenario.

This study evaluates capabilities as well as tactics, techniques, and procedures (TTPs). The following research questions are posed:

1. Which factors most significantly influence lethality and survivability of rocket artillery in a defense-of-Taiwan scenario?
2. In this scenario, what factor levels are most robust to varying adversary factors?

C. METHODOLOGY

A scenario is developed using the stochastic, agent-based simulation environment Map Aware Non-Uniform Automata (MANA) (McIntosh et al. 2007). The scenario is adapted from a recent wargame conducted to compare courses of action and strategies over

Chinese aggression towards Taiwan. Specifically, this wargame focuses on an amphibious assault of Taiwan. Four separate and progressively more complex experiments are implemented in MANA. An efficient design of experiments (DOE) is implemented to assess a range of factor levels in the last two experiments. Specifics concerning MANA, this scenario, and assembly of the DOE will be reviewed in following chapters.

Data generated from this simulation are analyzed using the statistical analysis software JMP (SAS 2021). Insights gained through this analysis can be considered for use in continued refinement of rocket artillery TTPs or as inputs to future studies and wargames.

D. ORGANIZATION

Chapter II provides a literature review and background covering artillery operations, USMC rocket artillery capabilities and TTPs, pacing threat capabilities and limitations, factors for the DOE, and previous research relevant to this study. Chapter III covers the adapted simulation scenario, modeling environment, as well as the conceptual and computer models used for data farming. Chapter IV examines factors more closely and provides an explanation of the experiment methodology, specifically the DOE used in each of the experiments and provides a justification for the use of DOE. Chapter V offers an analysis of the data farmed in each of the experiments. The analysis seeks to provide increased understanding of the factors most critical to rocket artillery success against a peer threat in the western Pacific. Chapter VI draws final conclusions concerning the proposed research questions. Recommendations for future studies in this area are also provided.

II. BACKGROUND AND LITERATURE REVIEW

Chapter II provides background on the artillery process and its employment, particularly in the USMC, Chinese strategy and military capabilities, and closes with descriptions of the factors that are assessed in this study.

A. ARTILLERY BACKGROUND

> The mission of artillery is to furnish close and continuous fire support by neutralizing, destroying, or suppressing targets that threaten the success of the supported unit.
>
> —Marine Corps Tactical Publication 3–10E (USMC 2018a)

This section outlines the basics of artillery operations and provides background into how artillery is structured and employed in the USMC.

1. Artillery Operations

The artillery process has three basic components which work together in order to accomplish its mission: target acquisition, the command and control (C2) system(s), and the weapon system itself. Target acquisition is the means by which units detect, identify, and locate a target with enough accuracy and precision to call for artillery. C2 systems ensure that fires are properly planned, coordinated, and controlled. The weapon system is the cannon or rocket launcher which will engage the target (USMC 2018a, p. 1-1). The following paragraphs describe how these three components work together.

Target acquisition can be accomplished in several ways. Forward observers can visually acquire targets, or they can use enhanced optics such as laser rangefinders to acquire and locate the targets. More recently, aircraft, manned or unmanned, and radar systems have been used for target acquisition as well. Upon positively identifying the target as a threat and establishing its location, the observer will create and transmit a call-for-fire (CFF). The CFF is a request which contains all the necessary information for the firing unit to prosecute that target. Depending on the C2 control structure in place, the CFF can be sent to one of two places. In centralized control, the CFF is transmitted to the Fire Support

Coordination Center (FSCC). The FSCC is responsible for clearing and deconflicting all fire missions in a particular battle space, and once complete, they will forward the CFF to the firing unit. In decentralized control, the CFF goes directly to the firing unit while the FSCC passively listens on the communications net to clear the fires.

Once the firing unit has received the request, the fire direction center (FDC) begins to compute a firing solution for the mission. They then transmit the firing solution to the weapon systems which can proceed to prosecute the target in accordance with the FDC's instructions. The observer then observes the effects and chooses to adjust fires, repeat, or end the fire mission.

2. USMC Artillery

As mentioned in Chapter I, Marine Corps artillery is in the early stages of implementing a comprehensive redesign in which 14 cannon batteries will be replaced by 14 rocket batteries. Currently, the force is organized into three active artillery regiments and one reserve regiment. The typical force organization calls for three battalions per regiment although this is not how the active regiments are currently structured. There are two cannon battalions in 10th Marine Regiment, one rocket and three cannon battalions in 11th Marine Regiment, and two cannon battalions in 12th Marine Regiment. According to the Tentative Manual for Expeditionary Advanced Base Operations (EABO), the expected organization for Marine artillery in 2030 will be hybrid battalions heavily weighted with rocket batteries over cannons (USMC 2021). These battalions will contain both High-Mobility Artillery Rocket System (HIMARS) and Navy Marine Expeditionary Ship Interdiction System (NMESIS) units. The increased prevalence of rocket artillery combined with limited institutional knowledge of employment methods compels the USMC to conduct research in this area.

The M142 HIMARS is the current rocket artillery platform in use by the Marine Corps. It consists of a Multiple Launch Rocket System (MLRS) launcher mounted atop a M1140 family of medium tactical vehicles 5-ton chassis. It is operated by a crew of three, and it contains all the equipment required to calculate technical firing data, conduct resupply, and communicate. The launcher can hold either six rockets or one missile depending on the ammunition loadout. In addition to firing precision munitions, HIMARS has a maximum range between 70 and 300 kilometers depending on the munition family and variant. Ammunition resupply is provided via the resupply system which is a medium tactical vehicle replacement modified with a flatbed trailer (USMC 2008).

In the past, Marine HIMARS units have been tasked to provide fire support at the Marine Expeditionary Force or division level. Once the force redesign is fully implemented, the greater number of rocket batteries will allow HIMARS units to support lower echelons of maneuver units as well as naval missions and priorities.

In terms of supporting relationships, Marine artillery has existed to support the infantry. An artillery regiment supports an infantry division, an artillery battalion supports an infantry regiment, and an artillery battery supports an infantry battalion. This structure is subject to change drastically following full implementation of FD30.

B. ADVERSARY BACKGROUND

The following section provides background on the adversary in this research's scenario. It discusses Chinese strategy, international relationships, recent acts of belligerence by China, and its military capabilities.

1. Chinese National Strategy

China's vast economic and military growth in the past several decades is no accident. The leadership of the ruling faction, the Chinese Communist Party (CCP), has clearly stated its strategic objectives of reaching parity with the United States. A report by the Center for International and Strategic Studies argues that the CCP's primary strategic aim is "to realize long-held nationalist aspirations to 'return' China to a position of strength, prosperity, and leadership on the world stage" (Cordesman et al. 2021, p. 18). The CCP views themselves as vying for position with other nations, particularly the United States, both regionally and globally.

Militarily, China, also known as the People's Republic of China (PRC), describes their strategy as one of "active defense" (Cordesman et al. 2021, p. 19). This does not suggest a lack of offensive or preemptive action. Rather, the PRC will justify their acts of perceived or actual aggression as defensive in nature to protect their national interests. With regards to capability, the PRC expects to have a “world-class” military by 2049. The DOD’s interpretation of “world-class” is a force that is on par with—or in certain facets superior to—the U.S. Military (DOD 2020). It is well understood among government and defense officials that China seeks to develop their military into one that can compete with the United States.

2. Relationships between China, Taiwan, and the United States

Since 1949, Taiwan’s government has been independent from that of the PRC. Taiwan has a democratic system of government, as opposed to the CCP which rules over mainland China. Taiwan maintains their independence from the PRC, while the PRC vows to someday unify the two countries (Maizland 2021). In January 2019, China’s president, Xi Jinping, refused to rule out reunification by force, stating that, “no option is excluded” (Sullivan 2021). This stance reflects China’s determination to remove the island’s current status and bring them back under the control of the CCP.

The mismatched viewpoint between China and Taiwan can largely be tied to an agreement known as the 1992 Consensus. This arrangement between the CCP and the governing party in Taiwan at the time supports the “one-China” policy, however the two sides hold different interpretations of that policy (Maizland 2021). It should be noted that Taiwan does not currently recognize this agreement.

The United States’ relationship with the two countries is complex. In 1979, the United States-People’s Republic of China Joint Communique established our diplomatic relationship with China, specifying our acknowledgement that the PRC is the sole legal government of China. However, we maintain an unofficial relationship with Taiwan that includes significant arms sales to their military (Department of State [DOS] 2018). The Taiwan Relations Act (H.R. 2479, 96th Cong. (1979)) specifies the legal foundation of our relationship. As it applies to this research, the resolution explains the United States’ stance on the defense of Taiwan:

> The United States shall provide Taiwan with arms of a defensive character and shall maintain the capacity of the United States to resist any resort to

> force or other forms of coercion that would jeopardize the security, or social or economic system, of the people of Taiwan.

It could be argued that in the eyes of the United States, Taiwan's current status and their geographic location in a strategically significant region contribute to the criticality of their defense. The United States' ongoing position has been that of "strategic ambiguity." That is, the U.S. will maintain the ability to defend Taiwan without publicly committing to this in order to maintain the status quo and continue productive relationships with both countries (Maizland 2021).

3. Chinese Aggression

In the past decade, the PRC has become more audacious in their actions and rhetoric towards territorial disputes and sovereignty. PRC leaders reiterate the desire and determination for reunification of Taiwan, suggesting that unification by force is not discounted. China also claims control over several strategically significant land features in the South China Sea and the waters surrounding them. These include the Spratly Islands, the Paracel Islands, and the Scarborough Shoal, some of which are also claimed by the Philippines, Taiwan, Vietnam, Malaysia, and Brunei (Council on Foreign Relations [CFR] 2021). They are also building artificial islands, bringing submarine reefs above the water to use for airstrips and other strategic infrastructure. The total area claimed by the PRC is delineated by the "nine-dash line," a U-shaped border that encompasses the majority of the South China Sea. Its validity has been challenged by the U.S. and others on the basis that it violates international law by claiming maritime territory with no land features to originate from (Bader 2014).

Recently, China has been increasing the number of aircraft it sends to violate Taiwan's air-defense identification zone. On October 4, 2021, the People's Liberation Army (PLA) sent 56 aircraft into the zone breaking the previous weekend's record for the most in a single day (Ellis 2021). This was assumed to be a response to a large-scale naval exercise conducted by the U.S. in the East Philippine Sea. China has also been conducting noteworthy exercises of their own. As one telling example, in August 2021, a PLA composite air and naval force held assault drills just off Taiwan's southern coast. The exercise was justified as “necessary to safeguard China’s sovereignty” (Associated Press [AP] 2021).

4. The People’s Liberation Army

The PLA is the military power behind the CCP. A large force of approximately two million, the PLA has been steadily transitioning from a rigid, infantry-focused, low-technology force into a capable, technologically sophisticated military with a focus on naval and air power (Campbell 2021, p. 1). The PLA’s modernization has been a conscious effort by the CCP leadership since the 1990s, and their growing power projection capabilities are a major source of concern for the United States and its allies.

Unlike most modern militaries, the PLA serves the CCP itself, not the state. As such, the PLA is a major contributor towards achieving the goals of the CCP. The CCP identified some of it major goals and aims in a defense white paper from July of 2019. Some of the aims pertinent to this research are listed here:

- To oppose and contain “Taiwan independence”
- To safeguard national sovereignty, unity, territorial integrity, and security
- To safeguard China’s maritime rights and interests (Campbell 2021, p. 14)

In the eyes of the CCP, the first two goals are intertwined; Taiwan’s independence is the greatest threat to China’s sovereignty, unity, and territorial integrity. Unification is and has been their primary national defense priority for decades (Campbell 2021, p. 15). Experts disagree on the possibility and potential timeline for when China may attempt unification by force, but most agree that it remains a top concern of the CCP.

Regarding maritime interests, China’s activity inside of the first island chain is illustrative of their increasing capabilities. It does not matter that they have not reached parity with the United States Navy in terms of global power projection. For now, they only need to compete with the U.S. regionally where they hold the advantage. And their rapidly growing naval proficiency indicates that they can compete with the U.S. in the Western Pacific Region.

The PLA is divided into four main branches: the Army, PLA Navy, PLA Air Force, and PLA Rocket Force. Additionally, there are two sub-branches to assist in overall control and joint operations: the Strategic Support Force and the Joint Logistics Support Force. Since this research primarily concerns the PLA Navy (PLAN), a brief background on its roles and capabilities is provided in the following paragraphs.

According to a report by the Congressional Research Service, the PLAN is composed of approximately 350 battle force ships, making it the largest naval force in the world (Campbell 2021, p. 29). The report also notes that its mission set has recently expanded from coastal and largely peripheral defense to include missions such as power projection and ensuring safe sea lanes for trade.

The report also describes the capabilities of the subordinate branches of the PLAN, the Naval Aviation Branch and the Marine Corps Branch. Its naval aviation capabilities include antisubmarine warfare, logistics support, early warning, maritime patrol, and maritime strike missions. The PLAN Marine Corps is designed for amphibious and expeditionary operations, and thus would have a significant role in any forcible Taiwan unification scenario. The report concludes that the PLAN is becoming increasingly modernized, replacing aging platforms with highly capable new ones. Some notable examples of modernization include aircraft carriers, amphibious ships, nuclear submarines, and fourth-generation carrier-based fighter aircraft.

C. STUDY FACTORS

The factors discussed in this section are integrated into the design of experiments (DOE) to gain insight into their effects on survivability and lethality as well as their relationships with each other. This is done through a collection of techniques known as data farming. When data farming, analysts deliberately build and manipulate their model in such a manner that the data produced will maximize the yield of their experiments (Sanchez 2018). Of note, factors common to this study and Captain Kadrmas' thesis include employment, time in position, and emplacement and displacement. Conclusions regarding these factors from his research are discussed in each respective section.

1. Employment Method

Artillery batteries can be consolidated as a whole battery or distributed down to the section/launcher/cannon level. There are advantages and disadvantages to these extremes and the levels between them. Traditionally, artillery has been employed as a consolidated battery (if not as a battalion or regiment). Consolidation at a higher level provides more manageable C2 requirements, colocation of key leaders, simpler logistics considerations, and a stronger defense around the unit's position. Some disadvantages with consolidation include greater signatures (light, noise, emissions) and closer proximity of artillery pieces which both aid the enemy in detecting, locating, and targeting artillery positions. Another disadvantage is the complete loss of fire support when the unit is not fire capable (FIRECAP).

The next distribution level down is known as split-battery. This consists of splitting the battery into two geographically dispersed firing platoons of three launchers each. This improves the units' ability to survive indirect fire but limits their ability to mutually support each other in the event of a ground attack. It also complicates C2 in that each platoon will have their own FDC receiving CFFs and controlling their respective launchers.

A battery can continue to disaggregate down to two-launcher units or even to individual launcher sections. This is known as conducting distributed operations. As disaggregation increases, so does survivability and coverage of fires during displacements. However, massing, mutual support, local security, and effective C2 become more difficult as the battery disaggregates. It should be noted that rocket launchers are generally more suited for distributed operations than cannons due to their organic C2 equipment. Employment also has impacts on other factors including time in position and emplacement and displacement.

One of the key findings of Captain Kadrmas' thesis is that increased disaggregation is critical for bolstering a cannon battery's survivability and lethality in a Russian counterbattery scenario (Kadrmas 2021). This study seeks to determine whether that finding holds for rocket batteries employed in a Taiwan defense scenario.

2. Ammunition Load Out

The M142 HIMARS launcher can be outfitted with a variety of munitions. The first delineation is between rockets and missiles. Each launcher can hold a rocket pod containing six 298-millimeter rockets or a missile pod containing one 607-millimeter missile. The Marine Corps primarily uses rockets and currently would need to rely on Army stockpiles to be allocated missile pods.

The Marine Corps uses two types of guided rockets in the M142, the M30 and M31. The M30 is the Dual-Purpose Improved Conventional Munition (DPICM); each munition contains 404 M101 grenades. The range of the M30 is from 15 to 84+ kilometers, and its GPS guidance system ensures a seven-meter circular error probable—50 percent of the rounds fired will land inside of a seven-meter radius of the target. The M31 Guided Multiple Launch Rocket System (GMLRS) delivers comparable accuracy and range as the M30 but with a different payload. The M31 contains a 200-pound high-explosive (HE) warhead which allows for the prosecution of targets using point-detonating, proximity, or delay fuses (USMC 2008, p. 5-1 – 5–2).

The missiles used in the M142 come from the Army Tactical Missile System (ATACMS) family of munitions. The missiles in this family are broken into five different types. The first two contain antipersonnel bomblets which are dispersed by the missile. The third contains an armor penetration warhead in the form of 13 shaped charge submunitions. The fourth ATACMS missile is a penetration warhead, and the last contains a 500-pound HE warhead. The ranges of these missiles vary, but generally can reach up to 270 kilometers (USMC 2008, p. 5-3). More specific measures of performance for the munitions employed by the M142 can be found in Appendix A (Table 5–1 from MCIP 3–16.02).

These different munitions provide variability not only in measures of performance, such as range and accuracy, but also in methods of employment. Situations in which unitary warhead missiles are the most appropriate choice are vastly different from those in which DPICM are employed. This thesis seeks to gain insight into which munitions are critical to lethality and survivability.

3. Time in Position

This thesis defines time in position as the length of time that a firing unit remains in a position before conducting a survivability move given that they do not receive a fire mission and are not targeted by the enemy while in that position. The tradeoff with this factor is one between survivability and responsive fire support.

A battery is detectable at any time by visual observation, unmanned aerial systems (UAS), or through its electronic emissions. However, the probability of detection increases greatly after firing a mission. At that point, any near-peer adversary will have the capability to locate the firing unit's location through counterbattery radar systems detecting the projectile. Since rockets fire their entire pod during a mission, tactically it makes sense to immediately displace upon firing. This is also the proper course of action if the battery is fired upon. The question arises, how long to stay in position if neither of these events occur?

A battery must conduct survivability moves to decrease the probability of detection by an enemy observer or acquisition system. The drawback of conducting these survivability moves is that the firing unit loses its ability to provide fire support. Displacement, movement, and emplacement take time, time that the unit is not FIRECAP. The more often a unit displaces, the more survivable they become. Unfortunately, their provided fire support becomes more intermittent.

This factor also relates to others in this study. If a unit is operating in a more distributed manner, then survivability moves will create less of a gap in fire support provided the moves are coordinated between units and positions. However, a battery operating at the consolidated level will leave their supported unit with zero artillery fires during their movement. There is also the consideration of firing unit size as it relates to targetability by the enemy. A single section or launcher may not meet the enemy's targeting requirements. That is, they may not be willing to risk unmasking their own firing units to prosecute such a small target. Time in position also relates to the next three factors, defensive fires, emplacement, and displacement. Their relationship is discussed in the next sections.

4. Defensive Fires

Defensive fires is a binary factor which studies the reaction of a firing unit receiving effective indirect fire. This research examines whether it is prudent for a HIMARS unit under fire to execute a defensive fire mission prior to displacement. Captain Turk found that a counter battery mission prior to displacing takes advantage of friendly radar capabilities and helps to limit the vulnerability of a firing unit during the actual process of displacement when they are not FIRECAP (Turk 2020). This research examines this factor as a simple binary yes or no. Does the firing unit employ this factor or not?

5. Emplacement and Displacement Time

Emplacement and displacement are the actions required for a battery to occupy and leave a firing position, respectively. With regard to emplacement, this research is specifically concerned with the time between a firing unit's arrival in a position and the time that it becomes FIRECAP. Conversely, displacement is the time between losing FIRECAP and physical movement out of the position.

Emplacement and displacement times plus the actual movement time comprise the total amount of time that a unit is not FIRECAP. The movement time is generally uncontrollable, but emplacement and displacement times can be decreased through individual unit proficiency. Additionally, faster displacement times should increase survivability by allowing a unit to depart the position before the enemy can target it. Captain Kadrmas found that for cannon artillery, emplacement and displacement times alone are not significant factors, but they produce some interesting interactions with other factors in his study (Kadrmas 2021).

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III. MODELING

This chapter introduces the simulation scenario, first at the strategic level, then at the operational level, and finally, at the tactical level where this simulation focuses. Chapter III also provides introductions to the conceptual and computer models that are used for analysis.

A. SIMULATION SCENARIO

The following scenario is adapted from an unclassified, publicly available wargame produced by Dr. Ian Sullivan, a special advisor for analysis and intelligence, surveillance, and reconnaissance at the U.S. Army's Training and Doctrine Command. The scenario presented has been adapted for this research's aims and is not meant to be predictive but is for analytical purposes alone.

1. Strategic Level Scenario

After years of successfully modernizing the People's Liberation Army (PLA), the People's Republic of China (Red) is now confident in their capability to force unification with Taiwan through an amphibious assault. As the United States (Blue) continues to bolster its forces and alliances in the Western Pacific, Red leadership feels that its window of opportunity is rapidly closing. Red opts to commit its forces to an all-out amphibious invasion of Taiwan with the goal of forcing the Taiwan authorities' submission before America and its allies can intervene.

To gain a foothold, the PLAN Marine Corps launches amphibious assaults on the Spratly and Paracel Islands on D-6 and D-5, respectively. These are depicted in Figure 1. On D-2, they occupy the southern-most Japanese Ryukyu Islands. Then on D-1, they conduct an amphibious assault against Taiwan forces holding Penghu Island just off Taiwan's western coast. To blunt the United States' ability to respond, the PLA Air Force targets air bases on Guam and Japan with ballistic missiles. Large numbers of the bombers and fighters stationed there are destroyed.

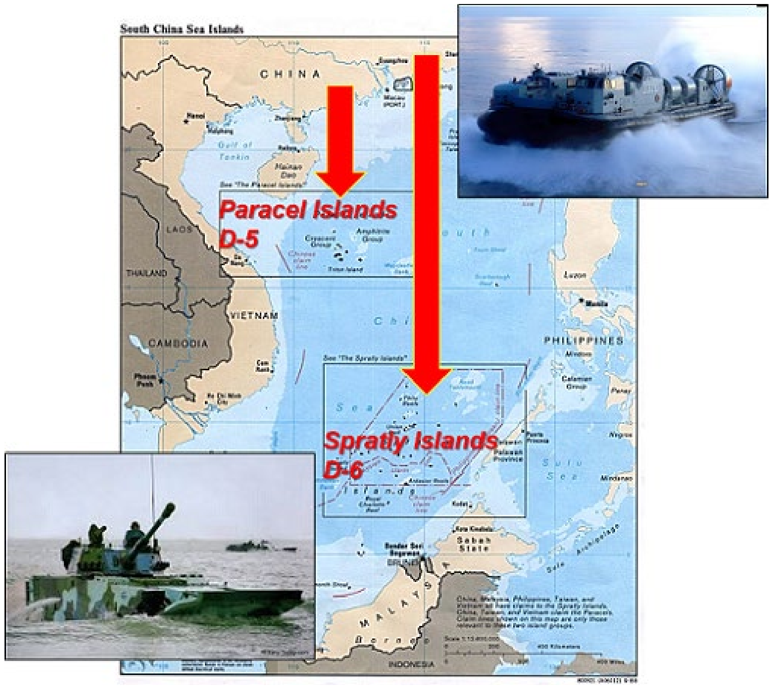

Figure 1. Notional Preparatory Attacks by PLA. Source: Sullivan (2021).

Taiwan forces are mobilized and begin manning defensive positions and fortifications around the island. Blue begins weighing options for assisting in the immediate defense of the island while simultaneously diverting forward-deployed naval forces to the vicinity of Taiwan.

2. Operational Level Scenario

Red is steaming their invasion force across the Taiwan Strait in a combination of amphibious PLAN ships and civilian merchant marine ships. They plan to conduct their main assault on Taiwan in the vicinity of the city of Hsinchu with one Marine Brigade landing southwest of the city in landing craft and one Airborne Brigade parachuting into a drop zone east of the city. Hsinchu is defended by one Taiwan Army Brigade.

The Red Marine Brigade's immediate objective after landing is to seize the strategically critical Taoyuan International Airport. The base is currently defended by one Taiwan battalion. Upon seizing the airbase, Red plans to use it to build up combat power in preparation for an assault east to seize Taipei. The airbase is hereafter referred to as Objective A.

Meanwhile, Blue is mobilizing the 3d Marine Expeditionary Brigade (MEB) out of Okinawa to reinforce the Taiwan forces currently preparing and hardening the island's defenses. Taiwan forces attempt to delay and harass Red's movement across the Strait using coastal defense cruise missiles. They experience limited success and manage to destroy a small number of merchant marine ships.

The 3d MEB lands their first wave of reinforcements on the east coast of Taiwan at Chiashan Air Force Base. Among those reinforcements is a HIMARS battalion. The Blue HIMARS battalion is tasked with occupying position areas for artillery (PAAs) to provide fires supporting the defense of Objective A in order to enable the Taiwan forces' containment of the landing forces.

3. Tactical Level Scenario

Red has landed south of Hsinchu and is currently establishing its beachhead and preparing to send its assault forces northeast towards Objective A. Red's Marine Brigade maneuver forces consist of four differently structured infantry battalions: an air assault battalion, and heavy, medium, and light combined arms battalions.

The combined arms battalions maintain their organic mobility through several vehicle variants to include tracked ZBD-05 Infantry Fighting Vehicles (IFVs), tracked ZTD-05 Assault Vehicles, 8-wheeled ZBL-09 IFVs, and 8-wheeled ZTL-11 Assault Vehicles. The maneuver forces are supported by PLZ-07 122-mm and PLZ-05 155-mm self-propelled howitzers integrated into the combined arms battalions. They are also typically supported by a battery of self-propelled MLRS, and two batteries of 152-mm towed artillery batteries in a separate artillery battalion. For this operation, Red has substituted one MLRS battery for one of the towed cannon batteries giving its artillery battalion a total of two MLRS batteries in order to maximize its long-range fires assets.

Blue consists of 18 M142 HIMARS launchers split into three batteries of six launchers each. Blue forces are establishing firing positions approximately 15–20 kilometers inland and approximately 60 kilometers southeast of Objective A. Table 1 provides a more detailed order of battle for both sides.

Terrain around Blue's positions is rural and flat, but the terrain between Blue and the objective area is dominated by a large tropical mountain range. The terrain around Red is sporadically populated with gentle rolling hills and dense vegetation. There are well-established road networks in both Red's and Blue's areas of operation allowing for reasonable mobility.

To avoid any unintentional replication of current Operation Plans, the simulation is overlayed onto a map of the Island of Hawaii which is similar to Taiwan in terms of battlefield geometries and terrain. Again, this model is not meant to be predictive, so this map allows for analysis at a lower classification level. The area of operations measures approximately 100 kilometers by 50 kilometers and is displayed in Figure 2.

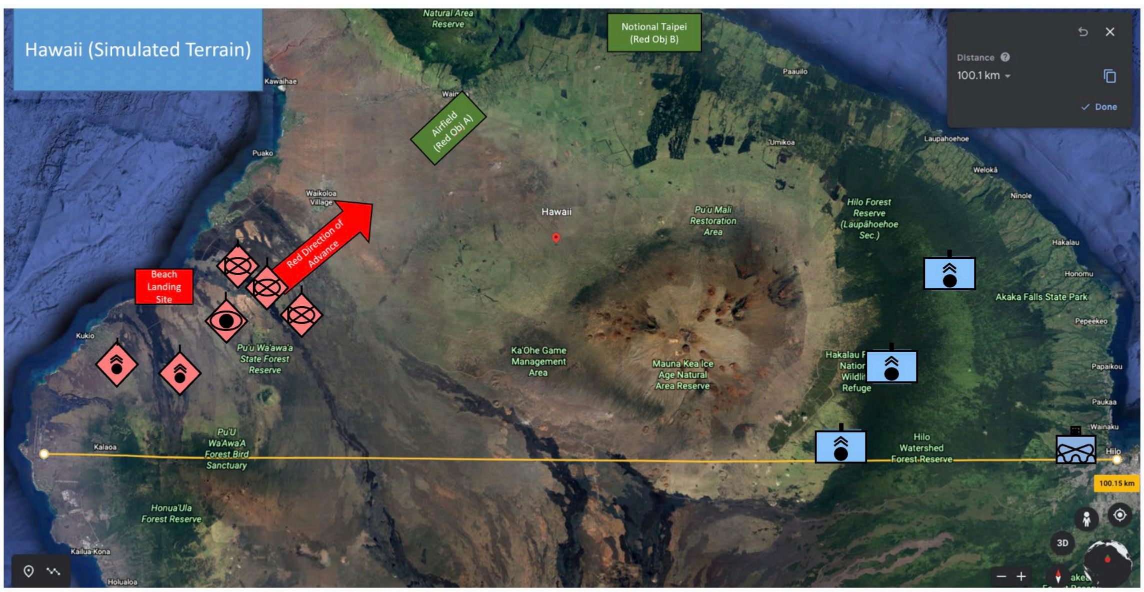

Figure 2. Simulated Area of Operations, Hawaii

B. CONCEPTUAL MODEL

The goal of this model is to gain insights about the employment of Marine Corps rocket artillery while defending Taiwan in an invasion scenario. An amphibious assault of this scale is a highly complex operation with hundreds of different units on each side. To appropriately scale and focus the model, it only considers units that are engaged in a smaller operation within this larger campaign. Specifically, this operation of interest is the seizure of a strategic airfield by a PLAN Marine Brigade, and its defense which is augmented by a USMC HIMARS battalion.

Red rapidly moves towards their objective to accomplish their mission of seizing the airfield. To simplify the model, Red has been reduced from one PLAN Marine Brigade to a single combined arms battalion consisting of three companies of 14 ZBD-05's each. While the mechanized forces focus on seizing the airfield, the two MLRS batteries have been tasked with suppressing Blue fire support. Since this is Red's only fires asset capable of ranging Blue, it focuses entirely on counterbattery missions. Red relies on UAS and counterbattery radar to acquire its targets. As long as the MLRS unit is FIRECAP, acquiring a target automatically triggers a fire mission.

Blue's mission is to destroy Red forces to prevent the seizure of the airfield. Due to the rapid onset of this operation, there is assumed to be limited communication or coordination between Blue and the Taiwan forces. Blue is providing their own target acquisition via organic UAS and counterbattery radar, and similar to Red, acquisition by Blue automatically generates a fire mission given that there is a FIRECAP unit to execute it. It should be noted that the Taiwan battalion is not included in order to focus the model on interactions between Red and Blue.

When a Red unit comes under fire, it immediately executes an emergency displacement. However, Blue defensive fires is a TTP factor analyzed in this study, and thus Blue's reactions vary between immediate displacement and rapidly firing one volley of rockets before conducting the emergency displacement. In initial experiments, Red conducts survivability moves at set times unless fired upon. Blue, on the other hand, conducts survivability moves at varying time intervals to study the effect of time in position on survivability and lethality. As a simplifying assumption, ground-based rocket fires are the only fire support considered for either side in this simulation.

C. COMPUTER MODEL

This section introduces the modeling environment used in this study and describes the agent personalities and states built into the model. As this research is building on the work by Captain Kadrmas, his model serves as the starting point. That is, many of the agents and state transition schemes are either directly repurposed from his model or altered slightly to meet new analysis goals. Agent capabilities and personalities are based on open-source data, primarily obtained from Janes.

1. MANA Overview

Map Aware Non-Uniform Automata (MANA) is an agent-based, stochastic, mission-level combat simulation environment developed by New Zealand's Defence Technology Agency (McIntosh et al. 2007). Agent-based models are built around autonomous agents interacting with each other and their environment based on pre-programmed "personalities" or tendencies. Agent-based modeling is well-suited for military concept exploration and validation due to its ability to simulate complex realistic behavior without needing to represent every aspect of the simulation with a mathematical model (Cares 2002). As implied by MANA's name, agents have awareness of their environment either through their own sensors or by communicating with other agents, and they are non-uniform, meaning that different classes of agents have their own unique parameters (Lucas 2021a).

Agents in MANA cannot follow any overarching commander's intent. Any action they take is the result of their parameter settings interacting with the environment around them. The modeler cannot predetermine the behavior. This limitation can often result in what is known as emergent behavior, behavior that is not explicitly programmed into the simulation.

MANA allows analysts to explore a broad range of inputs and outcomes efficiently. Agent personalities can change based on triggers on the battlefield which move the agent into a new state. This allows for the programmer to simulate a wide set of agent behaviors under varying conditions. The graphical user interface is intuitive and simple allowing for quick turnaround on building simulations and conducting analyses.

As mentioned, MANA is stochastic. This characteristic allows for a variety of outcomes in scenarios with identical parameter settings and terrain. Each simulation run is tracked by a pseudorandom seed number which is captured in the output to allow for further exploration of interesting results.

2. Agents, Squads, and Personalities

Agent parameters can be grouped into four fundamental types. The first type are personality weightings, which are numerical indications of an agent's baseline tendency to move towards or away from various objects on the battlefield. For example, an agent can be programmed to tend to avoid enemy agents, travel on easy-going terrain, and work to move to its next waypoint. The next parameter type is move constraints which work as modifiers for the personality settings. An example would be the combat move constraint which dictates a minimum ratio of friendly to enemy agents that must be present for a group of agents to engage. The third type are the tangible characteristics of the agents. These include speed, organic weapons, and communication links. As mentioned, these characteristics are obtained from open source databases such as Janes. The Appendix provides more detailed information on the characteristics of agents modeled. And the last type of parameters are the ways to adjust the movement of agents based on obstacles, terrain type, and stochasticity.

In MANA, agents are broken into squads. Squads can be any size, but the agents within it share the same personality and capabilities and switch as a group in between states. A state is a parameter setting which is tied to events on the battlefield. States are covered in greater detail throughout this chapter.

The transitions between states and the corresponding personalities of squads in those states are what allows MANA to simulate realistic tactical scenarios with a variety of different outcomes. Thus, great care must be taken to ensure the personalities and state transition triggers are reflective of what the analyst seeks to simulate. For example, a patrolling squad in MANA will enter the "Enemy Contact" state when a member of the patrol senses an enemy agent. If the goal of the patrol is to initiate contact, then the corresponding personality changes may include a decreased propensity to reach the next waypoint and an increased propensity to move towards enemy agents.

3. Terrain Map

In MANA, the battlefield is defined by a terrain map which is a collection of colored cells, each representing different types of terrain. Each type of terrain is defined by settings for the three parameters going, cover, and concealment. Going captures how terrain limits an agent's speed. Cover defines what level of protection the terrain provides from enemy fire. And concealment describes the level to which terrain hides an agent from visual acquisition by an enemy. As an example, Dense Bush terrain is defined by a going value of 0.4 (significantly limits mobility), a cover value of 0.15 (provides small amount of protection from enemy fire), and a concealment value of 0.35 (provides some concealment). The terrain map used is displayed in Figure 3.

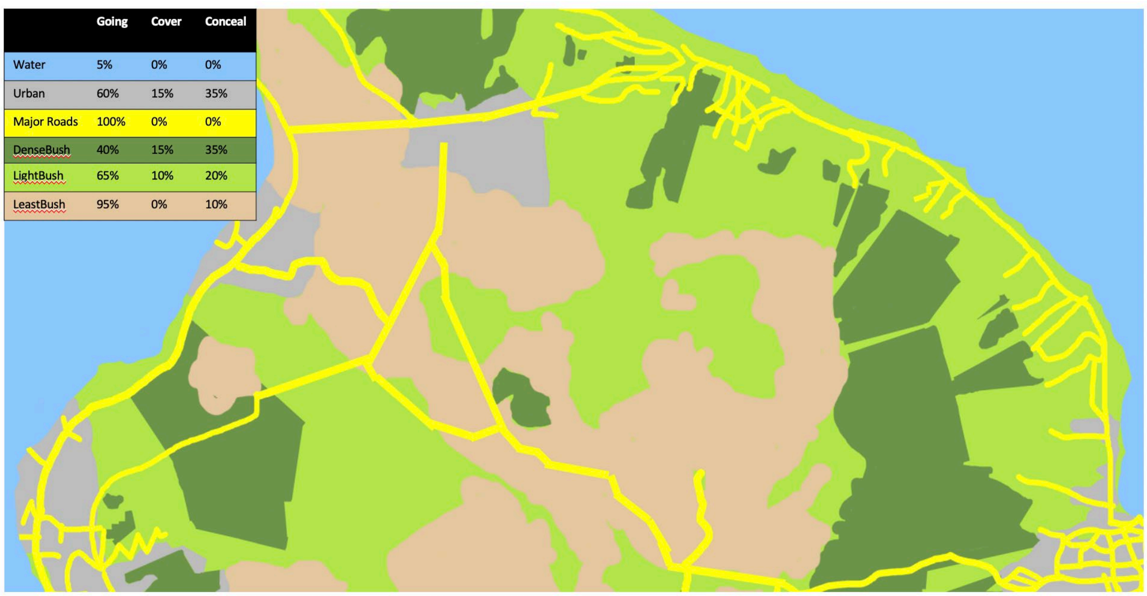

Figure 3. Simulation Terrain Map with Terrain Settings

Agents move around the battlefield according to their personalities. For example, a resupply convoy with a high propensity for easy going terrain will stick to improved roads with high going settings at the risk of having limited cover and concealment. On the other hand, a rifle squad on a reconnaissance patrol may have higher propensities to get to their next waypoint while maintaining cover and concealment which will clearly result in their taking a different route. These are simple examples of how agents' personality settings affect their behavior on the battlefield.

4. Acquisition and C2 Agents

As mentioned, both Blue and Red exclusively use UAS and counterbattery radar for target acquisition. This section describes the modeling logic behind these systems as well as their integration with C2 systems in the artillery process.

The two main actions for sensors in MANA are detection and classification. Detection is the sensing of an agent, whereas classification can be equated to positively identifying the agent's class and determination of friend or foe. To control which targets are detectable by which acquisition system, this model mirrors Captain Kadrmas' by assigning agents a class that can vary with their state:

- Class 1: Non-targetable (C2, Acquisition agents)
- Class 2: Undetectable (Displacing, Moving, or Emplacing)
- Class 3: FIRECAP, but have not recently fired (Masked)
- Class 4: FIRECAP, and have recently fired (Unmasked)
- Class 5: Maneuver agents, always detectable

To reflect each side's mission priorities, Red has a single UAS for target acquisition, and Blue employs two. They each operate in a predetermined search pattern over the respective target areas. The UAS agents have personality settings which cause them to loiter near detected agents. So, rather than immediately proceeding to the next waypoint, the UAS spends more time correctly classifying the agent. UAS can detect all FIRECAP firing agents (Class 3 or 4) and maneuver agents (Class 5). Once detection and classification occur, the system automatically sends a CFF to all FDCs. The CFF is transmitted with a 30-second latency to mimic real-world delays. The UAS ceases loitering after a personality-driven decision to continue to its next waypoint. Similar to Captain

Kadrmas' model, both sides' UAS agents are derived from tactical level reconnaissance UAS currently in use by Red and Blue forces.

Counterbattery radar provides forces with the capability to determine a firing unit's location by using a projectile's trajectory to determine its point of origin. As such, these systems are only be able to detect and classify firing agents who have recently fired (Class 4). Once these systems successfully detect and classify the agent, they perform the exact same steps as the UAS. They immediately generate a CFF and transmit it to the FDCs with a 30 second latency.

Typically, counterbattery units are held at the regimental level, and thus a single radar system supports an entire artillery battalion. This organization creates an issue of deconflicting counterfire missions. MANA is not able to deconflict these missions between the batteries with only one radar system. To circumvent this issue, the model applies a workaround originally implemented by Captain Kadrmas. One counterbattery radar with degraded performance is assigned to each battery, and the systems are instantiated at staggered times. In this case, degraded performance means that the detection times are slower, and the probability of classification is decreased. This workaround allows for three systems to have the aggregate performance of one fully operating radar. The staggered instantiation means that counterbattery fires are deconflicted as each battery only executes missions on targets found by their corresponding radar.

It is worth noting that the USMC's counterbattery radar system, the Ground/Air Task Oriented Radar (G/ATOR), does not possess adequate range to be employed in this scenario. The separation of Red and Blue forces is much farther than the unclassified 50-kilometer coverage for medium caliber rockets that G/ATOR provides. To meet modeling goals, it is assumed that both sides have sufficiently capable radar through relying on joint assets.

The battery FDCs represent the C2 nodes in this model. The FDCs are stationary and passively wait for CFFs to be sent from the acquisition agents. Once a CFF is received, the FDCs transmit fire commands to their respective firing units to execute the mission. The fire commands are sent with a 120-second latency to reflect mission processing time based on the artillery Training and Readiness standards (USMC 2018b). Upon transmitting the fire commands, FDCs return to passively standing by for targets. The state behavior diagrams for the acquisition and C2 agents demonstrate how they work together, and they are shown in Figure 4.

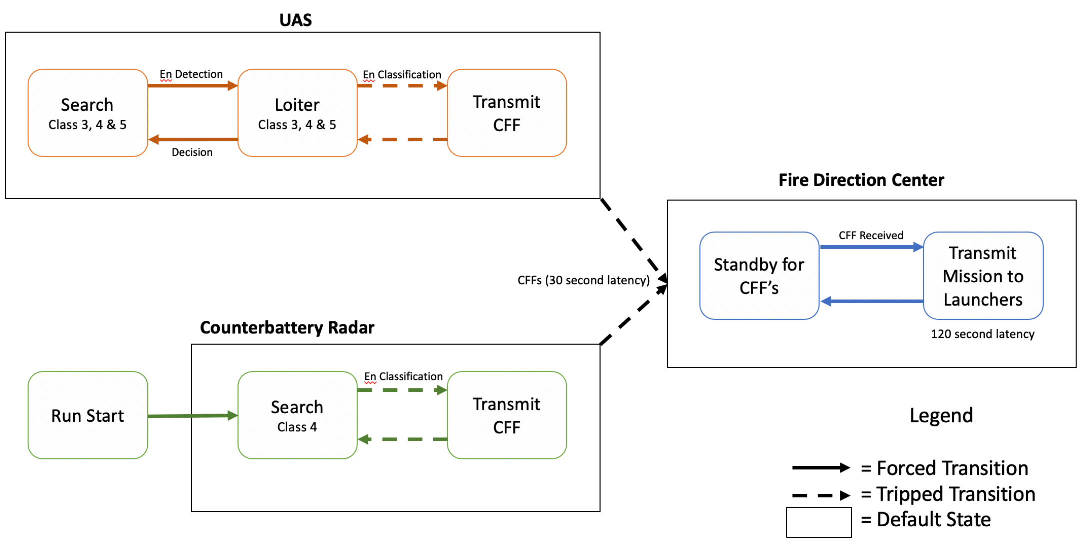

Figure 4. Acquisition and C2 Agent States and Behavior

5. Firing Agents

Red's firing agents are based on the MLRS agents used in Captain Kadrmas' model. They possess the same personality characteristics, just with slightly different behaviors in each state to reflect the differences in situation and mission. Figure 5 displays the state diagram for the Red MLRS batteries.

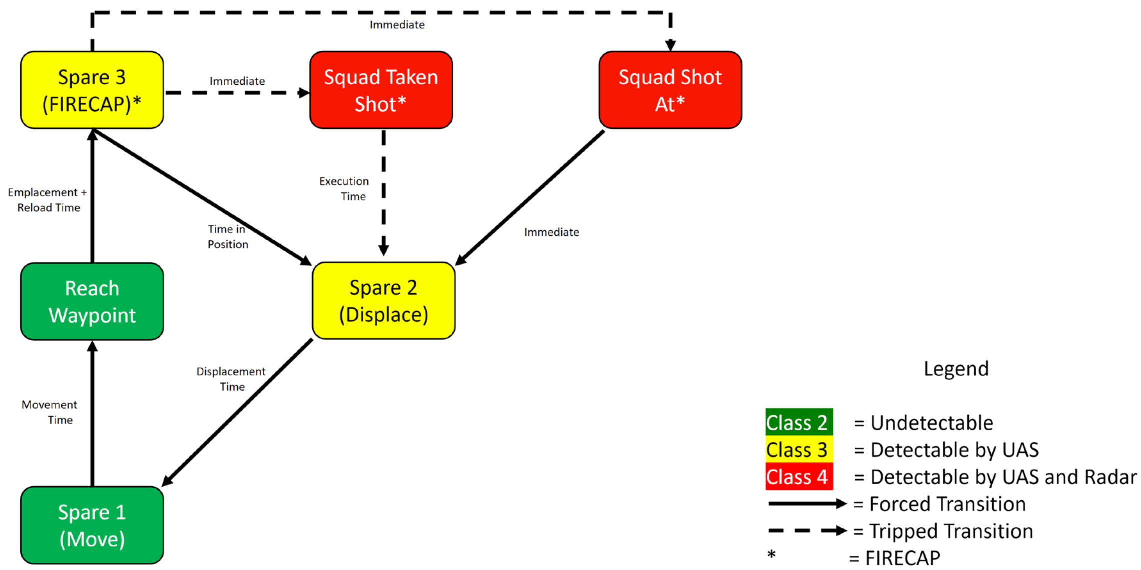

Figure 5. Red Firing Agent States and Behavior

Red firing agents start in the Spare 3 (FIRECAP) state which represents a unit that is emplaced in a firing position, FIRECAP, and is standing by for fire missions. Since they have not fired, they are Class 3 (detectable by UAS), and the use of hide points provides them some concealment. There are three events which can force a squad out of this state.

The first event is the receipt of a fire mission. At this point, the squad immediately executes the mission and transitions to the Squad Taken Shot state. They are now Class 4 and detectable by counterbattery radar in addition to UAS. Rocket artillery systems expend their entire rocket pod in a single mission, so once a squad enters the Squad Taken Shot state, they then transition to Spare 2 (Displace) after the duration of the mission execution.

The second event is receipt of incoming fire. They immediately transition to the Squad Shot At state where they also become Class 4. This transition also triggers an emergency displacement which sends the squad immediately to Spare 2 (Displace).

The last event that can force a squad out of Spare 3 is a pre-planned survivability move. That is, they have not received any missions or incoming fire, and the squad's time in position has expired. Once this time has passed, the squad immediately transitions to Spare 2 (Displace).

From Spare 2 (Displace), a squad's behavior is straightforward. After the extent of their displacement time, they enter Spare 1 (Move) while they conduct movement to their next waypoint or firing position. While in this state, the firing agents are in Class 2 and thus not targetable. At that point, they enter the Reach Waypoint state where they remain for their emplacement and reload time.

It is assumed that the agents are Class 2 during the duration of the Reach Waypoint state due to the advantage of only engaging a unit once it is fully emplaced. A unit that is only partially emplaced can more quickly displace to avoid incoming fire. Due to the risk incurred by a unit when it fires and unmasks itself to counterbattery radar, it is deemed more prudent to wait until complete emplacement before engaging. The reloading time is contained within this state when the agents are undetectable because of the prioritization of targets for Blue. They are focused on destroying and neutralizing maneuver agents, not the MLRS.

Blue's firing agents possess different capabilities based on the specifications of the M142 HIMARS Launcher. Their behavior, however, is very similar to the Red firing agents. Figure 6 displays the state diagram for Blue firing agents.

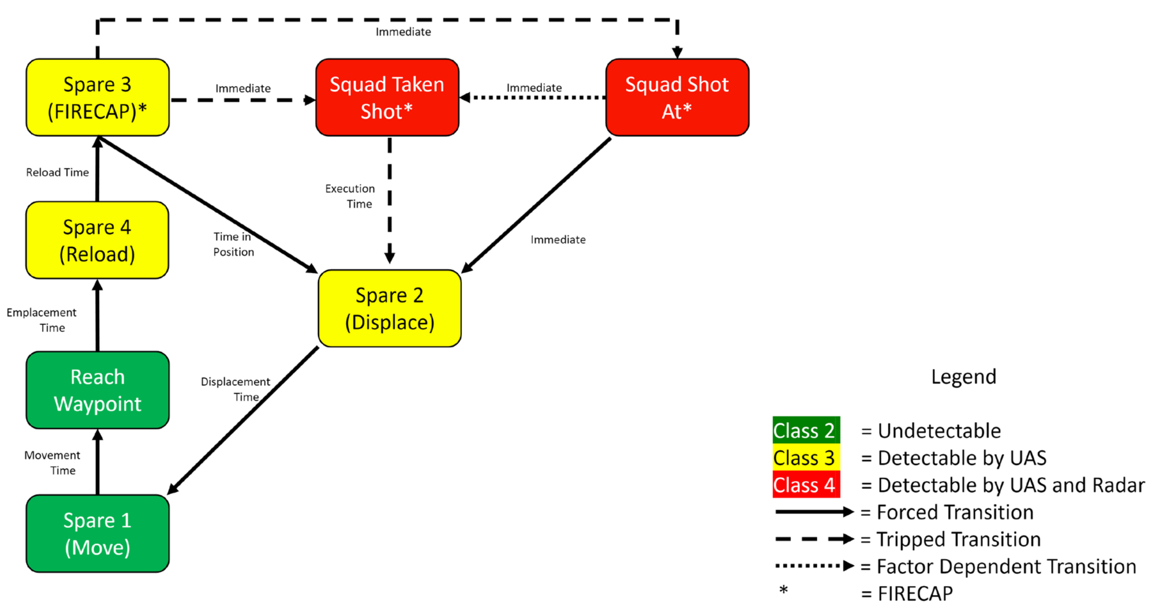

Figure 6. Blue Firing Agent States and Behavior

There are two main deviations that differentiate Blue behavior from Red behavior. First, the time that Blue spends reloading is captured in a separate state where the agents are Class 3, targetable by UAS. The reason for this dissimilarity is that MLRS are wholly focused on destroying Blue firing agents. Once the units are emplaced and conducting reloading operations, there is no reason that Red would not target them.

The second change is the arc from the Squad Shot At state to the Squad Taken Shot state. This is a factor-dependent transition which occurs if the defensive fires factor is set to "Yes." In this case, Blue's immediate response to taking fire is to fire a volley of defensive rockets before transitioning to displacement.

6. Maneuver Agents

In this scenario, Red is the only side with maneuver agents. These agents fall within the PLAN Marine Corps combined arms battalion structure. As such, they are designed to model the tracked ZBD-05 IFV and the self-propelled PLZ-07 howitzer. These agents are not within range to engage any Blue agents, so their only mission in the scenario is to reach Objective A (their final waypoint). They have only three different states with relatively simple behavior in each: Default, Reach Waypoint, and Reach Final Waypoint. While in their Default state, they have the maximum propensity to reach their next waypoint. Once they get to their next waypoint, they enter the Reach Waypoint state where they have increased cover and concealment and remain there for five minutes before reentering the Default state. This process continues until they reach their final waypoint and enter the Reach Final Waypoint where they remain for the duration of the simulation.

The purpose of these agents is to provide a measure of Blue's lethality. All maneuver agents are Class 5 and detectable by UAS alone. Since Blue's mission is to defend the airfield, Class 5 agents are their highest-priority target. A primary measure of effectiveness (MOE) in this simulation is the percentage of Red maneuver agents that reach the objective.

All agents are constructed based on open-source data acquired primarily from Janes. More specific details concerning the tangible characteristics of the platforms represented in MANA can be found in the Appendix. Table 1 provides orders of battle for each side.

Table 1. Orders of Battle

Blue		**Red**	
M142 HIMARS	18	PHL-16 MLRS	12
UAS	2	PLZ-07 Howitzer	6
Counterbattery Radar	3	ZBD-05	42
		UAS	1
		Counterbattery Rader	1

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IV. FACTORS AND DESIGN OF EXPERIMENTS

This research seeks to determine which factors are vital to Marine Corps rocket artillery lethality and survivability against China in a Taiwan invasion scenario. The factors have been introduced in Chapter II, but the following chapter more precisely describes integrating those factors into the model while also providing this research's DOE.

A. FACTORS AND LEVELS

To accomplish the goals of this thesis, factors are varied across an assortment of levels. Their impacts on the MOEs are then analyzed in metamodels. Chapter II introduced the six factors evaluated in this study. They are

- Employment Method
- Ammunition Load Out
- Time in Position
- Defensive Fires
- Emplacement Time
- Displacement Time

The factors can be broadly classified as either equipment based or TTP based. Equipment based factors are fundamentally affected by the platform or weapon system that the Marine Corps provides the warfighter to accomplish the mission. Typically, the process for implementing an equipment factor change is much slower due to constraints stemming from the military acquisitions process. TTP factors are driven by the operating procedures and command decisions of a unit. Changes to these factors can be more rapidly applied. The categorization of this study's factors is displayed in Table 2.

Table 2. Factor Categorization

Equipment Based Factors	TTP Based Factors
Ammunition Load Out	Employment Method
Emplacement Time	Time in Position
Displacement Time	Defensive Fires

1. Equipment-Based Factors

The three equipment-based factors are the ammunition loaded into the launchers and the emplacement and displacement times. Changing the *ammunition load out* affects the launchers in each of the states where the launchers are FIRECAP: Spare 3 (FIRECAP), Squad Taken Shot, and Squad Shot At. Of note, the Training and Readiness standards for conducting launcher reloads does not change for the ammunition being loaded, so reload time remains the same as this factor varies (USMC 2018b). Specifically in MANA, changes to the ammunition are mapped to corresponding changes in hits to kill Red agents, number of shots per launcher before reload, and hit rates as a function of distance between impact and the target.

Emplacement time is the time spent in the Reach Waypoint state before transitioning to the Spare 4 (Reload) state. *Displacement tim*e is the time spent in the Spare 2 (Displace) state before transitioning to Spare 1 (Move). These are considered equipment based due to the performance limits generally associated with self-propelled and towed artillery weapon systems. Figure 7 demonstrates where the equipment-based factors fall into the state diagram.

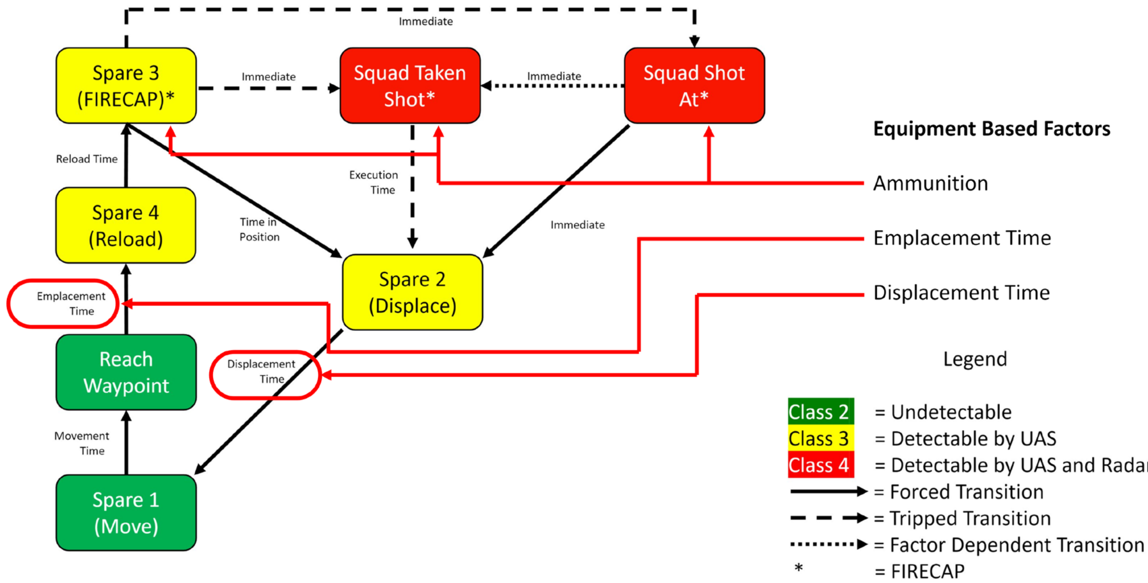


Figure 7. Equipment-Based Factor Locations in State Diagram

2. TTP-Based Factors

The three TTP-based factors are employment method, defensive fires, and time in position. Employment method cannot be varied by adjusting an input to the simulation, so this factor is varied by creating four separate MANA scenario files, which correspond to the different employment methods. The differences between these files are captured in the number of Blue firing squads, the agents per Blue firing squad, and the waypoints of these agents.

The traditional *employment method* is consolidated with the entire battery of six launchers located in a single firing position. The next step down is split battery, where the battery operates as two geographically dispersed platoons of three launchers each. In distributed operations, each launcher is geographically dispersed from the others. Although not typically used, this study looks at a fourth employment method, which falls between split battery and distributed. In this method, a battery breaks down into three sections of two launchers each. Figure 8 provides a visualization for the composition of the different employment methods.

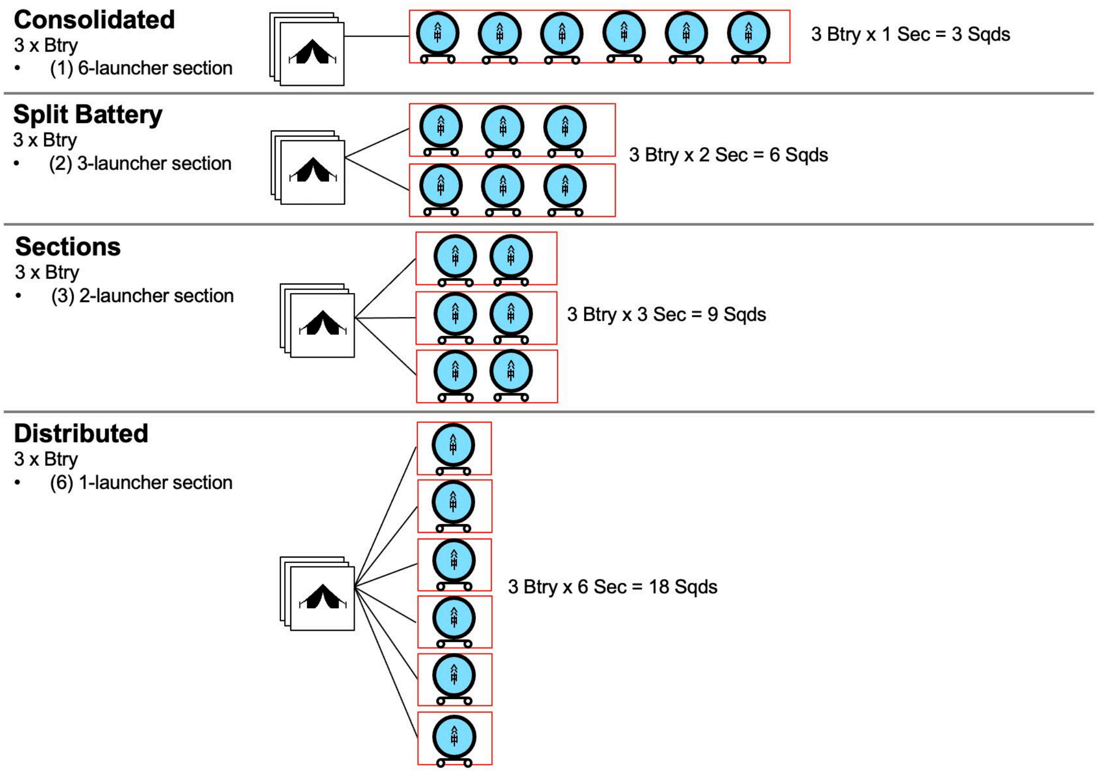


Figure 8. Employment Method Configurations

The *defensive fires* factor affects the agents in the Squad Shot At state. This factor determines whether there is a transition between Squad Shot At and Squad Taken Shot. When this factor is set to "Yes," Blue immediately fires a counterbattery mission after receiving enemy fire. Otherwise, they immediately begin displacing. *Time in position* is the time spent in Spare 3 (FIRECAP) before transitioning to Spare 2 (Displace) if the unit does not receive a fire mission or incoming fire. This factor is also referred to as time until conducting a survivability move. Figure 9 provides a visualization of where these factors fall in the state diagram.

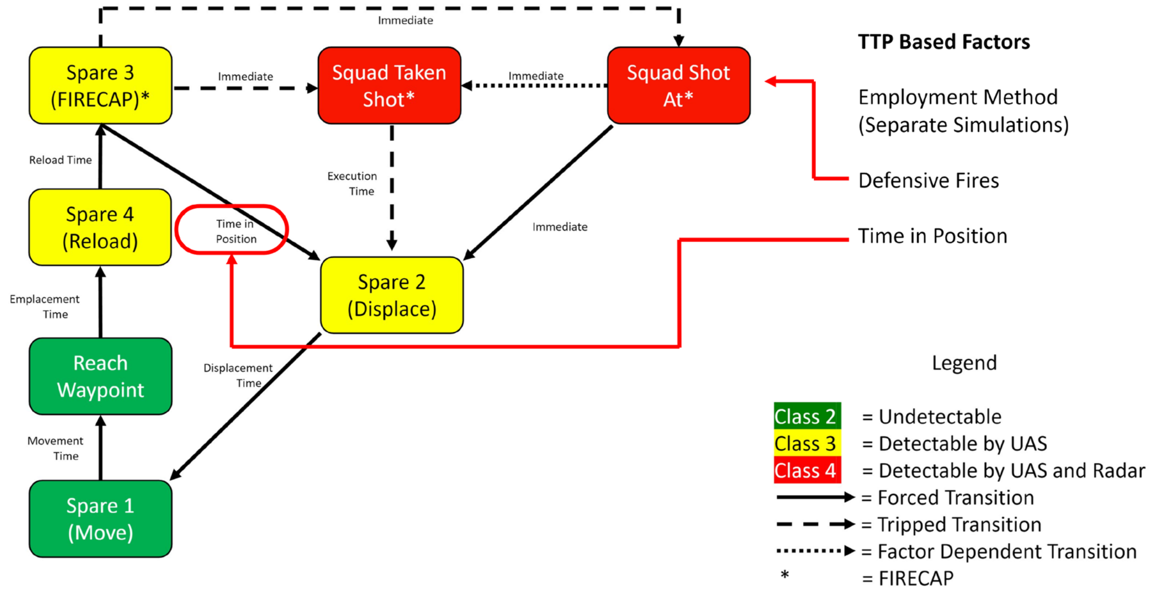


Figure 9. TTP-Based Factor Locations in State Diagram

3. Factor Levels

The six experiment factors are varied across a range of values to gain insights into their effects on the MOEs. Three of the factors are categorical because their levels are qualitative. These are the employment method, ammunition load out, and defensive fires. Due to their relative importance, each of their levels is examined in this thesis.

The other three factors, time in position, emplacement time, and displacement time, are continuous. The maximum and minimum values for their levels are selected to contain the published training and readiness standard for that task while also representing optimistic and pessimistic values. The idea behind this approach is to answer the following two questions regarding equipment and TTP factors, respectively. What would be possible if we had equipment that could achieve these effects? And what would be possible if we could train to this level of capability? Categorical and continuous factors and their levels are summarized in Figure 10.

Categorical						
Factor Num	Factor Name	Factor Type	Levels			Notes
1	Blue Employment	Categorical	Consolidated, SplitBtry, Sections, Distributed			(4) Separate Scenarios created, common situation, different employment method
2	Blue Ammunition Loadout	Categorical	M30, M31, M39, M48			M30/M31 from GMLRS family- 6 pods/launcher, range out to 84 km M30 contains 404 DPICM bomblets M31 carries 200lb HE warhead M39/M48 from ATACMs family- 1 pod/launcher, range out to 165, 270 respectively M39 contains 950 antipersonnel/material bomblets M48 carries 500lb HE warhead
3	Blue Defensive Fires	Categorical	Yes, No			Does the HIMARS squad fire a volley of rounds prior to displacing after receiving fire?
Discrete/Continuous						
Factor Num	Factor Name	Factor Type	Low	High	Units	Notes
4	Blue Time in Position	Continuous	300 (5)	1500 (25)	sec (min)	Time HIMARS squad will remain in position prior to conducting a survivability move (if no actions occur while in position)
5	Blue Emplacement Time	Continuous	30 (0.5)	600 (10)	sec (min)	Length of emplacement, time from Reach Waypoint to fallback to Spare 3
6	Blue Displacement Time	Continuous	30 (0.5)	600 (10)	sec (min)	Length of displacement, time from Spare 2 to fallback to Spare 1

Figure 10. Factors and Levels Summary

4. Factors Unique to Red

The final experiment in this research varies Red factors against the Blue factors from Figure 10 with the goal of finding Blue solutions which are robust to a range of Red tactics and capabilities. Each continuous Blue factor is varied for Red with three additional unique factors varied as well. The first unique factor is the ammunition configuration, which is treated as categorical. The two levels correspond to the two possible ammunition configurations for the PHL-16 MLRS in use by the PLA: (10) 300mm rockets or (8) 370mm rockets.

The next two Red factors are armor thickness and maneuver speed, and both are treated as continuous. The armor thickness pertains to all Red targetable agents and provides a way of modeling the uncertainty surrounding what kind of armor packages their vehicles may have. This is unique to Red as Blue vehicle weights are extremely limited by USMC expeditionary requirements and thus cannot be armored. Maneuver speed is unique to Red as it is the only side with maneuver agents. As this simulation does not include the Taiwan force defending the airfield, this factor allows for analyzing outcomes across a range of Red advancement speeds. In live combat, Red's speed would likely vary with the strength of the Taiwan defense. Figure 11 provides a complete summary of Red and Blue factors for use in the fourth experiment.

Categorical							
Factor #	**Factor Name**	**Factor Type**	**Levels**			**States**	**Notes**
1	Blue Employment	Categorical	Consolidated, SpltBtry, Sections, Distributed				(4) Separate Scenarios created, common situation, different employment method
2	Blue Ammunition Loadout	Categorical	M30, M31, M39, M48			All FIRECAP States	M30/M31 from GMLRS family- 6 pods/launcher, range out to 84 km M30 contains 404 DPICM bomblets M31 carries 200lb HE warhead M39/M48 from ATACMs family- 1 pod/launcher, range out to 165, 270 respectively M39 contains 950 antipersonnel/material bomblets M48 carries 500lb HE warhead
3	Blue Defensive Fires	Categorical	Yes, No			Squad Shot At	Does the HIMARS squad fire a volley of rounds prior to displacing after receiving fire?
4	Red Ammunition Loadout	Categorical	(10) 300mm rockets, (8) 370mm rockets			Spare 3	Which configuration are the Red MLRS launchers in? *(see RedAmmoMapping tab)*
Discrete/Continuous							
Factor #	**Factor Name**	**Factor Type**	**Low**	**High**	**Units**	**States**	**Notes**
5	Blue Time Until Survivability Move	Continuous	300 (5)	1500 (25)	sec (min)	Spare 3 (duration)	Time HIMARS squad will remain in position prior to conducting a survivability move (if no actions occur while in position)
6	Blue Emplacement Time	Continuous	30 (0.5)	600 (10)	sec (min)	Reach Waypoint (duration)	Length of emplacement, time from Reach Waypoint to fallback to Spare 3
7	Blue Displacement Time	Continuous	30 (0.5)	600 (10)	sec (min)	Spare 2 (duration)	Length of displacement, time from Spare 2 to fallback to Spare 1
8	Red Time Until Survivability Move	Continuous	300 (5)	1500 (25)	sec (min)	Spare 3 (duration)	Time MLRS squad will remain in position prior to conducting a survivability move (if no actions occur while in position)
9	Red Emplacement Time	Continuous	30 (0.5)	600 (10)	sec (min)	Reach Waypoint (duration)	Length of emplacement, time from Reach Waypoint to fallback to Spare 3
10	Red Displacement Time	Continuous	30 (0.5)	600 (10)	sec (min)	Spare 2 (duration)	Length of displacement, time from Spare 2 to fallback to Spare 1
11	Red Maneuver Speed	Continuous	15	35	km/h	Default (Movement)	Speed of advance to next waypoint
12	Red Armor Thickness	Continuous	0	30	mm	All	Armor thickness for Red firing and maneuver squads

Figure 11. Red and Blue Factors and Levels Summary

B. EXPERIMENT METHODOLOGY

This research is divided into four separate experiments, each progressively building on the previous one. The first experiment examines the variance of outcomes inherent to the model without varying any factors. The second experiment varies only the most easily implementable factor, Blue employment method. Experiment three varies all Blue factors to determine factors which are critical to Blue lethality and survivability. And lastly, experiment four varies Red and Blue factors to gain insight into Blue factor levels which are most robust against uncertain enemy capabilities and TTPs.

(1) Experiment One: Base Case

The goal of experiment one is to establish a baseline for comparison in future experiments. Equipment-based and TTP-based factors are set at levels which best represent current capabilities and tactics used by both sides. More detailed descriptions of the platforms and capabilities used can be found in the Appendix. The results of this experiment provide the modeler with an understanding of the wide variety of outcomes that are possible in a conflict similar to the model scenario.

(2) Experiment Two: Blue Employment Method

Experiment two focuses on the Blue factor which can most rapidly be changed in the operating forces: employment method. Currently, the Marine artillery force regularly trains as consolidated and split batteries, but implementation of section or distributed operations could be achieved through focused training. This experiment isolates this factor to determine its impact on Blue survivability and lethality in a defense-of-Taiwan scenario. All other factor levels remain the same as in experiment one.

(3) Experiment Three: Blue Factors

Experiment three varies all Blue factors across the categorical levels and continuous ranges presented in Figure 10. Red factors remain constant, so this experiment serves to provide insight into Blue factors which are most significant to achieving a balance of lethality and survivability against the enemy modeled as is.

(4) Experiment Four: Red and Blue Factors

The last experiment is the only one in which factors are varied for the Red force. The first three experiments pit Blue against a Red force whose tactics and capabilities are best estimated by available, unclassified sources. Sensible variation of all the factors presented in Figure 11 ensures this experiment can capture the true tactics and capabilities of the Red force. This experiment helps to combat uncertainty, by providing insight into Blue factor levels which are robust to a variety of Red capabilities and tactics.

C. DESIGN OF EXPERIMENTS

DOE is a technique for determining the necessary factor level inputs for use in a simulation experiment. An efficient DOE allows the modeler to examine the true impact of factors on the response while keeping computational requirements at a reasonable level (Vieira Jr et al. 2013). The following sections describe the DOE implemented in each experiment of this research and provides justification for the use of DOE in high-dimensional experiments.

1. Experiment One: Base Case

Since no factors are varied, no DOE is required in this experiment. The wide range of outcomes from this experiment provide a reference for the amount of variance present in the model attributable only to MANA's simulating aspects of combat which are fundamentally stochastic. This experiment is run for 1000 replications.

2. Experiment Two: Blue Employment Method

To sufficiently study how Blue employment method impacts the measures of effectiveness (MOEs), all levels are used for a total of four design points: consolidated, split-battery, section, and distributed. As mentioned, these design points are implemented as separate simulation files in MANA. Each design point is run for a total of 1000 replications.

While the primary goal of this experiment is to provide insights pertaining to Blue lethality and survivability, it also allows for a calculation of the required number of simulation runs per design point in experiments three and four. This is done through a power analysis to determine a sample size for a hypothesis test of comparing means. Statistical power refers to the probability of correctly rejecting the null hypothesis when it is indeed false (Lucas 2021b). Equation 1 is used to determine the required number of repetitions.

$$n = \left(\frac{\sigma(Z_\alpha + Z_\beta)}{(\mu_0 - \mu')}\right)^2 \tag{1}$$

Here n represents the number of repetitions, σ represents the estimated standard deviation, Z_α is the z-score for the desired confidence level, Z_β is the z-score for the desired power, and $\mu_0 - \mu'$ is the minimum practical difference the modeler wants to detect.

Experiment two makes this calculation possible by providing an estimated standard deviation. This value is estimated as the highest standard deviation of any of the MOEs across all employment scenarios. In this case, the value is 4.1, taken from Red Maneuver casualties in the distributed employment scenario. A desired confidence level of 90% and a desired power of 0.80 correspond to z-scores of 1.645 and 0.84, respectively. Those values and a minimum detectable difference of one casualty evaluates as 104 required replications, which is rounded down to 100 for convenience. Figure 12 displays the sample size required as a function of the minimum detectable difference for the z-scores stated previously.

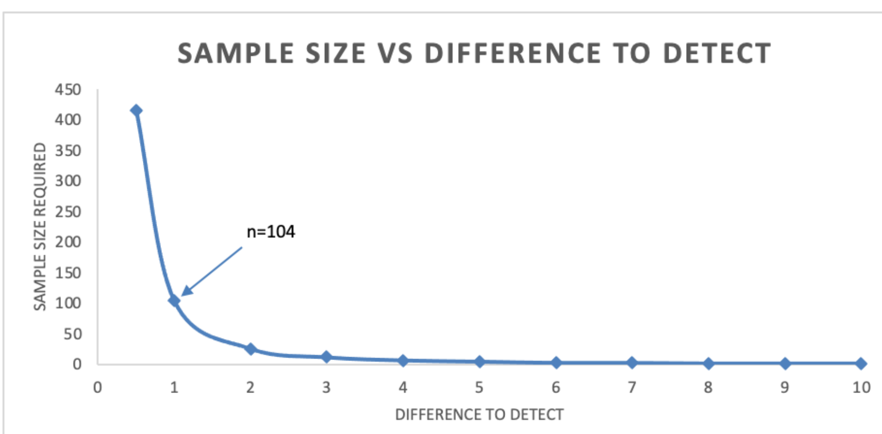


Figure 12. Sample Size Determination

3. Experiment Three: Blue Factors

Experiment three is the first implementation of a true DOE. Here, Blue factors are varied while Red's are held constant at levels that best represent what is known about their force. The first step to implementing the DOE is to map factor levels to tangible model data input. Again, employment method is varied by creating four distinct scenarios. All other factors are varied via model inputs.

Six total factors are varied for Blue, three categorical and three continuous. The categorical factors consist of a set number of levels, while the continuous factors' levels are evenly sampled between their maximum and minimum values. To construct the final DOE, three different components are built to achieve specific modeling goals with respect to different factors.

A full factorial DOE is applied for the three categorical factors. Due to the relative importance of each level within these factors, this is necessary to ensure that every combination of categorical factor levels is examined in the experiment. The full factorial of two factors with four levels (employment method and ammunition) and one factor with two levels (blue defensive fires) results in 32 total design points. Figure 13 presents a visualization of this design in three-dimensional space.

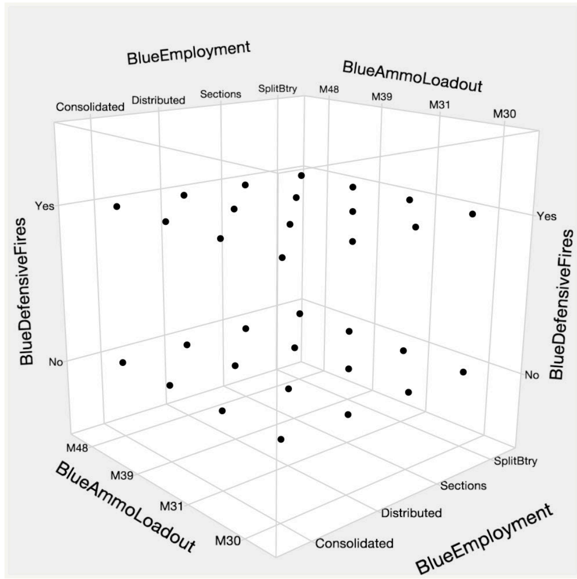


Figure 13. Experiment Three: Full Factorial for Categorical Factors

Next, the three continuous factors are evaluated in a Nearly Orthogonal Latin Hypercube (NOLH). Random Latin hypercubes are noted for their efficient, flexible, and space-filling properties which are achieved by taking independent permutations of integers from one to the number of design points (Sanchez et al. 2020, p.1136). NOLH designs, constructed by Cioppa and Lucas (2007), have the added benefit of near orthogonality which ensures factors are unconfounded. Cioppa and Lucas also note that this allows for independently estimating regression coefficients when conducting a main effects analysis through a metamodel. The NOLH for three continuous factors results in 17 design points. A visualization of the NOLH used is provided in Figure 14.

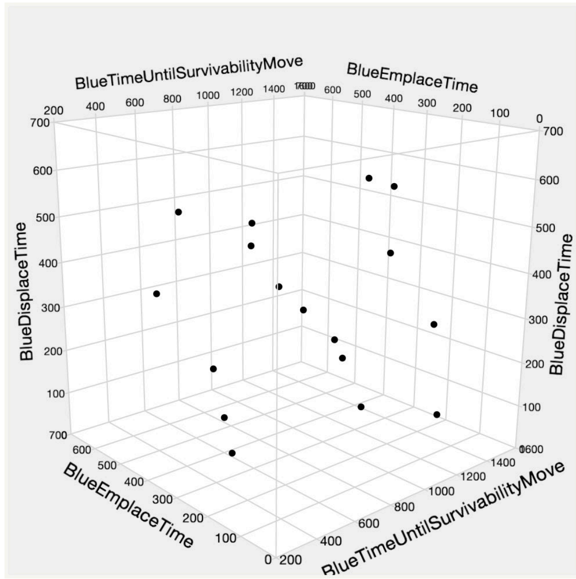


Figure 14. Experiment Three: NOLH for Continuous Factors

The NOLH provides sufficient space-filling behavior in the middle of the design space; however, it does not capture the extremes as adequately. To remedy this, an additional corner point DOE is added for the continuous factors in this study. The corner point DOE simply takes all the combinations of maximum and minimum values for the factors for an additional eight design points. The continuous factor DOE can now be represented by the NOLH combined with the end point DOE for a total of 25 design points. The improved coverage is demonstrated by the visualization of the combined DOE in Figure 15.

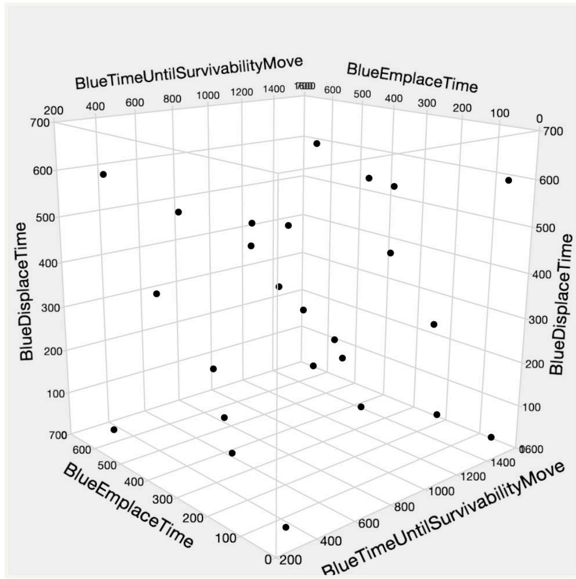


Figure 15. Experiment Three: NOLH + Corner Points for Continuous Factors

By crossing the 32-design-point categorical factor DOE with the 25-design-point continuous factor DOE, the full DOE is now 800 design points. This crossing allows every combination of categorical factors to be run with the exact same factor levels for the continuous factors. Using the 100 repetitions per design point from the power analysis, this comes to 80,000 simulated battles. The final experiment three design space is provided in a scatterplot matrix in Figure 16.

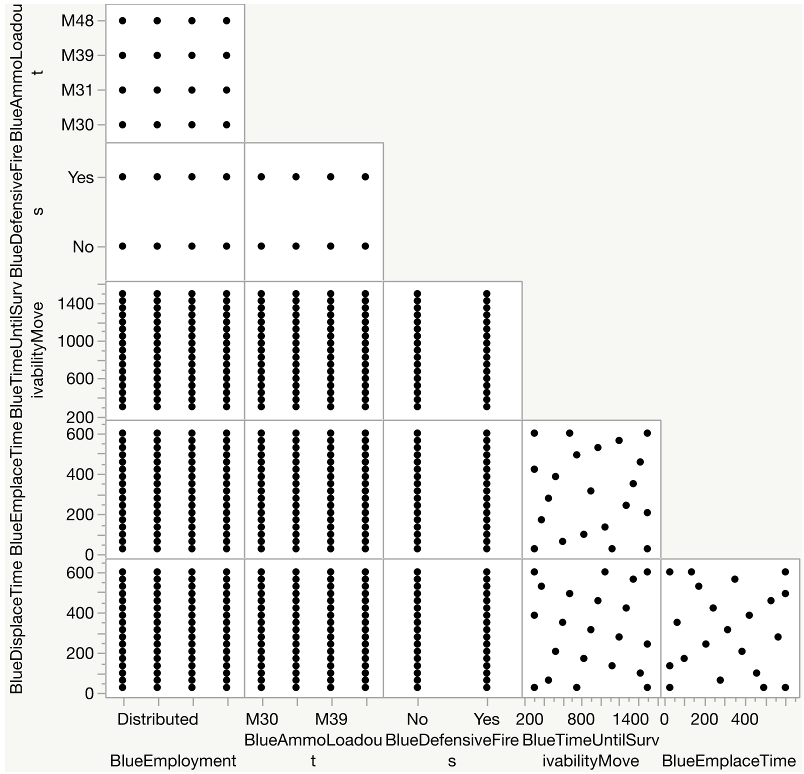


Figure 16. Experiment Three Final Design: Full Factorial x (NOLH + Corner Points)

4. Experiment Four: Red and Blue Factors

Experiment four crosses all combinations of Blue factor levels with Red factors. The Blue DOE alone is slightly altered from the experiment three DOE. The factors remain the same, but the NOLH is changed to a 2nd order NOLH which only requires 15 design points to capture three continuous factors (MacCalman et al. 2017), and the corner points are dropped from eight to four by using a fractional factorial. This brings the total design points for Blue down from 800 to 608. The Blue design space for experiment four is shown in Figure 17.

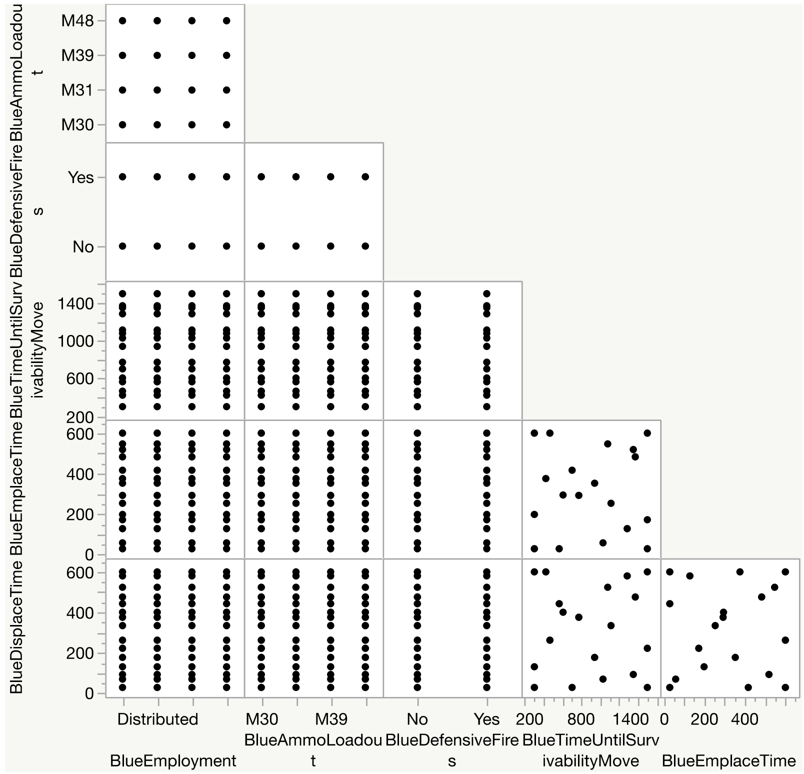


Figure 17. Experiment Four Blue Design: Full Factorial x (2nd Order NOLH + Corner Points)

The Red DOE is constructed in a Nearly Orthogonal and Balanced (NOB) design This design provides limited correlation between factors while also ensuring that each factor level occurs close to equally often (Vieira Jr et al. 2013). The NOB results in 26 design points, capturing one categorical and five continuous Red factors, and it is displayed in Figure 18.

The categorical factor unique to Red is the ammunition load out which consists of two levels: (10) 300mm rockets or (8) 370mm rockets. The continuous factors are the same three Blue continuous factors plus two exclusively Red factors: armor thickness and maneuver speed. These are unique to Red because of weight limitations on USMC equipment that preclude the use of armor and Blue's lack of maneuver agents in this scenario.

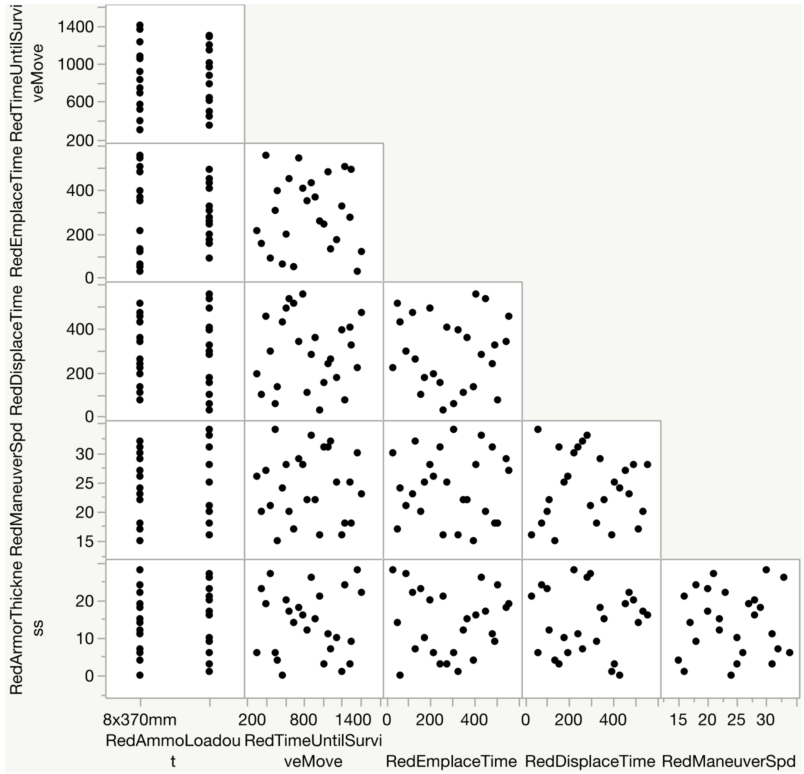


Figure 18. Experiment Four Red Design: NOB

The final design for experiment four is simply a cross of every Blue design point with every Red design point. This results in 15,808 design points. Keeping with the 100 replications per design point, experiment four consists of 1,580,800 simulated battles in MANA.

5. Justification for Design of Experiments

Efficiently implementing a DOE saves a modeler time and computing power while still allowing for an examination of a variety of factors over many levels. The benefits become strikingly clear in experiment four when the number of factors climbs. The previously introduced DOE contains 15,808 design points. By assuming a 168-processor computing cluster, 40 second run time for a single replication, and 100 replications per design point, this experiment runs for 4.4 days. By comparison, a full factorial of experiment four factors, with only four levels for continuous factors, results in 4,194,304 design points. Under the same assumptions, this experiment would take over three years to complete.

This simple example highlights the importance of DOE. Even with high powered computing clusters, experiments with seemingly few factors and levels quickly face run time issues. Efficient DOE allows for an analysis across a breadth of factors without losing information by limiting the number of levels to study. Due to the complexity of combat simulations, combat modelers often cannot expect to accurately predict outcomes or optimize performance (Lucas et al. 2002). Their goals instead should be gaining insights and identifying significant factors, interactions, and change points. Without DOE, military analysts cannot possibly explore all the regions of the design space efficiently while meeting these goals.

Using the DOE described in this chapter, this thesis was able to evaluate 12 total factors through 16,612 unique design points. The results are drawn from over 1.6 million simulated battles, which had a total run time of fewer than six days.

V. ANALYSIS

The following chapter reports on the analytic methods used in each of the four experiments to gain insights regarding the research questions introduced in Chapter I. To assess factor impacts on lethality and survivability, this analysis evaluates model outputs by examining their MOEs. The MOEs that capture lethality are the number of Red casualties for both maneuver and firing agents, as well as a binary variable which indicates whether or not Red seizes their objective. This variable defines Red's ability to seize the objective as equivalent to at least 50% of their maneuver forces surviving the engagement. A single MOE captures Blue survivability, and that is simply the number of Blue agents that survive the engagement.

A. EXPERIMENT ONE: BASE CASE

To reiterate, this experiment is an engagement between a Blue and Red force each with constant factor settings. Refer to Table 1 in Chapter III for detailed orders of battle represented in this experiment. By simulating the engagement 1,000 times, experiment one establishes a base line for the variability inherent in the model. It provides a measure of how much uncertainty is present in certain stochastic aspects of the model, even when all inputs other than random seed are held constant. It is important to restate that this model is not meant to be predictive, and therefore, differences between the numbers of casualties imposed by either side are more indicative of assumptions, missions, and force levels at the start, than they are of expected operational outcomes.

1. Experiment One Analysis

It is clear from this experiment that there is significant variability in potential simulation outcomes. Figure 19 provides a visualization of the casualty distributions for Red and Blue forces. For Red and Blue firing agents, the losses range from zero to 14 out of 18 agents, though both distributions are more heavily weighted on the lower end of that range. Both have a mean of approximately three casualties; however, the Red firing agents have a mode of zero casualties, while Blue's mode is much closer to its mean. The Red maneuver losses show even more variability, ranging from four to 31 out of 42 agents with a standard deviation of over five. The shape is different as well, being much more symmetric around the mean value of 14.5 casualties.

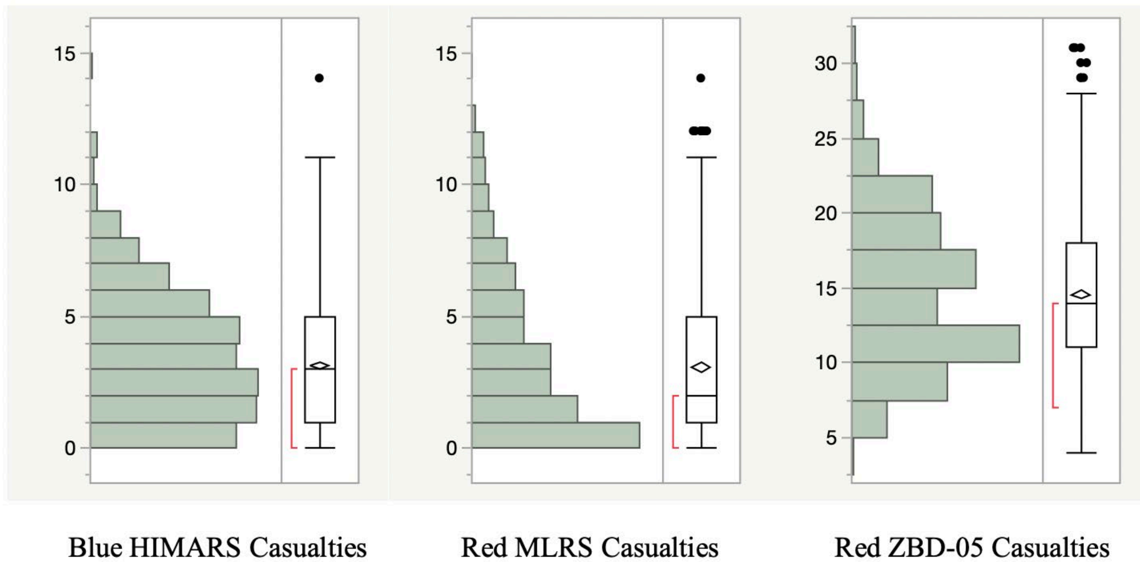


Figure 19. Experiment One Casualty Distributions

The mean of the maneuver casualties is also a higher percentage of the total number of agents of that type compared to firing agent losses on both sides. On average, Red lost 35% of their ZBD-05s, compared to 17% of their MLRSs. Blue's losses averaged to be 17% of their force. This is unsurprising given the mission prioritization of each force. Red is seizing the airfield, and Blue is defending it from Red maneuver agents. Figure 20 exhibits this outcome.

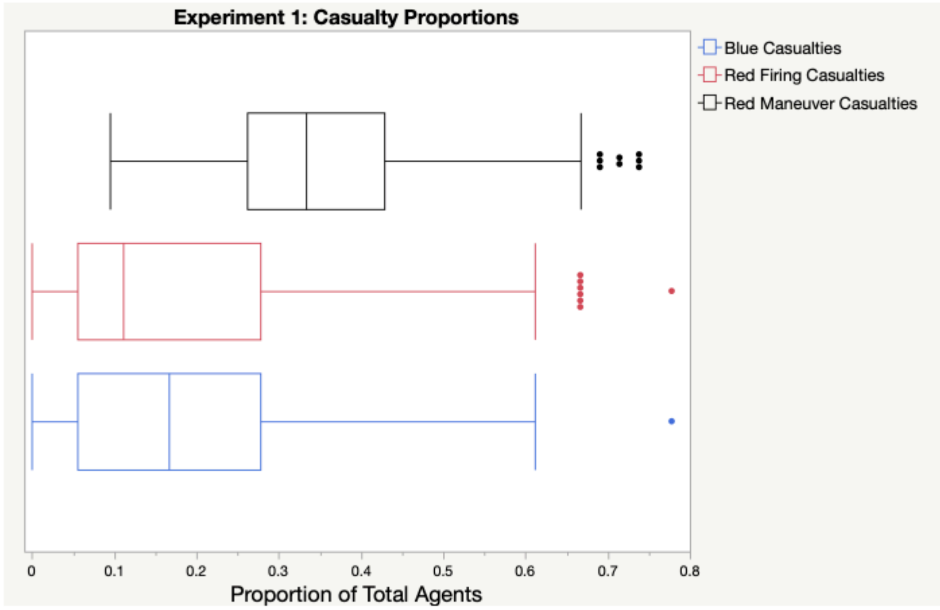


Figure 20. Experiment One Casualties as a Proportion of Total Agents

By this research's definition, Red successfully seizes their objective in 858 or 85.8% of the simulation runs. When considering the correlation between Red's success and Blue's casualties, the results are largely unsurprising. As Figure 21 shows, Blue casualties are lower when Red does not seize the objective. Presumably, limited attrition of Blue HIMARS units is important to preventing the seizure of the airfield.

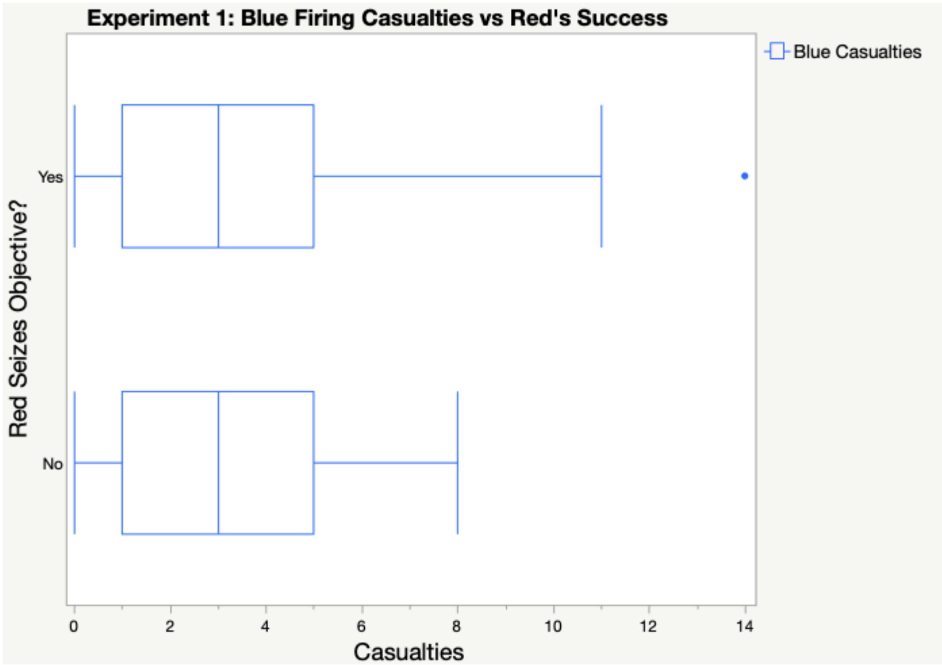


Figure 21. Blue Casualties vs. Red Success

The relationship between Red's firing casualties and Red's success may seem counterintuitive at first glance. Figure 22 demonstrates that Red firing casualties are also lower when Red fails. Initially, one may expect Red's casualties to be higher when they fail to seize their objective. However, when considering different types of Red agents, it becomes clear that the observed effect is expected. Red's success is only defined by the number of surviving maneuver agents. So, higher Red firing agent casualties simply means that Blue agents are preoccupied with counterbattery fire, allowing maneuver agents to accomplish their mission.

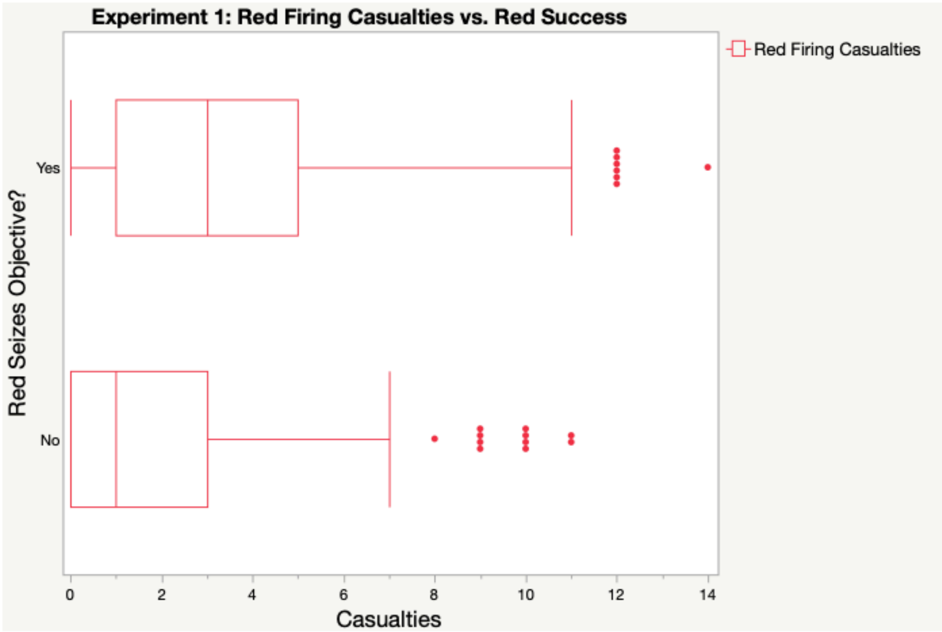


Figure 22. Red Firing Casualties vs. Red Success

2. Experiment One Insights

In addition to providing later experiments a baseline from which to compare, experiment one offers some insights. The first being the amount of intrinsic variance in the model. Without varying any factors, each MOE had a wide range of potential values. In later experiments, analysis is conducted on summary statistics from each design point, so the variance observed is primarily from different factor settings rather than model stochasticity.

Experiment one also provides the modeler with confidence that the model is behaving as designed by comparing distributions and correlations between certain MOEs. Experiment two continues to build on these results by examining the impact of Blue's employment method.

B. EXPERIMENT TWO: BLUE EMPLOYMENT METHOD

Experiment two only varies Blue employment method. As employment methods can be changed relatively easily through training and implementation of new operating procedures, this is selected as the first Blue factor to analyze. In order of decreased aggregation, the four possible methods are consolidated, split battery, section, and distributed. A separate simulation scenario file is built for each method, and each scenario file is run for 1,000 replications.

1. Experiment Two Analysis

Boxplots of Blue and Red agent casualties by employment method in Figure 23 demonstrate an apparent trend of increased lethality and survivability for Blue forces as they operate in increasingly more distributed methods. Both types of Red casualties rise while Blue casualties decrease.

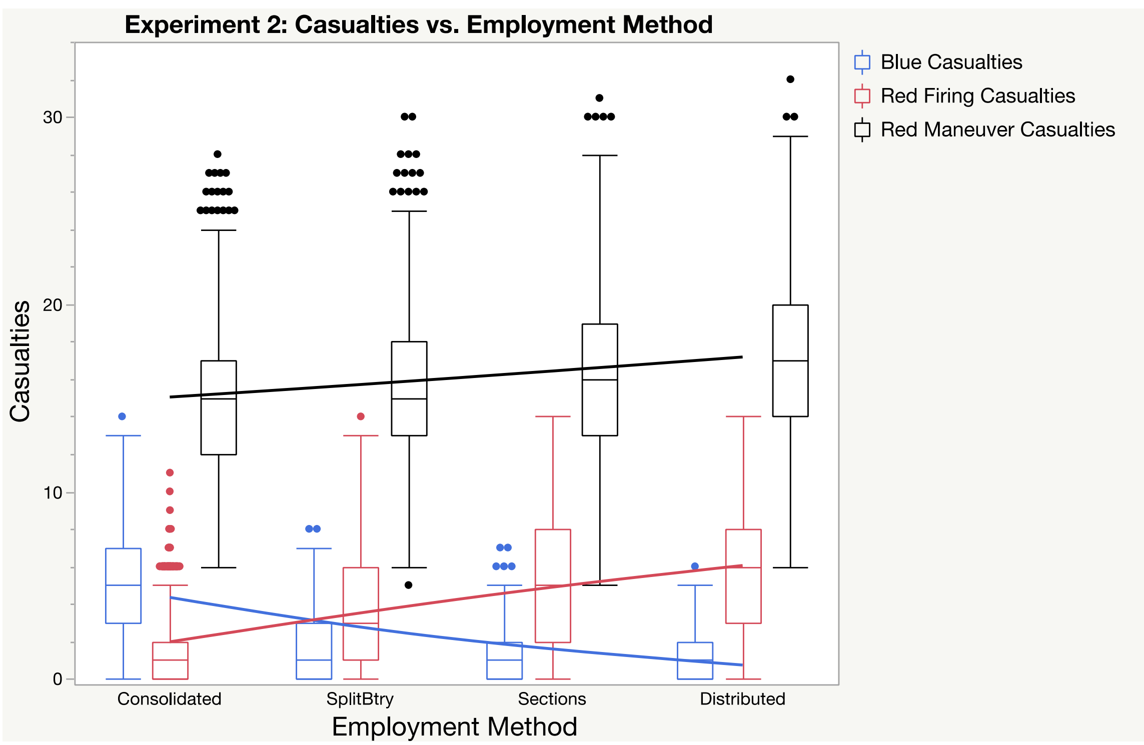


Figure 23. Casualties vs. Employment Method

This follows what Captain Kadrmas' research uncovered in a similar experiment (Kadrmas 2021). Increased dispersion results in more survivable Blue firing units, who are then able to inflict more destruction on Red agents. To determine whether the observed differences are truly statistically significant, more rigorous tests are implemented.

Performing a Kruskal-Wallis Test for equivalence of means results in a P-value less than 0.0001 for each of the types of casualties (Devore 2014, p. 671–672). This indicates that the means are not all equal, but it does not provide exactly which pairs of means are different. To determine which pairs contained differences, a post-hoc Tukey Test is executed on each MOE (Devore 2014, p. 420).

For the Blue casualties, the only pair whose means are not significantly different are split battery and section employment. In the case of Red firing casualties, all pairs are significantly different from each other, and for Red maneuver casualties, only consolidated and split battery employment fail to result in a statistically significant difference.

When considering the binary MOE of Red seizing the objective, the differences in means only become significant when moving more than one level. In other words, the differences between the three adjacent pairs of employment methods (consolidated-split battery, split battery-section, and section-distributed) are all insignificant. Figure 24 demonstrates this in an ordered differences report. Unsurprisingly, the biggest difference comes from the two most extreme employment methods. It is worth noting, however, that moving two levels from split battery to distributed provides greater increases in overall Blue success than moving two levels from consolidated to sections.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Consolidated	Distributed	0.0880000	0.0158263	0.047325	0.1286753	<.0001*
SplitBtry	Distributed	0.0720000	0.0158263	0.031325	0.1126753	<.0001*
Consolidated	Sections	0.0530000	0.0158263	0.012325	0.0936753	0.0045*
SplitBtry	Sections	0.0370000	0.0158263	-0.003675	0.0776753	0.0898
Sections	Distributed	0.0350000	0.0158263	-0.005675	0.0756753	0.1202
Consolidated	SplitBtry	0.0160000	0.0158263	-0.024675	0.0566753	0.7430

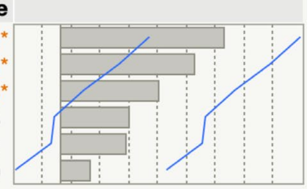


Figure 24. Ordered Differences Report on Red Success

2. Experiment Two Insights

The clearest insight drawn from experiment two is the importance of applying some dispersion to an artillery formation. The biggest gains in survivability and lethality separately came when moving from consolidated to split battery. Beyond that, the increases become slightly more incremental. However, when considering the Red seizure MOE or overall Blue success, no single jump between adjacent employment methods, led to a significant change in Blue's chances of success. Increasing distribution by two levels is the only way to guarantee that Blue could improve their chances of preventing the seizure of the airfield. And in this case, moving from split battery to distributed provides the greatest decrease in Red's success.

C. EXPERIMENT THREE: BLUE FACTORS

In experiment three, all Blue factors are varied in accordance with the DOE described in Chapter IV. In total, this experiment contains 800 design points, run for 100 replications each, for a total of 80,000 simulated battles. The analysis on this experiment is performed on the means of the design points. This ensures that the effects identified are the result of factor changes rather than random variance in the model.

Figure 25 provides the distributions of each of the three types of casualties. It is clear that the variability of each of the MOEs is vastly different. Blue casualties are centered on a mean of 1.5 with a standard deviation of 1.4. The low variance is demonstrated by the height of the Blue distribution, however, there is a long right tail indicating that certain factor combinations did result in much higher Blue casualties. Red casualties are much more symmetrically distributed, but both have higher means and variances. Red firing casualties appear to be bimodal with a mean of 5.9 and a standard deviation of 2.7, while Red maneuver casualties have an approximately triangular distribution and are centered on 19.1 with a relatively large standard deviation of 4.1.

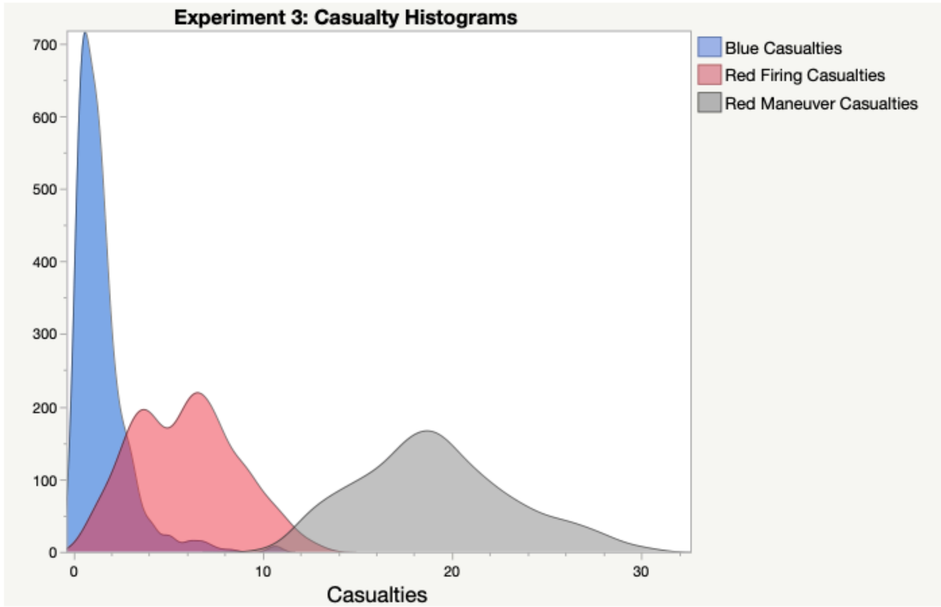


Figure 25. Experiment Three: Casualty Distributions

These distributions suggest that there are combinations of Blue factor settings which result in higher overall Red casualties and lower Blue casualties. The goal of this experiment is to identify those combinations, and more generally, key drivers of variability, through metamodel analysis.

1. Blue Survivability Analysis

a. Blue Survivability Partition Tree

Focusing first on Blue survivability, Figure 26 displays a partition tree with Blue casualties as the response variable. The tree achieved an R-squared value of 0.61 which indicates that these six splits explain well over half of the variance seen in Blue casualties (Devore 2014, p. 504). The first split is on Blue displacement time and suggests, unsurprisingly, that quicker displacement limits Blue casualties. The difference between the two branches is not trivial. A displacement time of over 137 seconds results in 1.8 casualties on average, which is close to the overall Blue casualty mean of 1.5. However, by keeping displacement times below 137 seconds, the mean decreases to 0.45. Faster displacement times also decrease the uncertainty associated with Blue casualties as represented by their standard deviations. The left branch's standard deviation drops to 0.34 while the right is at 1.5, which again is close to the overall Blue casualty standard deviation.

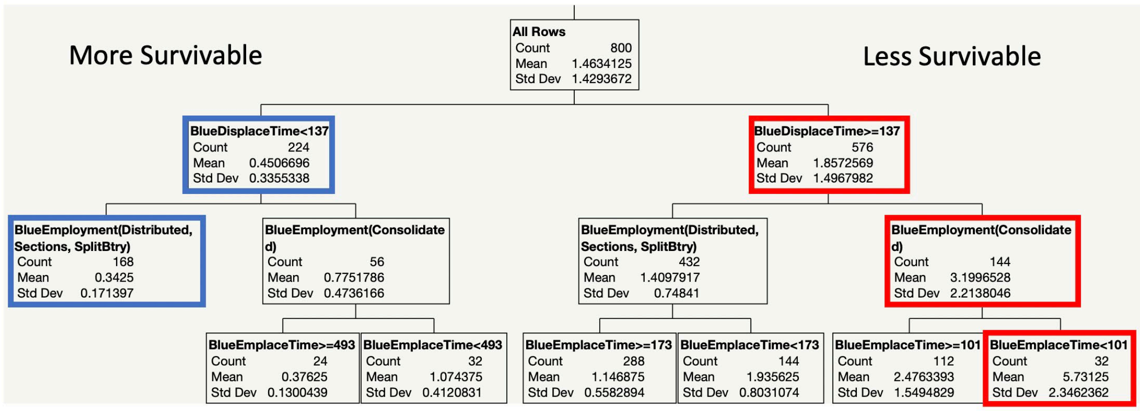


Figure 26. Blue Survivability Partition Tree

Each of the first two branches then splits on employment method, specifically between consolidated and every other method. Again, the split is intuitive as a consolidated battery is expected to be less survivable. What is more valuable, however, is the improvement that is gained simply by increasing distribution by one level to split battery. The mean casualties associated with the consolidated branch on both sides of the tree are over twice the mean casualties for the more distributed branch.

From there, the next split on three of the four branches is on emplacement time, with longer emplacement times corresponding to lower Blue casualties. This is likely an artifact of the modeling logic that firing agents are Class 2 or undetectable while emplacing. This is done to represent the supposition that an actively emplacing unit can more quickly conduct an emergency displacement than a fully emplaced one. For that reason, emplacing units are not fired upon until they had fully occupied the position. The result, then, is that by taking longer to emplace, Blue units have less overall time that they can be targeted and are thus experience a proportionate decrease in casualties. So tactically, units are more survivable if they can limit the overall time they are targetable.

Moving from more survivable to less survivable configurations from left to right, it can be observed that the change point for emplacement time gets progressively lower. In other words, when other factors make Blue less survivable, only extremely low emplacement times result in high Blue casualties. This interaction likely occurs because of the relative importance of factors. Once Blue is in a highly unfavorable configuration, emplacement time has less of an impact.

b. Blue Survivability Bootstrap Forest

To get a measure of variable importance, a bootstrap forest is constructed. Individual trees are constructed using a greedy algorithm, and one consequence is that a consistently "second best" factor in terms of the explaining the data may never enter a single tree. A bootstrap forest fits many trees, each time using only a subset of data and a subset of factors, and results are averaged across the ensemble (Hurley 2012). The column contributions from the bootstrap forest indicate which factors explain the most variability in the data. Figure 27 provides the contributions of the factors from a bootstrap forest composed of 100 trees.

Column Contributions

Term	Number of Splits	SS		Portion
BlueEmployment	2033	257.29135		0.2656
BlueEmplaceTime	2337	252.212449		0.2603
BlueDisplaceTime	1788	244.336017		0.2522
BlueDefensiveFires	1199	130.243191		0.1344
BlueTimeUntilSurvivabilityMove	2473	81.0780547		0.0837
BlueAmmoLoadout	1720	3.64663472		0.0038

Figure 27. Blue Survivability Variable Importance

These values are a heuristic measure of variable importance. Although displacement time is the first split in the partition tree, employment method and emplacement time are very close in terms of their power as predictors. However, all three of these factors are close in their relative importance and should be noted as highly impactful for Blue survivability.

c. *Blue Survivability Dominant Factors*

Figure 28 shows a density plot of Blue casualties by the separate employment methods. As consolidation increases, the distributions gets longer right tails. This suggests that while the majority of observations for each employment method result in low casualties, operating more distributed provides commanders with more confidence that catastrophic attrition of their forces will not occur.

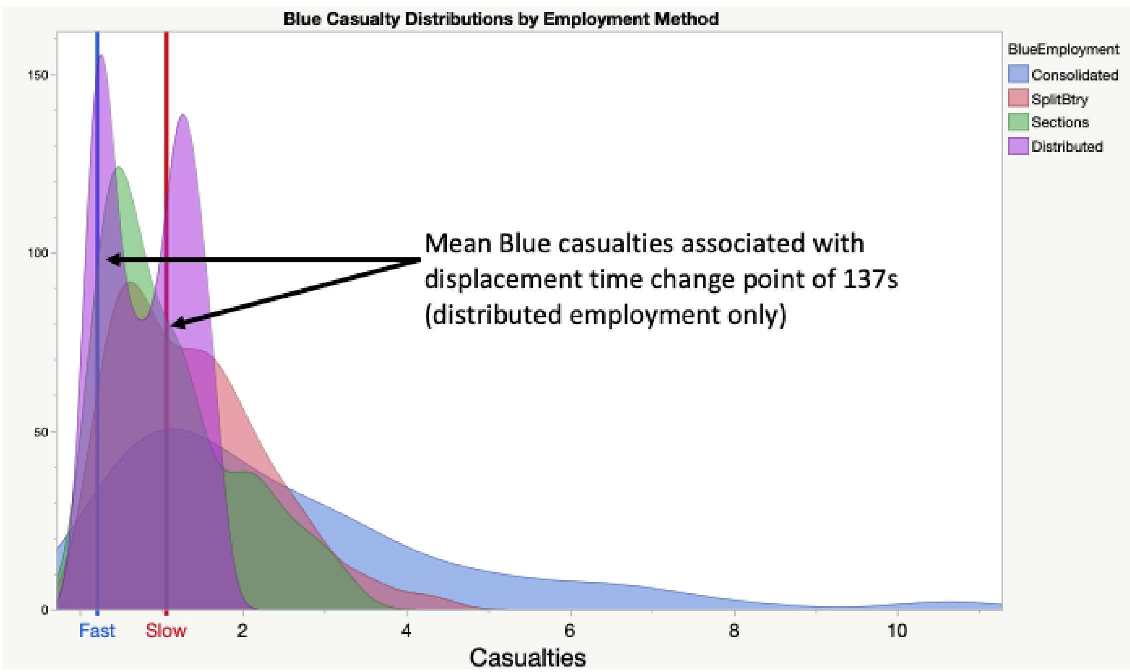


Figure 28. Blue Casualty Distributions vs. Employment Method

An additional observation from this plot is the extreme bimodality of the distributed method distribution. A partition tree on only the distributed employment design points results in a R-squared of 0.55 after only one split on displacement time. Specifically, the change point occurs right at a displacement time of 137 seconds. The vertical blue and red lines in Figure 28 denote the means of the fast displacement branch and the slow displacement branch from this tree.

Figure 29 shows this effect in a scatterplot with the split applied, as well as the tree itself. When displacement time is below 137 seconds, there is not a single occurrence of the mean Blue casualties rising above 0.5. However, when the displacement time is above that split value, a much greater range of outcomes in possible. It is possible that the 137 seconds corresponds to the Red mission processing time of 120 seconds plus additional rocket time of flight. In other words, if Blue forces can displace faster than Red can transition from mission receipt to rounds impacting, their survivability greatly increases.

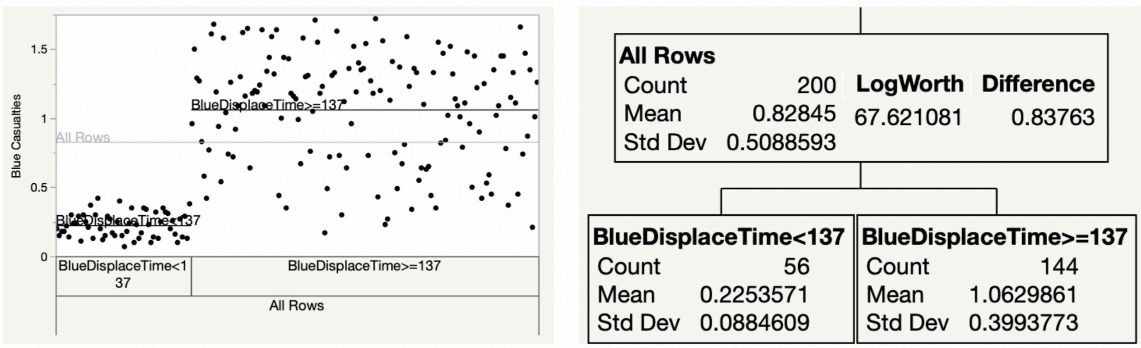


Figure 29. Blue Survivability Partition Tree on Only Distributed Design Points

A contour plot provides an easily interpretable visualization for two continuous factors' impacts on the response. Figure 30 shows the effect of emplacement and displacement time on Blue casualties. It supports the finding from the partition tree; fast displacement and slow emplacement raise Blue's survivability. Put more practically, by spending less time in a targetable state, Blue lowers their expected casualties.

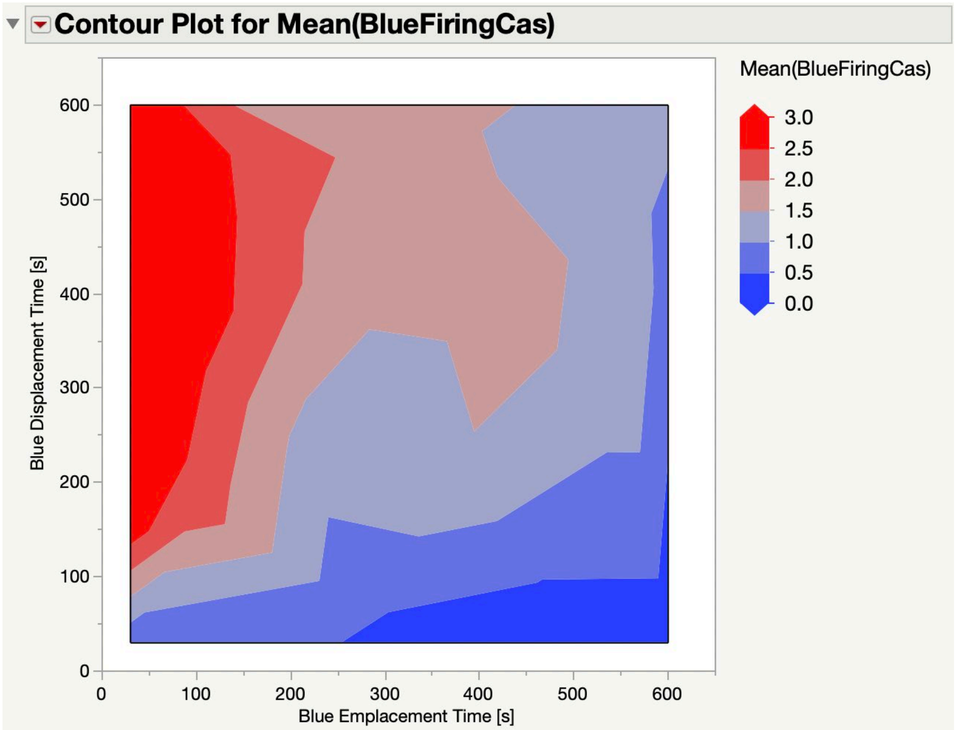


Figure 30. Contour Plot of Blue Casualties vs. Emplacement and Displacement Time

2. Blue Lethality Analysis

To analyze Blue lethality, two MOEs must be considered. Since Blue's priority is to prevent the airfield seizure by Red maneuver agents, the primary MOE of interest is Red maneuver casualties. However, Red firing casualties also provide a measure of lethality, and thus, they are studied as well.

a. Blue Lethality Partition Tree: Red Maneuver Casualties

Figure 31 presents a partition tree, this time with Red maneuver casualties as the response. In this case, six splits are able to achieve an R-squared of 0.63. The first split in this tree is between M30 ammunition and all others. The different ammunition types were briefly introduced in Chapter II, but as a reference, Table 3 explains the differences in nomenclature.

Table 3. HIMARS Ammunition Descriptions

Nomenclature	Type	Rockets per Pod
M30	DPICM	6
M31	HE	6
M39	DPICM	1
M48	HE	1

So, the most effective munition to maximize Red casualties is the smaller, but more numerous DPICM. For a mechanized force, advancing on an objective, this is unsurprising. Of note, employment of DPICM generally comes with significant civilian considerations which were outside the scope of this analysis. The next split, on both branches, is on displacement time. Lower displacement time, specifically below 279 seconds, is significant in increasing Red maneuver casualties. On both sides, this split results in a nontrivial difference of approximately three Red casualties.

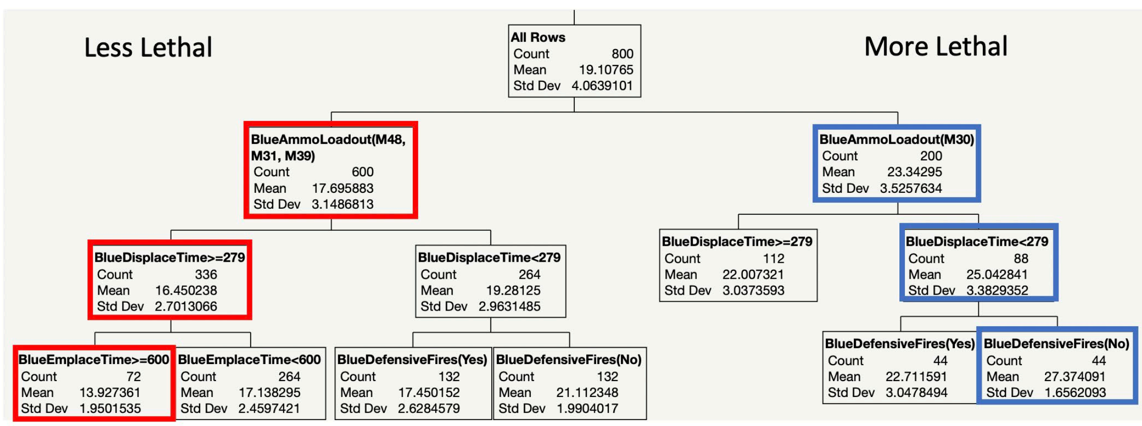


Figure 31. Blue Lethality (Red Maneuver Casualties) Partition Tree

Continuing down the left side of tree, which constitutes the worst conditions for Blue lethality, emplacement time again emerges as an important factor. In this case, lower emplacement time results in more Red casualties. This represents a tradeoff between emplacement time's impact on survivability and lethality. Shorter emplacement time results in more time in position, FIRECAP, which increases lethality by improving responsiveness but decreases survivability by increasing the time that the unit is vulnerable.

Along two other branches shown, the defensive fires setting emerges as a critical factor. It appears that firing a volley of rockets in response to incoming fire actually decreases the number of Red maneuver casualties. This effect is likely the result of a combination of features of the model. Since defensive fires are counterbattery and thus aimed at Red firing agents, there would not be an expectation of seeing the Red maneuver casualties rise. Additionally, since the time it takes to execute the fire mission is time that Blue can be targeted, it effectively increases their displacement time. This results in higher Blue casualties which leads to less Blue agents available to attrite Red. So, this factor potentially provides an example of survivability and lethality being correlated. Blue cannot be lethal if they are dead. This effect is more succinctly demonstrated by the overlayed histograms in Figure 32. While the difference in casualties is not exaggerated, it is present and nontrivial.

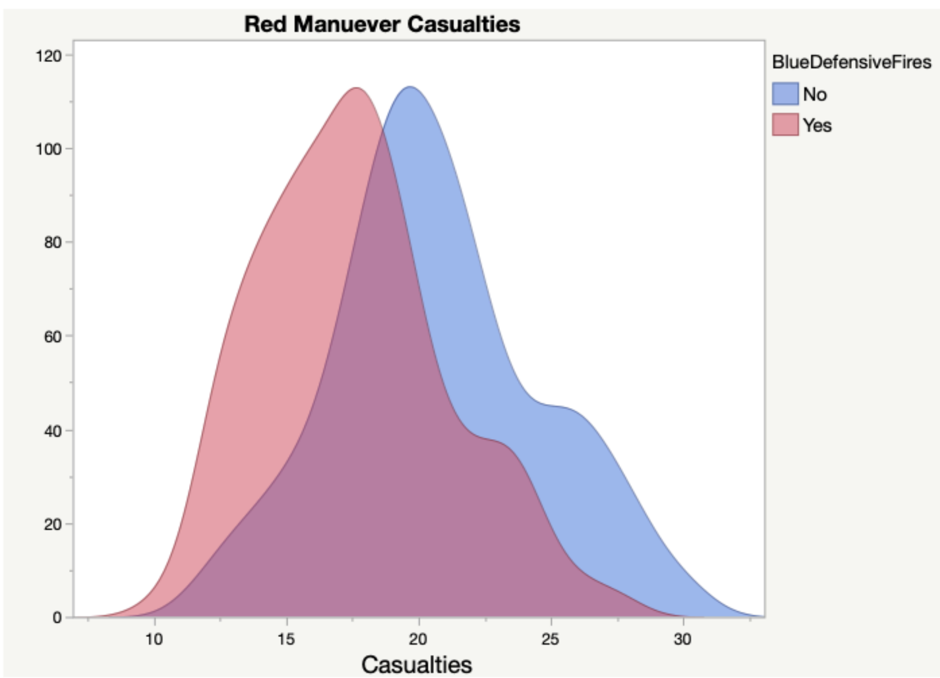


Figure 32. Red Maneuver Casualties vs. Defensive Fires

b. Blue Lethality (Red Maneuver Casualties) Bootstrap Forest

Similar to the survivability analysis, a bootstrap forest is used to gain an understanding of relative variable importance. Figure 33 provides that heuristic for a 100-tree bootstrap forest with Red maneuver casualties as the response. The ammunition proves to be the most important factor by far, while defensive fires and displacement time are second and third. As discussed above, when predicting Red maneuver casualties, these two factors are somewhat correlated because conducting defensive fires does effectively increase a unit's displacement time. Emplacement time is also relatively important while the last two variables do not contribute much to the response.

Column Contributions

Term	Number of Splits	SS	Portion
BlueAmmoLoadout	2196	3237.24346	0.4101
BlueDefensiveFires	453	1283.56229	0.1626
BlueDisplaceTime	1783	1257.00356	0.1593
BlueEmplaceTime	2037	1171.94073	0.1485
BlueTimeUntilSurvivabilityMove	2322	679.988591	0.0862
BlueEmployment	2947	263.33532	0.0334

Figure 33. Blue Lethality (Red Maneuver Casualties) Variable Importance

The two most important factors are categorical and can be visualized neatly by boxplots. Figure 34 shows that the impact of the defensive fires factor does not interact at all with the ammunition loadout factor. In other words, ammunition's effect on the response does not change based on whether or not defensive fires are employed. Referencing Table 2 along with Figure 34, it is clear that DPICM are more effective for Blue's lethality. And it appears more prudent to load the launchers with the smaller rockets in order to have more of them. It should be noted that this simulation did not take into account the range increase associated with the larger munitions as even the shortest-range rockets could reach the objective area from Blue's positions. Had there been potential for the smaller rockets being outranged, it is likely that these results would differ.

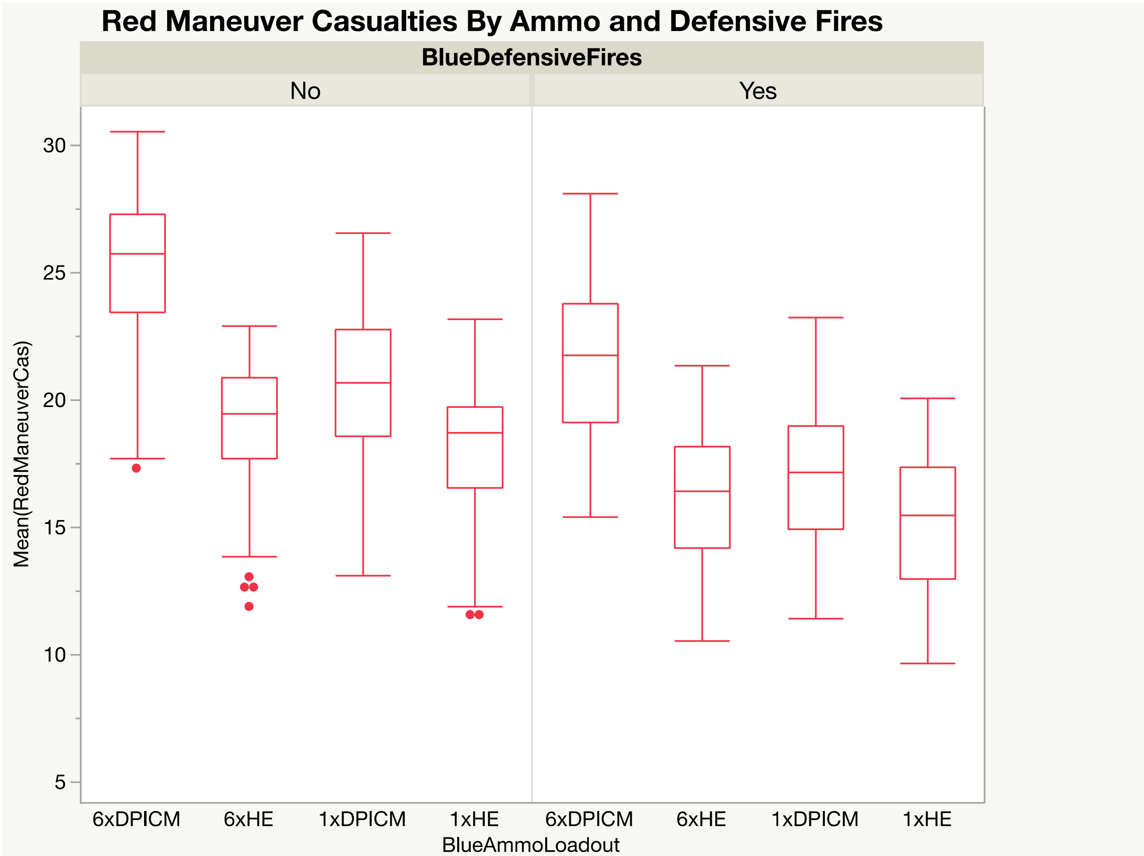


Figure 34. Red Maneuver Casualties vs. Ammunition and Defensive Fires

Using another contour plot, Figure 35 presents emplacement and displacement times' influence on Red maneuver casualties. This demonstrates the conflicting nature of emplacement time as it relates to survivability and lethality. Here, low emplacement time is critical for raising Red casualties. The impact of displacement time on lethality matches its effect on survivability.

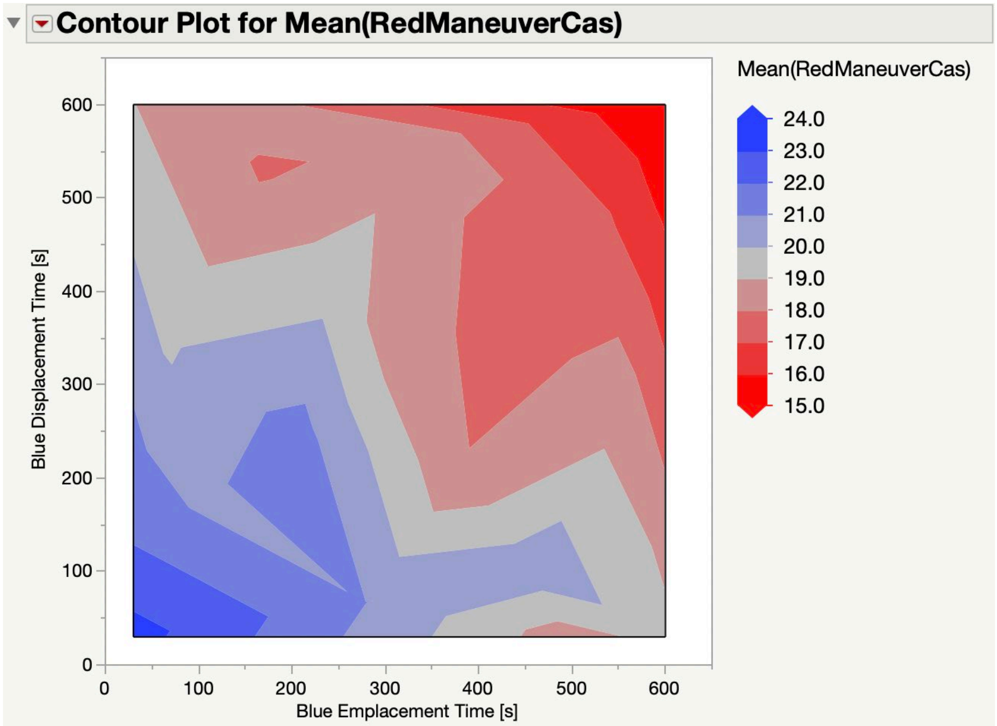


Figure 35. Contour Plot of Red Maneuver Casualties vs. Emplacement and Displacement Time

c. Blue Lethality (Red Firing Casualties) Partition Tree

To continue the analysis on Blue's lethality, a third partition tree with Red firing casualties as the response is constructed and displayed in Figure 36. In six splits, this tree explains 61.1% of the variance in the response. The first split again is on ammunition, although this time, both the smaller and larger caliber DPICM are grouped together. The next split matches on both sides of the tree and should be very familiar. Consolidated is separated from the other three employment methods, suggesting that even a small amount of distribution down to the platoon level in a split battery construct increases the unit's lethality in addition to its survivability. The final layer of splits is all on displacement times, with the reoccurring theme of faster displacement resulting in greater lethality. However, along the right-most branch, which represents the best conditions for Blue lethality, the change point for displacement time is much slower. This suggests that a unit can tradeoff some speed in their displacement by using more effective ammunition such as DPICM and operating distributed without a loss in lethality.

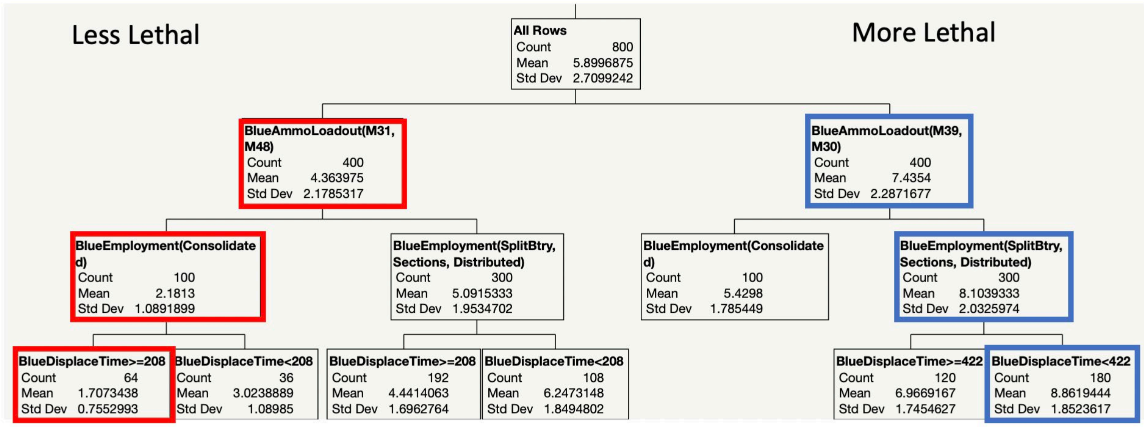


Figure 36. Blue Lethality (Red Firing Casualties) Partition Tree

d. *Blue Lethality (Red Firing Casualties) Bootstrap Forest*

Again, a bootstrap forest is constructed to compare the variable importance for the two Blue lethality MOEs. Figure 37 displays the column contributions. It is observed that employment method is significantly more impactful for Red firing casualties than Red maneuver casualties. Defensive fires, emplacement time, and displacement time all remain impactful and relatively close.

Column Contributions

Term	Number of Splits	SS	Portion
BlueAmmoLoadout	1714	1271.87728	0.3590
BlueEmployment	1985	799.382465	0.2256
BlueDefensiveFires	878	482.095059	0.1361
BlueDisplaceTime	2378	475.814159	0.1343
BlueEmplaceTime	2781	454.138817	0.1282
BlueTimeUntilSurvivabilityMove	2177	59.4584122	0.0168

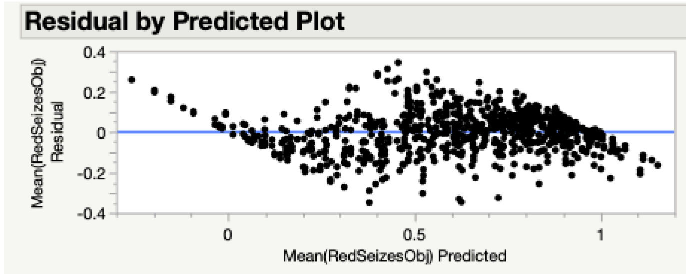
Figure 37. Blue Lethality (Red Firing Casualties) Variable Importance

The impacts of other variables remain largely the same as they are on Red maneuver casualties. Lower emplacement and displacement times, DPICM, more numerous smaller rockets, and no defensive fires all result in greater Blue lethality.

e. Stepwise Linear Regression on Red's Successful Seizure

The next metamodel is a stepwise linear regression with Red's successful seizure as the response. Stepwise regression allows for iteratively removing unimportant factors by comparing their impact on some model selection criteria (Bassett 2021). This is a measure of Blue's success, but it more directly relates to Blue lethality as it is delineated by whether or not 50% of Red's maneuver force survives the engagement. Since this analysis is conducted on the means of the 100 binary responses for each design point, the response values can be thought to represent probability of Red's success. This model delivers an adjusted R-squared of 0.87 with all six main effects, seven two-way interactions, and one quadratic term.

The residual vs. predicted plot in Figure 38 exhibits that although the mean residual is approximately zero, there is some heteroscedasticity present, especially at the limits. The normal quantile plot in Figure 38 fails to suggest that the residuals are not distributed normally. Therefore, the model satisfies two of the three assumptions usually required for regression. Typically, this would require transformations of predictors or the response in order to satisfy the constant variance assumption. However, since the goal of the model is gaining insight and not making predictions, the model is deemed useful as it stands, given that transformations will serve to reduce interpretability (Kleinjnen et al. 2005).



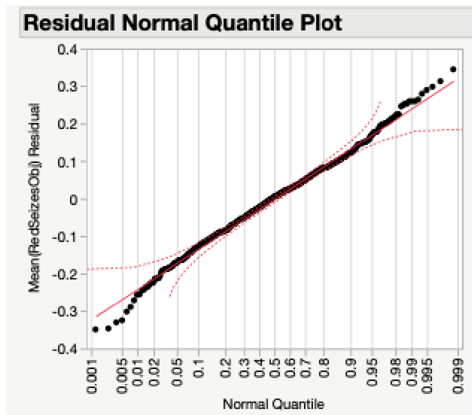
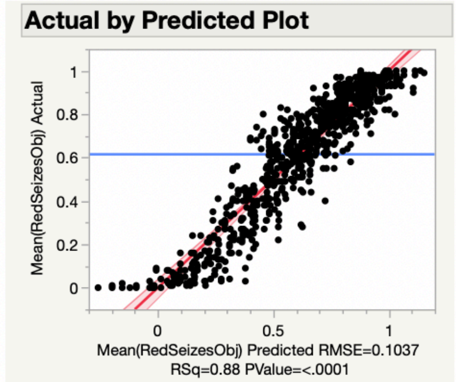


Figure 38. Regression Diagnostic Plots

Figure 39 provides a summary of the model and includes an actual vs. predicted value plot along with sorted coefficient estimates. The interpretations of the top four variable coefficients provide some valuable insight. The coefficient for the [M30] level of ammunition loadout explains that the main effect of Blue's use of six DPICM rockets lowers Red's average rate of success by 19%. Similarly, the main effect of setting defensive fires to "No" decreases Red's rate of success by 11%. For displacement and emplacement time main effects, Blue getting slower by 100 seconds results in Red improving their chances of success by 4.7% and 4.4%, respectively.



Summary of Fit

RSquare	0.87633
RSquare Adj	0.873803
Root Mean Square Error	0.103745
Mean of Response	0.614663
Observations (or Sum Wgts)	800

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
BlueAmmoLoadout{M30-M39&M31&M48}	-0.193956	0.004301	-45.10	<.0001*
BlueDefensiveFires[No]	-0.112813	0.003668	-30.76	<.0001*
BlueDisplaceTime	0.0004687	0.000017	27.62	<.0001*
BlueEmplaceTime	0.0004426	0.000017	26.07	<.0001*
BlueEmployment{Distributed&Sections-Consolidated&SplitBtry}	-0.052313	0.003668	-14.26	<.0001*
BlueAmmoLoadout{M39-M31&M48}	-0.058513	0.004492	-13.03	<.0001*
BlueDefensiveFires[No]*(BlueTimeUntilSurvivabilityMove-900)	0.0000836	8.062e-6	10.37	<.0001*
BlueTimeUntilSurvivabilityMove	-6.681e-5	8.062e-6	-8.29	<.0001*
BlueDefensiveFires[No]*(BlueDisplaceTime-315.04)	0.0001315	0.000017	7.74	<.0001*
BlueAmmoLoadout{M31-M48}	-0.035675	0.005187	-6.88	<.0001*
(BlueTimeUntilSurvivabilityMove-900)*(BlueTimeUntilSurvivabilityMove-900)	-1.676e-7	2.542e-8	-6.59	<.0001*
(BlueAmmoLoadout{M39-M31&M48}+0.25)*BlueDefensiveFires[No]	-0.028132	0.004424	-6.36	<.0001*
BlueDefensiveFires[No]*(BlueEmplaceTime-315.04)	0.0001015	0.000017	5.98	<.0001*
(BlueAmmoLoadout{M39-M31&M48}+0.25)*(BlueDisplaceTime-315.04)	0.0001105	2.047e-5	5.40	<.0001*
(BlueAmmoLoadout{M30-M39&M31&M48}+0.5)*(BlueTimeUntilSurvivabilityMove-900)	-0.000045	9.309e-6	-4.84	<.0001*
(BlueAmmoLoadout{M39-M31&M48}+0.25)*(BlueEmplaceTime-315.04)	8.6436e-5	2.047e-5	4.22	<.0001*

Figure 39. Red Success Stepwise Linear Regression

The most impactful interaction identified in this model is between defensive fires and time until conducting a survivability move. Until now, the latter has not been identified as a significant factor for Blue lethality or survivability. As demonstrated in the interaction profiler in Figure 40, when defensive fires are set to "No," time until survivability move's impact on Red's success resembles a negative quadratic function where the extremes result in lower success than the middle settings. However, when the factor is switched to "Yes," time until survivability move becomes negatively correlated with Red's success, although still in a quadratic manner.

The reason for this interaction is not entirely clear, although the two distinct impacts of time until survivability move are not surprising. It can be hypothesized that by Blue spending more or less time in position improves their success by either increasing their lethality by spending more time FIRECAP or increases their survivability by making themselves less targetable. Similarly, as this factor increases, Red's success decreases because Blue spends more time in position which results in greater Red attrition.

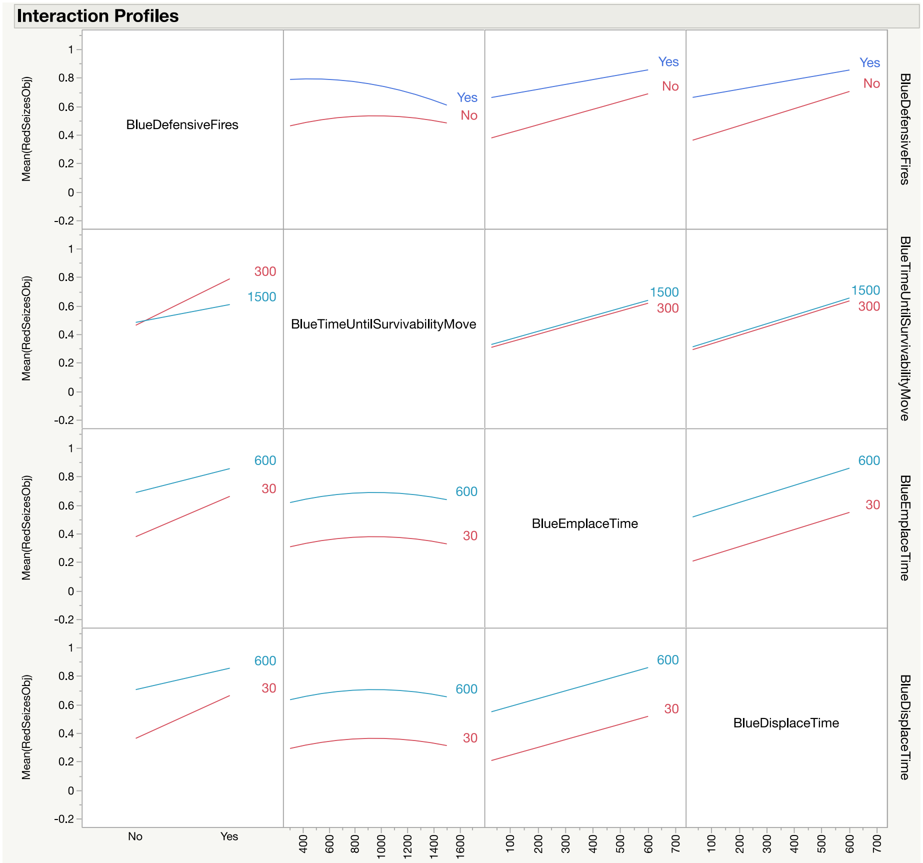


Figure 40. Interaction Profiles for Defensive Fires and Other Factors

It is also observed from Figure 40 that emplacement and displacement time have similar interactions with defensive fires. Changing these two factors simply changes the slope of defensive fires' impact on Red success. Higher emplacement and displacement times result in a less dramatic difference between the two levels for defensive fires. This interaction is logical because the delay incurred by conducting defensive fires will have a smaller relative effect when displacement and emplacement are already high.

3. Experiment Three Insights

Experiment three provides strong support for specific tactics and capabilities to improve survivability and lethality. The most consolidated formation that a rocket battery should employ should be split battery. Aggregating at the consolidated level increases risk of mission failure and loss of friendly forces. Displacement time has a consistent impact on both survivability and lethality; faster is better for Blue forces. Ammunition has a strong impact on lethality and negligible impact on survivability. Using smaller, more numerous DPICM rockets is the most lethal configuration.

By emplacing slowly, a Blue unit spends less time in a targetable state and then experiences a proportionate decrease in their own casualties. However, this also results in less responsive fire support and a corresponding decrease in lethality. This tradeoff is analyzed further in the experiment four analysis. Defensive fires should not be employed as they serve to decrease lethality and survivability. Time until conducting survivability moves is the least impactful factor with only minor impacts on the MOEs.

D. EXPERIMENT FOUR: RED AND BLUE FACTORS

Experiment three's analysis provides insight into the Blue factor settings that maximize survivability and lethality. Experiment four builds on this analysis by varying Red factors to determine which Blue factor settings are resistant to uncontrollable changes by Red. Previously, the Red force has been approximated by what is known about their tactics and capabilities. With the knowledge that this best-approximation is imprecise, true tactics and capabilities are expected to be captured within a range of factor levels. To simplify the analysis, two MOEs are analyzed, Blue losses and the total Red losses given by the sum of maneuver and firing agent casualties.

The goals of experiment four's analysis are threefold. First, this analysis seeks to find a robust Blue solution through the use of a loss function. Rather than relying on mean performance alone, a robust solution achieves high mean performance while remaining insensitive to variance in the system due to uncontrollable factors (Sanchez and Sanchez 2020, p. 60). This solution may be different than the solution which simply provides the highest mean performance. The robust solution is more appropriate for combat modeling due to the inherent uncertainty associated with conflict.

The second goal of this analysis is to determine the impact of Blue factors on the MOEs' mean values and variance. Their impacts on the mean values can be compared with experiment three's analysis to identify inconsistencies. Their influences on variance provide insight into which factors drive variability in the response.

The last goal focuses on identifying tradeoffs. Possible tradeoffs are between effects on target mean performance and variance where improving performance also increases uncertainty. Tradeoffs could also be between survivability and lethality where a factor has an opposite effect on them. Any tradeoffs present are carefully considered to determine the settings that perform acceptably with respect to lethality, survivability, and variance in the response.

1. Quadratic Loss Function

To determine the critical factors for rocket artillery lethality and survivability, it is not enough to simply analyze the mean values associated with the corresponding MOEs. Modelers must also consider the variance in the response brought on by the factors. The purpose of a loss function is to balance the two conflicting desired attributes of a solution, accuracy in the form of a mean that is close to the intended target and precision in the form of low variance despite varying levels of uncontrollable factors. A loss function penalizes an MOE for its distance from a target value and for its variance. The quadratic loss function used in this research is given by

$$\ell_{Y_x} = c(Y_x - \tau)^2 \tag{2}$$

where c is a cost constant, Y_x is the response for design point x, and tau (τ) is the target value (Sanchez and Sanchez 2020, p. 65). The loss function for this application does not require a cost scaling so c is set to 1. The expected loss is given by the form

$$E[\ell_{Y_x}] = \sigma^2_{Y_x} + (E[Y_x] - \tau)^2 \tag{3}$$

where $\sigma^2_{Y_x}$ is the variance of Y_x, $E[Y_x]$ is the mean of Y_x, and τ remains the target value (Sanchez and Sanchez 2020, p. 65). The values in this equation as they correspond to lethality and survivability are:

- Blue lethality: Y_x= Red casualties, τ= 60 (maximum number of casualties possible)

- Blue survivability: Y_x= Blue casualties, τ= 0 (minimum number of casualties possible)

In this experiment, Blue factors are varied over 608 unique design points. These design points are then crossed with all combinations of Red factors (26 design points) and run for 100 replications. This results in 2,600 simulated battles per Blue design point. By taking summary statistics of the mean and standard deviations of the MOEs over these 2,600 battles, the expected loss is calculated for each Blue construct.

The goal is to find Blue constructs which minimize loss for Blue and Red casualties. This can be done graphically by plotting Red casualty losses vs. Blue casualty losses and examining which points minimize loss for both. The collection of these points is known as the Pareto Optimal Frontier and is denoted by the points connected by the blue dashed line in Figure 41 (Sanchez 2021).

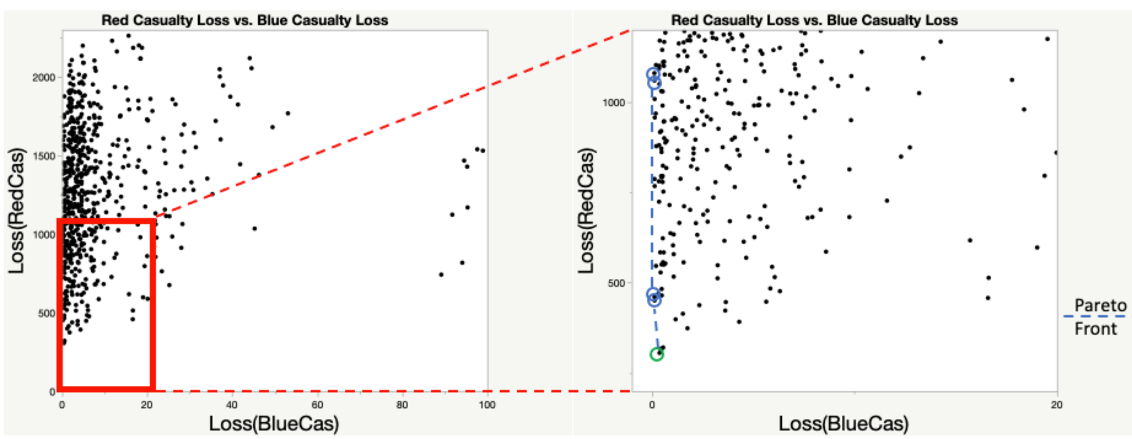


Figure 41. Pareto Optimal Frontier for Minimizing Blue and Red Casualty Loss

The green circled point represents the design point with the best Blue construct for minimizing both losses. The details of this design point are as follows:

- Employment: Distributed
- Ammunition: M30 (6x DPICM)

- Defensive Fires: No
- Time in Position: 1500 seconds
- Emplacement Time: 30 seconds
- Displacement Time: 30 seconds

This configuration represents the maximum time considered for time in position and the minimum times considered for emplacement and displacement times. This unique combination of factor levels may not be possible or practical to achieve, so additional metamodel analysis is conducted to provide further understanding of a robust solution.

2. Blue Survivability Analysis

Blue survivability is analyzed in the robust case by constructing metamodels with responses related to the mean and variance of Blue casualties for each unique design point.

a. Blue Survivability (Blue Casualty Loss) Partition Tree

First, a partition tree is constructed using only Blue factors. In this case, the goal is to minimize Blue casualty loss, so the ideal path follows the leftmost branches down the tree. The tree in Figure 42 only achieves an R-squared of 0.29 after six splits. This limited explained variance indicates that Red factor settings may have a large impact on Blue survivability. It is clear that the most important factor is employment method, and the right branch of this tree indicates that the single worst tactic or capability that the Blue force can employ is operating at the consolidated level. By comparing the best possible Blue configuration mean loss with the overall mean loss, the importance of displacement time and employment method are demonstrated. Operating in sections or fully distributed and displacing in under 132 seconds, drops the mean Blue casualty loss down from 8.1 to 0.5.

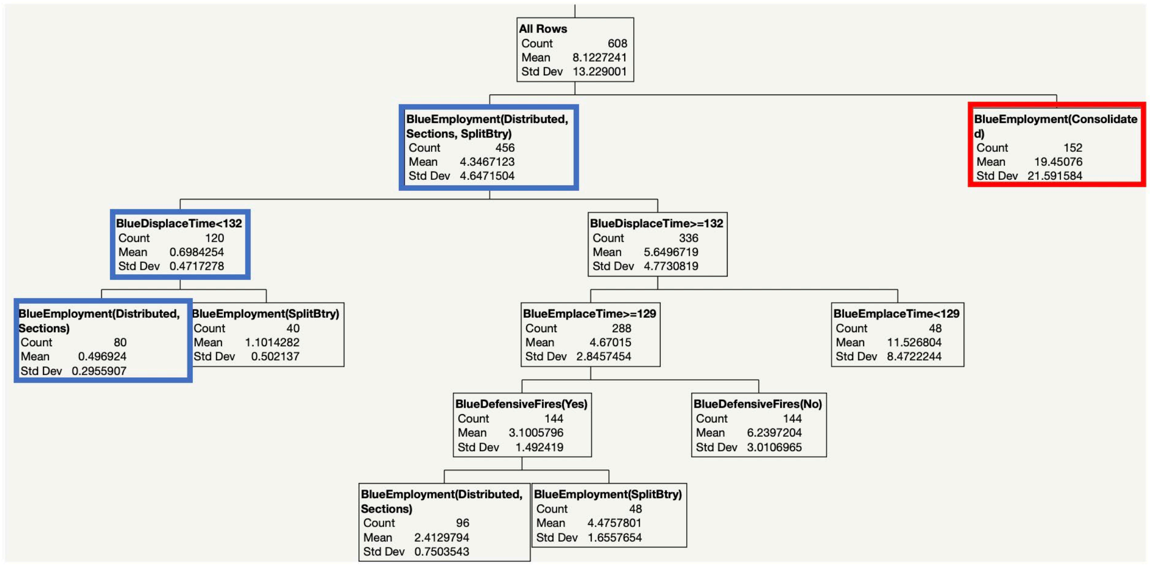


Figure 42. Blue Survivability (Blue Casualty Loss) Partition Tree

Other factors critical for a consistently survivable Blue force include fast displacement time and potentially operating more distributed than split battery at the section or individual launcher level. On the middle branch, longer emplacement times arise as better for survivability. Interestingly, employment of defensive fires appears in this tree as beneficial for improving consistent survivability. This effect is absent in the experiment three analysis. Figure 43 provides the relative variable importance for Blue factors as given by a bootstrap forest with 100 trees. Referencing Figure 27 from the experiment three analysis, the variable importance remains fundamentally the same.

Column Contributions

Term	Number of Splits	SS	Portion
BlueEmployment	1626	18891.3074	0.3032
BlueEmplaceTime	1855	16309.468	0.2618
BlueDisplaceTime	1453	13776.6725	0.2211
BlueDefensiveFires	1015	9488.06926	0.1523
BlueTimeUntilSurvivabilityMove	1608	3677.18265	0.0590
BlueAmmoLoadout	1148	157.233942	0.0025

Figure 43. Blue Survivability (Blue Casualty Loss) Variable Importance

b. Blue Survivability (Blue Casualties) Linear Regression

The next model analyzed is a least squares fit linear regression performed with both the mean and standard deviation of Blue casualties as the responses. The model only considers main effects of Blue factors in order to focus the analysis on which factor settings achieve mean performance near the target and relatively low variability around that mean. It also allows for a comparison of tradeoffs between mean performance and variability. This model achieves an R-squared of 0.69 and 0.83 for mean and standard deviation respectively, giving it more than twice the explanatory power of the survivability partition tree. This also implies that Blue factors provide more influence over the variability in their survivability than in the mean values.

Figure 44 provides a summary of the estimated coefficients for each response. The blue box surrounds the mean Blue casualties coefficients and the green box surrounds the model with standard deviation of the Blue casualties as the response.

Sorted Parameter Estimates for Mean(BlueCas)

Term	Estimate	Std Error	t Ratio	Prob>|t|
BlueEmployment[Consolidated]	1.3448545	0.059695	22.53	<.0001*
BlueDisplaceTime	0.0034361	0.000165	20.80	<.0001*
BlueEmplaceTime	-0.002348	0.000172	-13.67	<.0001*
BlueDefensiveFires[No]	0.4092447	0.034465	11.87	<.0001*
BlueEmployment[Sections]	-0.441089	0.059695	-7.39	<.0001*
BlueTimeUntilSurvivabilityMove	-0.000579	8.025e-5	-7.22	<.0001*
BlueEmployment[SplitBtry]	-0.142051	0.059695	-2.38	0.0176*
BlueAmmoLoadout[M30]	-0.10618	0.059695	-1.78	0.0758
BlueAmmoLoadout[M31]	0.0597938	0.059695	1.00	0.3169
BlueAmmoLoadout[M39]	-0.018561	0.059695	-0.31	0.7560

Sorted Parameter Estimates for StdDev(BlueCas)

Term	Estimate	Std Error	t Ratio	Prob>|t|
BlueEmployment[Consolidated]	0.6734612	0.018646	36.12	<.0001*
BlueDisplaceTime	0.0017875	5.16e-5	34.64	<.0001*
BlueEmplaceTime	-0.000663	5.365e-5	-12.36	<.0001*
BlueEmployment[Sections]	-0.217729	0.018646	-11.68	<.0001*
BlueDefensiveFires[No]	0.1052073	0.010765	9.77	<.0001*
BlueTimeUntilSurvivabilityMove	-8.072e-5	0.000025	-3.22	0.0014*
BlueAmmoLoadout[M30]	-0.031956	0.018646	-1.71	0.0871
BlueAmmoLoadout[M31]	0.0234711	0.018646	1.26	0.2086
BlueAmmoLoadout[M39]	-0.009817	0.018646	-0.53	0.5987
BlueEmployment[SplitBtry]	-0.005787	0.018646	-0.31	0.7564

Figure 44. Blue Survivability Mean and Standard Deviation Regression Coefficient Estimates

The first three factors have similar effects on mean and standard deviation, which also follows what has been found thus far in the analysis. No factors are found to have opposite effects on mean and standard deviation, but defensive fires and time until survivability move have diminished influence on standard deviation compared to the mean.

The prediction profiler in Figure 45 provides more information about factors' influence on mean and standard deviation. Moving from sections to distributed employment has limited impact on decreasing mean casualties, but it resulted in a significant drop in uncertainty. Similarly, displacement time has a stronger effect on variability than the mean, as evidenced by the steeper slope of the bottom plot.

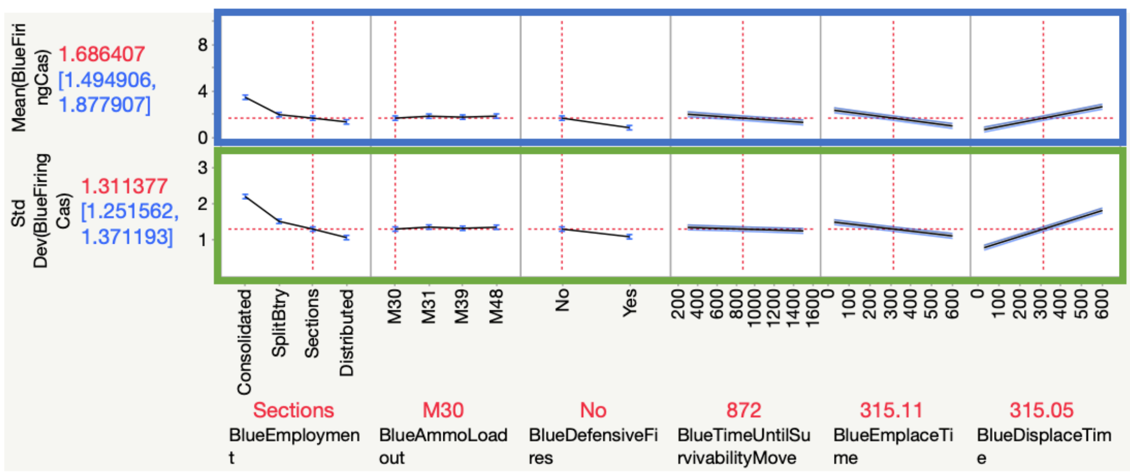


Figure 45. Prediction Profiler for Blue Survivability Mean and Standard Deviation

Based on the metamodel analysis for Blue survivability, it can be concluded that a robust survivable force as measured by their own casualties will operate at the following generalized factors levels:

- Distributed employment
- Less emphasis on fast emplacement
- Fast displacement

- Defensive fires employed
- More time between survivability moves

This configuration is compared to the most robust lethal configuration to identify where tradeoffs between the two exist. The most lethal Blue construct is analyzed and proposed in the next section.

3. Blue Lethality Analysis

Blue lethality is analyzed through metamodels constructed first with Red casualty losses as the response and then by examining the mean and variability associated with the Red casualty counts.

a. Blue Lethality (Red Casualty Loss) Partition Tree

Figure 46 shows the partition tree of only Blue factors with Red casualty loss as the response. This tree explains much more of the variance in the response than the survivability tree with an R-squared of 0.69 after seven splits. This tree supports the findings from experiment three in that ammunition is the single most important factor in Blue lethality. The best configuration given by this tree is a Blue force loaded with 6x DPICM rockets per launcher and not employing defensive fires. On other branches of the tree, there is further support for fast emplacement and displacement times. The best configuration represents a decrease in mean Red casualty loss from the overall mean of 1271.8 to 867.8.

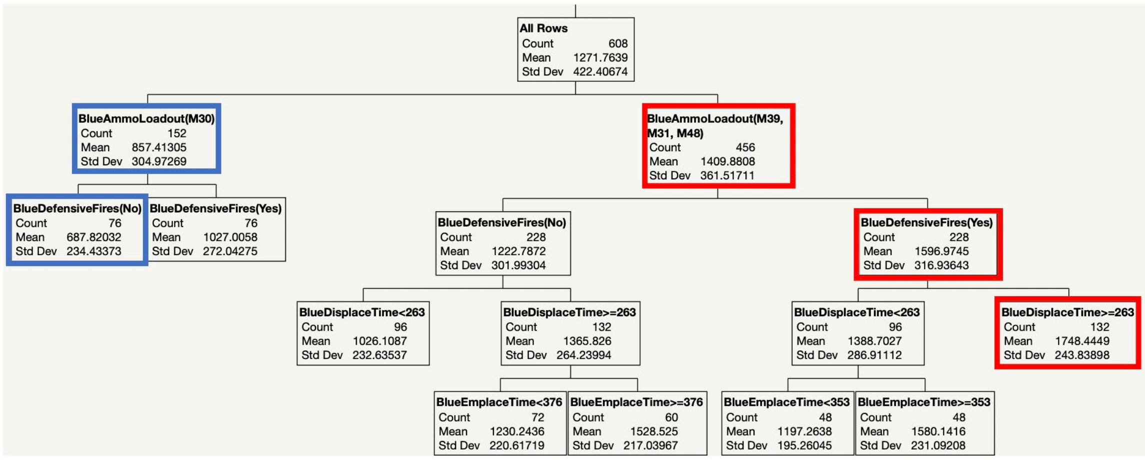


Figure 46. Blue Lethality (Red Casualty Loss) Partition Tree

A bootstrap forest is also constructed with Red casualty loss as the response. The variable importance heuristic is provided in Figure 47. When comparing this to the variable importance in experiment three, both Red maneuver and firing casualties must be considered. The combined Red casualty loss variable importance matches closely with the most significant factors from the Red maneuver casualties heuristic.

However, there is one significant departure from the Red firing variable importance. Employment method is the second most important factor in the Red firing casualty analysis from experiment three, and here it is much less influential. The greater number of Red maneuver agents gives it more influence when analyzing combined Red casualties. Given that Blue's mission is to prevent the airfield seizure by Red maneuver agents, the combined casualty counts is considered to be the correct measure of Blue's lethality.

Column Contributions				
Term	Number of Splits	SS		Portion
BlueAmmoLoadout	1397	26957959.2		0.4120
BlueDefensiveFires	376	12973906.1		0.1983
BlueDisplaceTime	1622	11278290		0.1723
BlueEmplaceTime	1942	7836571.46		0.1198
BlueEmployment	2455	5223768.94		0.0798
BlueTimeUntilSurvivabilityMove	1250	1168013.9		0.0178

Figure 47. Blue Lethality (Red Casualty Loss) Variable Importance

b. Blue Lethality (Red Casualties) Linear Regression

To further explore factors affecting Blue lethality, this section reviews a least squares linear regression using Blue factors as predictors, with the mean and standard deviation of Red casualties as the responses. This metamodel provides explanatory power of 0.94 and 0.36 for mean and standard deviation, respectively. These values indicate that Blue factors dominate the Red factors in determining mean Blue lethality, but have less of an effect on variability.

Figure 48 provides the estimated coefficients associated with both responses. There are clear discrepancies between the factors' effects on mean and variability. First, all factors are significant in the mean response model. In the standard deviation model, time until survivability move, emplacement time, and split battery employment are all insignificant at the 0.05 level, and displacement time is just on the cusp of being insignificant.

Sorted Parameter Estimates for Mean(RedCas)

Term	Estimate	Std Error	t Ratio	Prob>|t|
BlueAmmoLoadout[M30]	6.4237753	0.110819	57.97	<.0001*
BlueDefensiveFires[No]	2.6553036	0.063981	41.50	<.0001*
BlueDisplaceTime	-0.01135	0.000307	-37.01	<.0001*
BlueEmplaceTime	-0.009953	0.000319	-31.21	<.0001*
BlueAmmoLoadout[M31]	-2.96625	0.110819	-26.77	<.0001*
BlueEmployment[Consolidated]	-2.491936	0.110819	-22.49	<.0001*
BlueEmployment[Sections]	1.3459894	0.110819	12.15	<.0001*
BlueTimeUntilSurvivabilityMove	0.0015763	0.000149	10.58	<.0001*
BlueEmployment[SplitBtry]	-0.842206	0.110819	-7.60	<.0001*
BlueAmmoLoadout[M39]	0.5031705	0.110819	4.54	<.0001*

Sorted Parameter Estimates for StdDev(RedCas)

Term	Estimate	Std Error	t Ratio	Prob>|t|
BlueAmmoLoadout[M30]	0.2817608	0.020679	13.63	<.0001*
BlueAmmoLoadout[M39]	-0.191316	0.020679	-9.25	<.0001*
BlueAmmoLoadout[M31]	0.111042	0.020679	5.37	<.0001*
BlueEmployment[Consolidated]	-0.090762	0.020679	-4.39	<.0001*
BlueEmployment[Sections]	0.0519791	0.020679	2.51	0.0122*
BlueDefensiveFires[No]	-0.02674	0.011939	-2.24	0.0255*
BlueDisplaceTime	0.0001144	5.723e-5	2.00	0.0461*
BlueTimeUntilSurvivabilityMove	-4.255e-5	2.78e-5	-1.53	0.1264
BlueEmplaceTime	8.6814e-5	5.951e-5	1.46	0.1451
BlueEmployment[SplitBtry]	0.0196247	0.020679	0.95	0.3430

Figure 48. Blue Lethality Mean and Standard Deviation Regression Coefficient Estimates

These effects are more easily visualized in the prediction profiler in Figure 49. Here, the lessened influence of defensive fires, time until survivability move, emplacement time, and displacement time on standard deviation is demonstrated by the difference in slope of their prediction plots.

Blue employment also appears to have dissimilar effects on mean and variance. The relationship between employment method and mean Red casualties indicates that more distributed units are more lethal. When considering variance, however, getting more distributed increases variance until reaching the fully distributed level at which point it decreases slightly.

Ammunition also has inconsistent impacts on the two responses. The effect on the mean follows the findings from experiment three. DPICM and smaller-caliber, more numerous rockets are more lethal. However, the size of the rocket is more critical to the variability with the larger rockets corresponding to lower uncertainty. Even with this discrepancy, M30 employment appears to be the best option as its ability to inflict casualties is much greater than its relative increase in variability. Ultimately, this metamodel suggests that every Blue factor has different impacts on mean and variability.

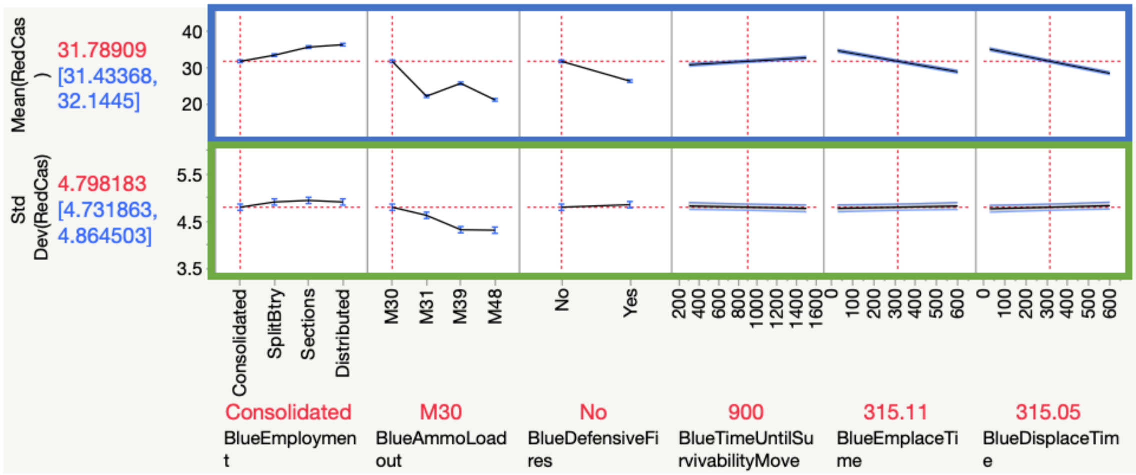


Figure 49. Prediction Profiler for Blue Lethality Mean and Standard Deviation

This analysis supports that the generalized Blue configuration, which lends itself to the greatest lethality against Red forces is as follows:

- Employment of M30 ammunition (6xDPICM)
- Some level of distributed employment (at least split battery)
- No defensive fires employed
- Fast emplacement
- Fast displacement
- More time between survivability moves

Three factors are consistent whether the goal is to minimize Blue casualties or maximize Red casualties. These are distributed employment, displacement time, and time in position. Ammunition is a critical factor for lethality but has little effect on survivability. Then, there are two factors with conflicting levels depending on the goal of maximizing either survivability or lethality. These are employment of defensive fires and emplacement time. The following section seeks to find the balance between these opposing factors.

4. Balancing of Opposing Factors

To compare the impacts of the opposing factors on survivability and lethality, an additional metamodel is created with Blue and Red casualties as the responses. All Blue factor main effects are considered.

Figure 50 displays the prediction profiler for defensive fires. The top plot predicts Blue casualties depending on defensive fires, so the goal is the lowest possible value. The bottom plot predicts Red casualties, and thus the highest possible value is the goal. When considering the difference in slope magnitude between the two lines, it is clear that not employing defensive fires produces a stronger positive impact on lethality than it negatively affects survivability.

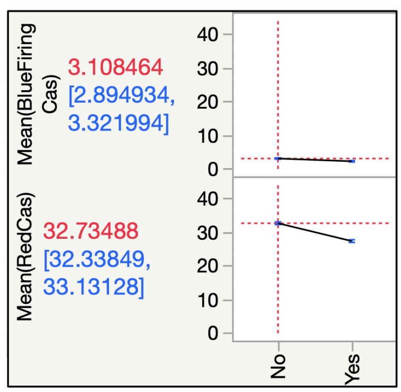


Figure 50. Defensive Fires Prediction Profiler for Blue and Red Casualties

In Figure 51, emplacement time is the factor of interest again with Blue casualties predicted on the top and Red casualties on the bottom. Similar to defensive fires, the positive impact of a fast emplacement time on lethality outweighs the more negligible negative effect on survivability. This is evidenced by the steeper slope of the line predicting Red casualties.

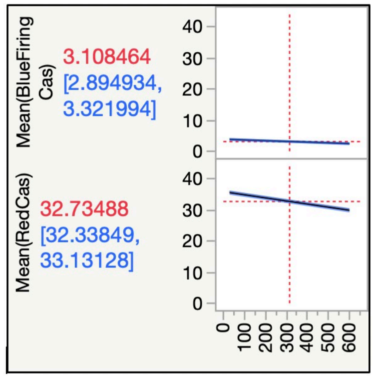


Figure 51. Emplacement Time Prediction Profiler for Blue and Red Casualties

5. Red Factor Analysis

Thus far, the experiment four analysis treats Blue factors as controllable and Red factors as uncontrollable. While this provides valuable insight into robust Blue configurations, there is further understanding to be gained by examining the impact of Red factors. The following metamodels are constructed to include Red factors.

a. Blue Survivability Partition Trees

First, a partition tree including both Red and Blue factors with Blue casualties as the response is formed (not shown). A Red factor does not appear until the eighth split in the tree. Specifically, the split demonstrates that the longer Red spends between survivability moves results in fewer Blue casualties. To gain more understanding of the impact of Red factors, Figure 52 displays a second tree with only Red factors. After six splits, the tree produces an R-squared of only 0.044, indicating that Blue factors are dominant in influencing their own survivability. Again, Red's time in position is the dominant factor, with longer times being more favorable for Blue survivability. Red displacement time is the next split on the left branch of the tree, with higher values associated with lower Blue casualties. Continuing down the leftmost branch, the last split is on emplacement time. Once again, longer times are associated with better Blue survivability. Red's least lethal configuration only represents a decrease of less than 0.4 Blue casualties from the overall mean.

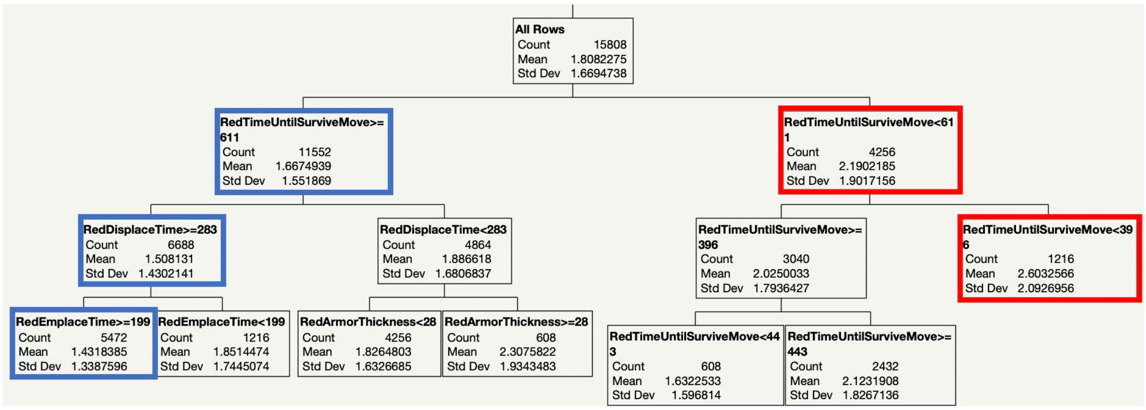


Figure 52. Blue Survivability Partition Tree: Red Factors Only

b. Blue Survivability Linear Regression

To further consider Red factors' impacts on Blue survivability, a least squares linear regression is constructed using only main effects of Red factors. The model fits the data poorly, explaining only 4% of the variance in the response. However, the model does provide coefficient estimates of the Red factors which is helpful for gaining insight. Figure 53 provides these estimates. Red's maneuver speed and armor thickness are relatively unimportant, which is intuitive considering the response is the number of Blue casualties. Similar to the partition tree, emplacement time, displacement time, and time until a survivability move are all negatively correlated with Blue casualties. From Red's perspective, this suggests that a Red force which is slow to emplace and displace and waits longer between survivability moves is less lethal against Blue. Another finding from this model is that Red's 8x370mm munition configuration is more lethal than their 10x300mm configuration.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
RedEmplaceTime	-0.001307	8.123e-5	-16.08	<.0001*
RedDisplaceTime	-0.001275	8.238e-5	-15.47	<.0001*
RedTimeUntilSurviveMove	-0.000464	3.915e-5	-11.84	<.0001*
RedAmmoLoadout[8x370mm]	0.1109463	0.01299	8.54	<.0001*
RedManeuverSpd	-0.004828	0.002301	-2.10	0.0359*
RedArmorThickness	0.0025623	0.001548	1.66	0.0979

Figure 53. Blue Survivability Linear Regression Coefficient Estimates: Red Factors Only

c. *Blue Lethality Partition Trees*

Now turning to lethality, a partition tree of both Red and Blue factors with Red casualties as the response is constructed. Blue factors are even more dominant than in the survivability partition tree. At 50 splits with an R-squared of 0.92, there are no Red factors in the tree. A second tree is created using only Red factors and is displayed in Figure 54. Expectedly, the model delivers an extremely small R-squared (0.02 at six splits). The only three factors in the tree are the same three that were most important for Blue survivability: emplacement time, displacement time, and time in position. In this case, faster emplacement times result in more Red casualties. This is similar to the effect seen with Blue emplacement time. Faster emplacement time means more time in a targetable state for Red which increases their casualties.

There are some interesting interactions between time in position and displacement time. When displacement time is high, less time in position is more favorable for Blue lethality. However, when displacement time is low, longer time in position results in more Red casualties. The author hypothesizes that this is tied to an overall time in a targetable state. When Red displaces quickly, Blue needs them to spend more time in position prior to that displacement in order to attrite them. Conversely, when Red displaces slowly, Blue is less reliant on a long time in that position for successful fire mission execution. To further demonstrate the dominance of Blue factors, the difference between Red's least survivable configuration and the overall mean number of Red casualties is less than 0.4.

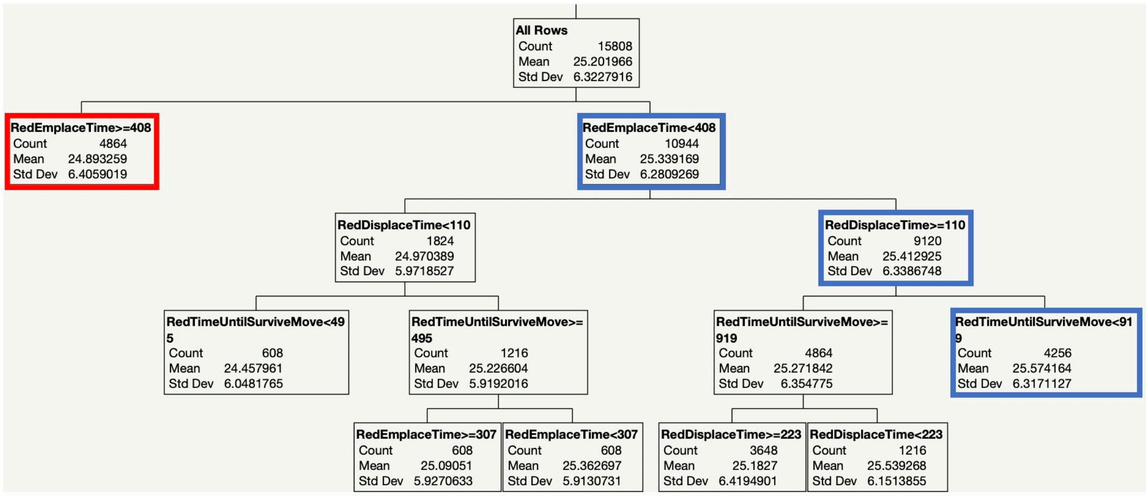


Figure 54. Blue Lethality Partition Tree: Red Factors Only

d. Blue Lethality Linear Regression

The last metamodel with Red factors is a least squares linear regression with Red casualties as the response. Again, due to the Blue factors' domination in terms of their influence on the response, this model explains very little of the variance (less than 1%). Figure 55 provides the estimated coefficients, and interestingly, the only statistically significant Red factor is emplacement time. Red's emplacement time has a very slight negative correlation with Red casualties. If they take longer to emplace, they are more survivable. This is presumably for the same reason that Blue's emplacement time has a similar effect on Blue casualties.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
RedEmplaceTime	-0.001309	0.000314	-4.16	<.0001*
RedArmorThickness	-0.009102	0.005989	-1.52	0.1286
RedAmmoLoadout[8x370mm]	0.0602272	0.050266	1.20	0.2309
RedTimeUntilSurviveMove	-0.000121	0.000152	-0.80	0.4232
RedManeuverSpd	-0.005541	0.008902	-0.62	0.5337
RedDisplaceTime	9.5416e-5	0.000319	0.30	0.7647

Figure 55. Blue Lethality Linear Regression Coefficient Estimates: Red Factors Only

6. Experiment Four Insights

Experiment four supports many of the findings from previous experiments. For example, distributed employment is the most robust method for Blue lethality and survivability. The M30 (6xDPICM) munition is still the most lethal and thus the best choice despite its slight positive impact on variability. Displacement time remains a critical factor with faster times increasing Blue's lethality and survivability. Time in position remains a relatively unimpactful factor when compared to others. However, it is more apparent in this experiment, that more time in between survivability moves slightly increased Blue's lethality and survivability.

There are also some new findings uncovered in experiment four. For example, applying defensive fires emerges as an influential factor for increasing Blue survivability. This is absent from analysis of previous experiments and contradicts defensive fires' impact on lethality which presents a tradeoff. Upon closer examination, avoiding employment of defensive fires is more beneficial towards lethality than it is detrimental to survivability.

Emplacement time presents a tradeoff that is observed in experiment three as well. Fast emplacement time increases time that the unit is FIRECAP and as a result, increases their ability to inflict casualties on the enemy. However, it also increases their overall time in a targetable state which proportionately raises their own casualties as well. In studying this tradeoff more closely, experiment four's analysis shows that fast emplacement time has a greater positive effect on lethality than its negative effect on survivability. The conclusions from these two tradeoffs, no defensive fires and fast emplacement, match the configuration found to minimize Red and Blue casualty loss as given in the quadratic loss function analysis.

The last primary insight from the Red factor analysis in experiment four is that Blue factors drive the response, and Red factors are relatively uninfluential. This may be due to the fact that Blue is allocated two UAS for target acquisition as opposed to Red's one. However, this analysis does suggest that a slower, less nimble Red force will be limited in their lethality against Blue.

VI. CONCLUSIONS AND RECOMMENDATIONS

The following chapter summarizes the insight gained from the analysis in Chapter V and translates these findings into recommendations for the Marine Corps to consider implementing in the rocket artillery force. This research can be both extended and improved. Thus, it presents various opportunities for future work which are also examined and included in this chapter.

A. SUMMARY OF FINDINGS

1. Experiment One

The purpose of experiment one is to establish a base line for the variability in the model and ensure that the model is behaving as designed. As no inputs other than random number seed are varied, the only real finding from this experiment is that there is significant variability in the MOEs based on aspects of combat which are modeled stochastically by MANA.

2. Experiment Two

Experiment two varies Blue employment method to study its impact on lethality and survivability. The results are clear that more distributed Blue units not only limit their own casualties but are able to inflict more upon the enemy. The greatest one-step improvement in survivability occurs when shifting from fully consolidated employment to a split battery construct. For lethality, the greatest one-step improvement varies depending on the type of Red agents being targeted. For Red maneuver agents, that greatest improvement occurs when moving from split battery to sections, and for Red firing agents, it is when moving from consolidated to split battery.

3. Experiment Three

Experiment three varies all Blue factors to determine which emerge as critical to lethality and survivability. The findings from experiment two are supported. Employment method is the single most influential factor for survivability, and also greatly impacts lethality. Fast displacement is crucial for increasing Blue's survivability and lethality.

Further, when fast displacement is combined with fully distributed employment, the variability of Blue casualties is greatly diminished, providing the commander with some certainty regarding worst case scenarios. Ammunition is the dominant factor for lethality, but provides little impact to survivability. Specifically, the most lethal configuration is launchers loaded with 6xDPICM rockets, as opposed to higher-caliber single rockets or unitary warheads.

Fast emplacement leads to more time in a targetable state for Blue, and thus results in a proportional increase in Blue casualties. However, it also leads to more time in a FIRECAP state, which allows Blue to impose more casualties on Red. Employment of defensive fires serves to limit Blue's ability to attrite Red, and increases Blue's own attrition. Lastly, time between survivability moves is overall the least impactful factor, failing to have substantial influence over lethality or survivability. This experiment's analysis also uncovered some minor interactions between emplacement time and displacement time with defensive fires. When these times are higher, defensive fires becomes less impactful on survivability or lethality due to the diminished relative impact of its delay.

4. Experiment Four

In experiment four, both sides' factors are varied with Blue's treated as controllable and Red's treated as uncontrollable. This allowed for an analysis of factors critical to Blue's lethality and survivability despite uncertainty surrounding Red's specific tactics and capabilities.

The first analytical method used in this experiment is a loss function analysis. Through examination of the Pareto Front of design points which minimize Red and Blue casualty losses, the optimal Blue configuration for lethality and survivability is obtained. This configuration is summarized by the following Blue factor levels: fully distributed employment, M30 (6xDPICM) ammunition, maximally fast emplacement and displacement times, no defensive fires, and maximum time in between survivability moves.

Further metamodel analysis examined these factors' impacts on variability as well as the means of MOEs. Employment method, ammunition, emplacement time, and displacement time effects are largely consistent with their effects on the means from experiment three. The M30 ammunition resulted in slightly more variability in the Red casualty response, but its increase in lethality outweighs this disadvantage.

Defensive fires demonstrated a different effect on survivability than what is found in experiment three. In the robust experiment, employment of defensive fires increased Blue survivability, which presents a tradeoff for this factor. It is found that defensive fires' positive effect on survivability is much less substantial than its negative impact on lethality. Thus, defensive fires should not be employed. The other tradeoff relates to emplacement time, and similarly, its impact on lethality is discovered to be more dominant, which suggests that fast emplacement is more advantageous to the Blue force. Time in position's effect emerges as slightly stronger in experiment four than it is in experiment three. Specifically, longer time between survivability moves increases lethality and survivability.

B. RECOMMENDATIONS

This study provides support for several key recommendations which should be considered for implementation or future studies. The first recommendation is in support of more distributed employment methods. Typically, USMC artillery batteries operate either consolidated or in a split battery construct. It is the author's recommendation that the highest level of aggregation for a rocket artillery battery should be split battery. Operating as a consolidated battery in a contested environment presents an unacceptable level of risk to the force and mission. This recommendation would be relatively simple to implement by commander guidance and focused training, however, it does present some challenges, specifically with regard to C2 and logistics. These challenges are summarized later in this chapter.

The second primary recommendation is to increase the intentional training on emplacement and displacement drills for Marine rocket artillery crews. While the weapon system itself presents a limit for the possible speed of emplacement and displacement, crews should seek to maximize the capabilities of the platform. Rocket artillery diverges from cannon artillery in the manpower required to operate the weapon system during fire missions. The automation of the launcher allows for less training concerning conduct of fire missions in favor of more training in rapid emplacement and displacement. Again, implementation of this recommendation is simply reliant on commander priorities and guidance.

Following the theme of rapid emplacement and displacement, the author recommends that defensive fires are not executed when a rocket battery is fired upon. The priority should be immediate displacement rather than counterbattery actions. This research found that while defensive fires slightly increased a unit's survivability, its decrement to lethality is overwhelming and thus, should be avoided.

The next recommendation is regarding employment of M30 (DPICM) rockets and is less readily actionable. The results of this study show that the M30 is far superior to its corresponding unitary warhead munition in terms of inflicting casualties on the enemy. However, as M30 carries hundreds of bomblets which are scattered over a wide area, it requires significant consideration of dud rates and civilian impacts before it is employed.

The last recommendation from this research is for commanders to consider their priorities when task-organizing and preparing for a particular mission. This research demonstrates tradeoffs between factors with regard to their effect on survivability and lethality. There may be situations when a commander expects to operate inside an enemy's weapons engagement zone for an extended period of time. This would likely influence the commander into prioritizing survivability. Conversely, there may be other operations where the enemy and friendly situation dictate that lethality takes precedence. In these cases, it is recommended that commanders carefully consider how they employ their forces in order to maximize their chances of successfully accomplishing their given mission. The following force configurations are recommended by the author to prioritize survivability and lethality, respectively.

1. Survivability

A commander concerned with maximizing his unit's survivability, possibly at the expense of its lethality, should consider the following recommended tactics:

- Distributed employment

- Little emphasis on fast emplacement
- Maximum emphasis on fast displacement
- Defensive fires employed
- More time between survivability moves

2. Lethality

A commander who seeks to prioritize his unit's lethality, possibly at the expense of their own survivability, should consider employing the following construct:

- Use of M30 [6xDPICM] ammunition
- Split battery employment
- Maximum emphasis on fast emplacement
- Maximum emphasis on fast displacement
- No defensive fires
- More time between survivability moves

C. FUTURE WORK

This research focused narrowly on a specific scenario in which Blue HIMARS engaged Red forces attempting to seize a piece of critical infrastructure. The limited scope is necessary to frame the problem and focus the analysis, but it also presents opportunities for future work. The author offers two broad areas for future research.

1. Inclusion of Command and Control and Logistics

The first area of potential additional research is directly tied to the author's recommendation of distributed employment methods. While this research has shown that increased distribution enhances a unit's survivability and lethality, the impacts to C2 and logistics were not considered. As a battery's distribution progressively increases, C2 and logistics systems would both be strained. This is especially true of HIMARS batteries, where high level fire support deconfliction is necessary, and launchers fire an entire pod of rockets during each mission. This research did not consider control or clearance of fires, and the only logistics consideration is the time spent in resupply state to rearm the launchers.

There may be a level of distributed employment at which the increased burden on C2 or logistics may result in overall reduced effectiveness for the unit. It would be useful to know whether this change point exists and if so, at what level. Further research may also uncover other interactions between C2, logistics, and the factors in this study. A deeper understanding of how these two critical warfighting functions influence HIMARS employment would be highly valuable.

2. Simulation Scenario Extension

The scenario examined in this simulation is a sub-operation of a much larger overall operation. One area for future research is to add complexity by extending the scenario. There are several ways in which this could be done. One is by including Taiwan forces in the battle and including a more complete order of battle for Blue and Red. This would add more realism to the casualty numbers while also potentially uncovering valuable insights.

The scenario could also be extended by simulating the Red force amphibious landing as well as the ground assault. The Tentative Manual for EABO suggests that future USMC rocket battalions will be a hybrid mix of HIMARS batteries and NMESIS anti-ship missile batteries (USMC 2021). A broader simulation such as this could then examine factors which influence a battalion's ability to conduct anti-ship and anti-vehicle/personnel fires simultaneously.

The last scenario extension would be to simply include targets at varying ranges. One of the findings in this research is that more numerous, medium-caliber rockets were more effective than fewer, large-caliber rockets. However, due to the geography of this simulation scenario, no targets were considered outside the range of the medium-caliber rockets. The author believes that a simulation which includes a mix of medium and long-range targets would likely produce different findings with regard to ammunition lethality.

D. CONCLUSION

The goal of this thesis is to determine the critical factors for maximizing USMC HIMARS lethality and survivability to support the Marine artillery community's substantial pivot towards longer range precision fires. It is the author's hope that some of the findings from this research prompt discussion, lead to future research, and provide commanders with training priorities that will prepare their units for potential future conflict.

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APPENDIX. BLUE AND RED FORCES MODELED

A. BLUE FORCES

Blue is modeled as a HIMARS battalion supported by UAS and counterbattery radar assets. Specifically, the force is composed of M142 HIMARS launchers, RQ-21 Blackjack UAS, and AN/TPS-80 G/ATOR systems.

The M142 launcher can be loaded with six 227 mm GMLRS munitions with a range out to 84 kilometers, or one 610 mm ATACMS munition with a range out to 270 kilometers (USMC 2008, p. 5-4). According to Janes, the chassis is a version of the six-wheeled Army Family of Medium Tactical Vehicles (Janes 2021d). Janes also describes that while armor kits can be added, the base level of armor for the crew in the cab of the vehicle only provides protection from the rocket blast and foreign object debris. The standard practice for HIMARS launchers is to completely empty their pod of munitions on a single fire mission; this takes less than 60 seconds for the crew to complete. The fire control and communication systems necessary for conduct of fire missions are all organic to the vehicle. Figure 56 displays a HIMARS launcher operating off the deck of an amphibious ship.

Figure 56. M142 HIMARS Launcher. Source: Fuentes (2017).

The RQ-21 Blackjack is a small tactical UAS which provides continuous target acquisition and reconnaissance for Blue forces. According to Janes, its sensor suite consists of an electro-optic imager, an infrared imager, a laser range-finder, as well as communications equipment (Janes 2021b). Janes also reports that it can provide up to 16 hours of flight time, cruising at 111 km/h, with a range of approximately 92 kilometers. Figure 57 shows a Blackjack being launched.

Figure 57. RQ-21 Blackjack Launch. Source: Janes (2021b).

The AN/TPS-80 Ground/Air Task-Oriented Radar (G/ATOR) system is a multi-role radar used by the Marine Corps. It is used exclusively for counterbattery in this simulation. As mentioned in Chapter III, its 50-kilometer range for detecting medium-caliber rockets is insufficient in this simulation due to the geographic distance between Blue and Red forces. For modeling purposes, it is assumed that Blue and Red are both sourced adequate radar systems to meet their mission requirements.

B. RED FORCES

Red forces are modeled after a PLAN Marine Corps combined arms battalion supported by artillery. The combined arms battalion consists of three maneuver companies mechanized in various IFVs and assault vehicles, all from the Type 05 family. In the model itself, all Red infantry are in ZBD-05 IFVs, which are tracked amphibious vehicles outfitted with a 30 mm cannon, a 7.62 mm machinegun, and anti-tank guided missiles (Janes 2021e). Janes also reports that these vehicles can travel at 60 km/h and have armor that can stop rounds up to 25 mm. Figure 58 exhibits one of these IFVs.

Figure 58. ZBD-05 IFV. Source: Hanson (2020).

The maneuver forces are supported by self-propelled howitzers which also come from the Type 05 family, the PLZ-07B. It is an amphibious vehicle designed to travel with ZBD's in order to provide organic indirect fire support. Its cannon is 122 mm with a range of up to 22 kilometers, capable of firing six to eight rounds per minute (Janes 2021e). The range of these weapon systems limits their ability to conduct counterbattery fire, so they are notionally tasked with providing fires directly in support of the assault.

The maneuver forces are also supported by MLRS, specifically the PHL-16. This rocket system is capable of ranging 70–130 kilometers depending on its ammunition configuration (Janes 2021c). These agents are designated to provide counterbattery fires against Blue in the simulation. Figure 59 provides an image of one of these launchers.

Figure 59. PHL-16 MLRS. Source: Janes (2021c).

Red's UAS platform used for target acquisition is based on the CH-3 medium UAS. Janes reports that it cruises at 180 km/h, with a range of 200 kilometers and approximately 12 hours of endurance (Janes 2021f). It also contains the necessary targeting capabilities in its sensor suite. Figure 60 displays a CH-3 preparing for takeoff.

Figure 60. CH-3 UAS. Source: Janes (2021f).

Red's counterbattery radar platform is based on the BL-904 artillery location radar. This radar system can track up to nine targets in a 90-degree arc (Janes 2021a). Similar to the G/ATOR, its unclassified detection range for medium caliber rockets is insufficient for use in this scenario. To allow for the analysis, it is assumed that joint systems are allocated to meet Red's requirements.

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LIST OF REFERENCES

Associated Press (2021) China's military conducts assault drills in seas near Taiwan. Accessed December 8, 2021, https://www.defensenews.com/training-sim/2021/08/17/chinas-military-conducts-assault-drills-in-seas-near-taiwan/.

Bader JA (2014) The U.S. and China's nine-dash line: Ending the ambiguity. Brookings. Accessed December 2, 2021, https://www.brookings.edu/opinions/the-u-s-and-chinas-nine-dash-line-ending-the-ambiguity/.

Bassett R (2021) Model and variable selection. Class notes, Data Analysis, February 8, 2021, Department of Operations Research, Naval Postgraduate School, Monterey, CA.

Campbell C (2021) China's military: The People's Liberation Army (PLA). Report R46808, Congressional Research Service, Washington, DC. https://sgp.fas.org/crs/row/R46808.pdf.

Cancian MF (2020) The Marine Corps' radical shift toward China. Center for Strategic & International Studies. Accessed December 6, 2021, https://www.csis.org/analysis/marine-corps-radical-shift-toward-china.

Cares JR (2002) The use of agent-based models in military concept development. Proceedings of the 2002 INFORMS Winter Simulation Conference, https://informs-sim.org/wsc02papers/123.pdf.

Cioppa TM, Lucas TW (2007) Efficient nearly orthogonal and space-filling Latin hypercubes. *Technometrics* 49(1), 45–55, https://calhoun.nps.edu/handle/10945/35341.

Cohen RS, Chandler N, Efron S, Frederick B, Han E, Klein K, Morgan FE, Rhoades AL, Shatz HJ, Shokh Y (2020) Peering into the crystal ball: Holistically assessing the Future of Warfare. Research Brief RB-10073-AF, RAND Corporation, Santa Monica, CA. https://www.rand.org/pubs/research_briefs/RB10073.html.

Cordesman AH, Hwang G (2021) Chinese strategy and military forces in 2021: a graphic net assessment, Center for Strategic and International Studies. Accessed December 7, 2021, https://www.csis.org/analysis/updated-report-chinese-strategy-and-military-forces-2021.

Council on Foreign Relations (2021) Global conflict tracker: territorial disputes in the South China Sea, https://www.cfr.org/global-conflict-tracker/conflict/territorial-disputes-south-china-sea.

Department of Defense (2020) Military and security development involving the People's Republic of China: Annual report to Congress. Washington, DC, https://media.defense.gov/2020/Sep/01/2002488689/-1/-1/1/2020-DOD-CHINA-MILITARY-POWER-REPORT-FINAL.PDF.

Department of Defense (2018) Summary of the national defense strategy of the United States of America. Washington, DC, https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf.

Department of State (2018) U.S. relations with Taiwan, https://www.state.gov/u-s-relations-with-taiwan/.

Devore JL (2014) *Probability and Statistics for Engineering and the Sciences*, 9th ed. (Cengage Learning, Boston, MA).

Ellis S (2021) Dueling U.S., China military drills highlight rising Taiwan risk. Bloomberg. Accessed December 8, 2021, https://www.bloomberg.com/news/articles/2021-10-05/dueling-u-s-china-military-drills-highlight-rising-taiwan-risk.

Fuentes G (2017) Marines fire HIMARS from ship in sea control experiment with Navy. United States Naval Institute. Accessed May 8, 2022, https://news.usni.org/2017/10/24/marines-fire-himars-ship-sea-control-experiment-navy.

Garamone J (2021) Official talks DOD policy role in Chinese pacing threat, integrated deterrence. U.S. Department of Defense. Accessed December 6, 2021, https://www.defense.gov/News/News-Stories/Article/Article/2641068/official-talks-dod-policy-role-in-chinese-pacing-threat-integrated-deterrence/.

Gates R (2011) Speech to Cadets. United States Military Academy, West Point, NY, https://www.stripes.com/news/text-of-secretary-of-defense-robert-gates-feb-25-2011-speech-at-west-point-1.136145.

Hanson M (2020) China's Marine Corps is on the rise, *Proceedings* 146(4), https://www.usni.org/magazines/proceedings/2020/april/chinas-marine-corps-rise.

Hurley GJ (2012) JMP Pro bootstrap forest. Paper JM-04, MWSUG 2012 Conference Proceedings, Minneapolis, MN, https://www.mwsug.org/proceedings/2012/JM/MWSUG-2012-JM04.pdf.

Janes (2021a) Fire-Control Radar – BL-904 artillery-location and fire-correction radar. Accessed November 24, 2021, https://customer.janes.com/Janes/Display/JC4I2006-JC4IL.

Janes (2021b) Insitu RQ-21A Blackjack. Accessed November 24, 2021, https://customer.janes.com/Janes/Display/JUAVA726-JUAV.

Janes (2021c) Land warfare platforms: Artillery & air defense- AR1, AR1A, AR2 (300 mm), AR3 (300/370 mm). Accessed November 24, 2021, https://customer.janes.com/Janes/Display/JAA_A106-JAAD.

Janes (2021d) M142 227 mm (6-round) high-mobility artillery rocket system (HIMARS). Accessed November 24, 2021, https://customer.janes.com/Janes/Display/JAA_0662-JAAD.

Janes (2021e) Type 05; ZBD-05, ZTD-05, PLZ-07B. Accessed November 24, 2021, https://customer.janes.com/Janes/Display/JAA_A071-JAFV.

Janes (2021f) Unmanned aerial vehicles – ALIT/CASC CH-3 series. Accessed November 24, 2021, https://customer.janes.com/Janes/Display/JUAVA410-JUAV.

Kadrmas C (2021) Robust analysis of critical factors for cannon artillery lethality and survivability in peer conflict. Master's thesis, Department of Operations Research, Naval Postgraduate School Monterey, CA. https://calhoun.nps.edu/handle/10945/67751.

Kleinjen JPC, Sanchez SM, Lucas TW, Cioppa TM (2005) State-of-the-art-review: A user's guide to the brave new world of designing simulation experiments. *INFORMS Journal on Computing,* 17(3), https://pubsonline-informs-org.libproxy.nps.edu/doi/10.1287/ijoc.1050.0136.

Lucas TW, Sanchez SM, Brown L, Vinyard W (2002) Better designs for high-dimensional explorations of distillations. *Maneuver Warfare Science.* http://faculty.nps.edu/smsanche/docs/betterdesigns.pdf.

Lucas TW (2021a) Map Aware Non-Uniform Automata (MANA) overview. Class notes, Introduction to Joint Combat Modeling, November 2, Department of Operations Research, Naval Postgraduate School, Monterey, CA.

Lucas TW (2021b) Test of hypotheses. Class notes, Statistics, February 16, Department of Operations Research, Naval Postgraduate School, Monterey, CA.

MacCalman AD, Vieira H, Lucas TW (2017) Second order nearly orthogonal Latin hypercubes for exploring stochastic simulations. *Journal of Simulation,* 11(2), 2017, 137–150, https://calhoun.nps.edu/handle/10945/57854.

Maizland L (2021) Why China-Taiwan relations are so tense. Council on Foreign Relations. Accessed December 2, 2021, https://www.cfr.org/backgrounder/china-taiwan-relations-tension-us-policy.

McIntosh GC, Galligan DP, Anderson MA, Lauren MK (2007) *MANA (Map Aware Non-Uniform Automata) Version 4 User Manual* (Operations Analysis Section, Defence Technology Agency, Auckland, New Zealand).

SAS (2021) JMP Pro 15. https://www.jmp.com/en_us/home.html.

Sanchez SM (2018) Data farming: Reaping insights from simulation models. *Chance*, 2(31), 45–52, https://chance.amstat.org/2018/04/data-farming/.

Sanchez SM (2021) Top ten questions to ask during analysis. Class notes, Simulation Analysis, August 24, Department of Operations Research, Naval Postgraduate School, Monterey, CA.

Sanchez SM, Sanchez PJ (2020) Robustness revisited: Simulation optimization viewed through a different lens. Proceedings of the 2020 INFORMS Winter Simulation Conference (Virtual Conference), https://informs-sim.org/wsc20papers/005.pdf.

Sanchez SM, Sanchez PJ, Wan H (2020) Work smarter, not harder: A tutorial on designing and conducting simulation experiments. Proceedings of the 2020 INFORMS Winter Simulation Conference (Virtual Conference), https://informs-sim.org/wsc20papers/135.pdf.

Sullivan I (2021) No option is excluded: Using wargaming to envision a Chinese assault on Taiwan. All Partners Access Network. Accessed November 16, 2021, https://community.apan.org/wg/tradoc-g2/mad-scientist/m/articles-of-interest/380503.

Turk J (2020) Analysis of artillery survivability in distributed operations. Master's thesis, Department of Defense Analysis, Naval Postgraduate School Monterey, CA. https://calhoun.nps.edu/handle/10945/64893.

United States Marine Corps (2008) *Marine Rocket Battery Operations*, MCIP 3–16.02, Quantico, VA.

United States Marine Corps (2018a) *Artillery Operations*, MCTP 3-10E, Quantico, VA, https://www.marines.mil/Portals/1/Publications/MCTP%203-10E%20GN.pdf?ver=2020-02-12-115230-233.

United States Marine Corps (2018b) *Artillery Training and Readiness Manual*. NAVMC 3500.7C, Quantico, VA, https://www.marines.mil/Portals/1/Publications/NAVMC%203500.7C%20Artillery%20T-R%20Manual.pdf?ver=2020-04-21-123905-510.

United States Marine Corps (2019) *Commandant's Planning Guidance*. Quantico, VA, https://www.hqmc.marines.mil/Portals/142/Docs/%2038th%20Commandant%27s%20Planning%20Guidance_2019.pdf?ver=2019-07-16-200152-700.

United States Marine Corps (2020) *CMC38 Force Design 2030 Report Phase I and II* (Force Design 2030), Quantico, VA, https://www.hqmc.marines.mil/Portals/142/Docs/CMC38%20Force%20Design%202030%20Report%20Phase%20I%20and%20II.pdf?ver=2020-03-26-121328-460.

United States Marine Corps (2021) *Tentative Manual for Expeditionary Advanced Base Operations*, Quantico, VA, https://www.mcwl.marines.mil/TMEABO/.

Vieira H, Sanchez S, Kienitz K, Belderrain M (2013) Efficient, nearly orthogonal-and-balanced, mixed designs: An effective way to conduct trade-off analyses via simulation, *Journal of Simulation*, 7:4, 264–275.

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