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# AN OPERATIONAL EFFECTIVENESS ANALYSIS ON SMALL ARMS SHOOTING PRECISION IN CLOSE QUARTERS BATTLE

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Monterey, CA; Naval Postgraduate School

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# THESIS

## AN OPERATIONAL EFFECTIVENESS ANALYSIS ON SMALL ARMS SHOOTING PRECISION IN CLOSE QUARTERS BATTLE

by

Kenny Hong Hao Teo

September 2022

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# AN OPERATIONAL EFFECTIVENESS ANALYSIS ON SMALL ARMS SHOOTING PRECISION IN CLOSE QUARTERS BATTLE

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Submitted in partial fulfillment of the
requirements for the degree of

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| DOE | Design of Experiment |
| DP | Design Point |
| DTA | Defense Technology Agency |
| IPT | Integrated Project Team |
| JSWB | Joint Services Wound Ballistics |
| MANA-V | Map Aware Non-Uniform Automata - Five |
| MOE | Measures of Effectiveness |
| NATO | North Atlantic Treaty Organization |
| NPS | Naval Postgraduate School |
| RCP | Relative Combat Power |
| SEED | Simulation Experiments and Efficient Designs |
| UAV | Unmanned Aerial Vehicle |
| UGV | Unmanned Ground Vehicle |

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# EXECUTIVE SUMMARY

## A. RESEARCH OBJECTIVE

Militaries across the globe are competing to harness artificial intelligence and unmanned capabilities to improve individual operational effectiveness, while reducing risks to combatants. Many studies on this topic have led to improvement in individual operational effectiveness in terms of lethality, mobility, and interoperability; however, few studies have explored improving accuracy through the use of technology.

Using agent-based modeling and simulation, this thesis studies the impact of a rifleman's shooting accuracy on operational effectiveness in close-quarters combat. The goal is to determine how improvements in shooting accuracy may reduce casualties, increase the probability of mission success, and potentially reduce manpower or ammunition (soldier's load) requirements. This thesis also establishes clear expectations and requirements for the design of next generation force structure, individual marksmanship training, requirements of unmanned systems, and artificial intelligence-enabled weapons equipping to aid shooting accuracy improvements for future combat.

## B. MODEL AND SCENARIO

The simulated battlefield is a dense urban terrain with 100 single-level buildings based on a section of Range 200 (185 m × 165 m), at the U.S. Marine Corps Base in Twentynine Palms, California, that was designed to simulate the Jolan District, Al-Fallujah, Iraq.

The hypothetical scenario used in the simulation involves a platoon of insurgents (red force) composed of non-uniform, non-state actors who are defending three key buildings, deploying one insurgent squad in each building. The intent of the red force insurgents is to terrorize the community by performing surprise attacks and fighting to their deaths to inflict maximum casualties. A coalition company (blue force) was deployed to maneuver from east to west in a bid to eliminate all threats (red force) to reinstate peace and stability. As part of the company's attack maneuver, each platoon is tasked to secure a key building (see Figure 1). The intent of the blue force dismounted coalition company is to secure the urban terrain and ensure the safety of the local populace by denying the red force the ability to cause harm.

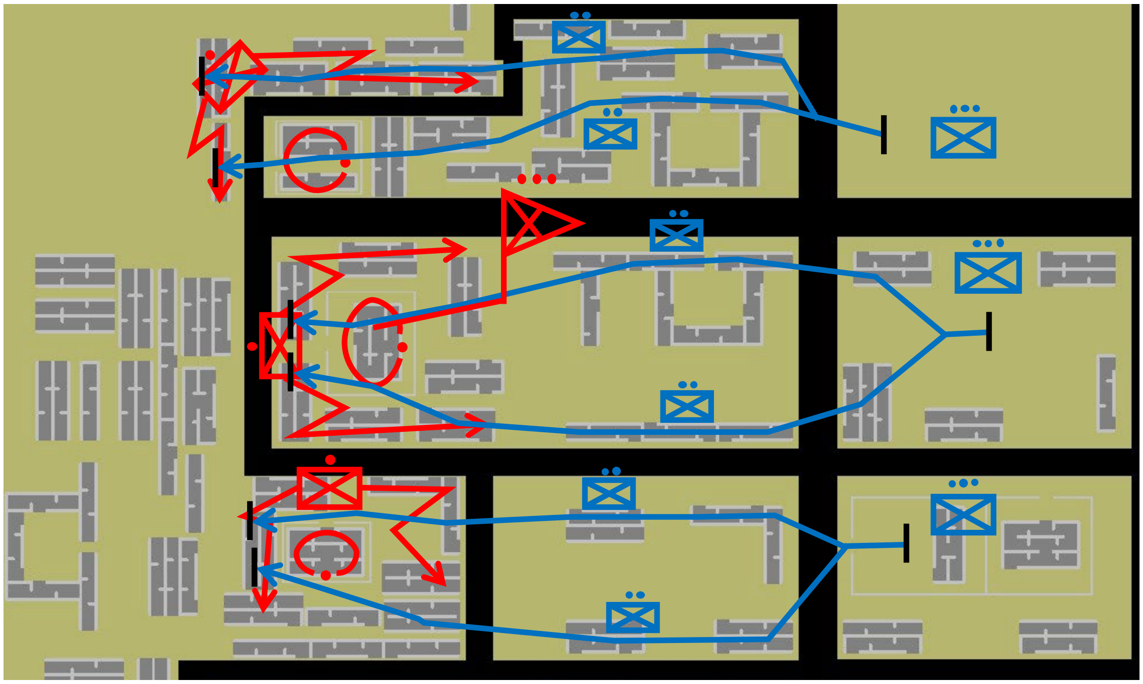


Figure 1. Red Force's Defense Deployment and Blue Force's Attack Maneuver

## C. DESIGN OF EXPERIMENTS

A full factorial design of experiments was used to generate data, the analysis of which supports the research goals. The number of design points can be determined by identifying inputs or factors that may have qualitative or quantitative impact on the outcome and assigning these factors with appropriate values (or levels), which can be nominal, discrete, or continuous over a specified range. Depending on the number of factors, levels, model run time, and computing resources, a full factorial set of experiments, which tests every possible combination of inputs in a brute force manner, the simulation experiments could take a prohibitive amount of time, perhaps many years to complete.

To address the research goals, a sequential analysis campaign was devised involving a base case analysis, followed by three sets of experiments. Each experiment set in the analysis campaign was designed to inform subsequent experiments. This was done to funnel the huge combat possibilities manageably into valuable insights. Insights from previous experimental sets were taken into consideration when designing the next set of experiments to focus the desired scenario and reduce the design space.

Instead of having to conduct expensive physical experiments, simulation provides substantial advantage by being able to conduct multiple runs to provide a better understanding of how inputs to a system or process can affect the outcome at a small fraction of the cost. The base model was created with many simplifications and assumptions to allow exploration of factors that the author posited as significant to the study. After calculations and conservative estimates, the required sample size for each design point was determined to be 1,000 replications in order to detect a militarily significant difference of +/- one blue casualty suffered, as it was deemed to be the most useful measure of effectiveness. Throughout the experiments, the environmental variables and red force variables remained constant. All red agents had a 0.5 P-hit with their primary weapons, and the blue force always had a 3:1 manpower advantage.

Experiment Set 1 explored the current operational context, in which only the blue force's P-hit was varied to determine the impact of the blue force's P-hit, totaling 20,000 simulated battles. Experiment Set 2 was done with the consideration of limited marksmen soldiers in the company. Replicating each design point 1,000 times would therefore require more than five billion simulated battles. However, with reasonable simplifications and incorporating the minimum optimal P-hit from Experiment Set 1, it was possible to effectively examine the design space with 126,000 simulated battles.

To further determine the maximum manpower savings, improvement in blue P-hit was scaled across two other factors (number of teams and number of soldiers per team) in Experiment Set 3. Yet, this would lead to a total of almost 21 billion simulated battles. By reducing manpower options logically based on the blue force organic force structure and implementing the principles concluded from Experiment Set 2, the design space was reduced to 108,000 simulated battles.

## D. RESULTS

After more than 250,000 simulated battles conducted using a model developed with the Map Aware Non-Uniform Automata - Five (MANA-V) software, the output generated was able to provide sufficient data to address the research goals. An improvement in individual shooting accuracy in close-quarters combat has the potential to attain a 50% reduction in manpower requirements and a 50% reduction in blue casualties. While this linear reduction is not ideal, it is not surprising, as there were no efforts made to improve the protection or body armor of the combatants. With the reduced manpower, however, the time taken for the smaller combat force to cover the same area of operations would be tripled. Ammunition requirements would also increase, as the smaller combat force would need to focus fire to cover maneuvering team members.

When considering the requirements of unmanned or artificial intelligence-enabled weapon systems to support future close-quarters combat, it will be essential to include the shooting accuracy of P-hit 0.9 as one of the requirements. Furthermore, additional resources should be put to better use and not be invested in trying to improve the shooting accuracy beyond P-hit 0.9.

# THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made within the time available to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

# I. INTRODUCTION

*"We are only as fast as our slowest team member"*

— Unknown

## A. BACKGROUND AND MOTIVATION

As militaries across the globe are competing to harness artificial intelligence and unmanned capabilities to improve individual operational effectiveness while reducing risks to combatants, several studies have explored this topic. This thesis is a continuation of one such study, the Naval Postgraduate School (NPS) master's thesis, "Effectiveness of the Individual Rifleman in an Infantry Squad," by Martin, Perez, and Peterman (2017). Their research framed individual operational effectiveness performance into four primary evaluation factors to optimize, namely: (1) Lethality, (2) Accuracy, (3) Mobility, and (4) Interoperability.

Although many studies have led to improvement in individual operational effectiveness in terms of lethality, mobility, and interoperability, few studies have explored improving accuracy through the use of technology. This thesis studies the impact of a rifleman's shooting accuracy on operational effectiveness in close-quarters combat. The goal is to determine how improvements in shooting accuracy may reduce casualties, save lives, and potentially reduce manpower or ammunition (soldier's load) requirements. The findings may also lead to clearer expectations and requirements when exploring artificial intelligence-enabled weapons and unmanned systems to aid in shooting accuracy improvements in future warfare.

## B. RESEARCH QUESTIONS

<u>Primary</u>: With an improvement in individual shooting accuracy in close-quarters combat, what are the savings in terms of the individual's own force's casualty rate and manpower requirements to achieve the same mission outcome?

<u>Subsidiary</u>: What are the shooting accuracy requirements of unmanned or artificial intelligence-enabled weapon systems for future close-quarters combat?

## C. BENEFITS OF THE STUDY

This thesis establishes clear expectations and requirements when exploring the design of next generation force structure, individual marksmanship training, and requirements for unmanned systems and artificial intelligence-enabled weapons equipping in aiding shooting accuracy improvements for future combat.

## D. PAST AND CONCURRENT EFFORTS

Militaries across the globe and many past studies have explored the operational effectiveness of the individual soldier in combat. In the next chapter, the literature review summarizes a couple of efforts that are part of a larger collective framework for individual operational effectiveness in urban operations.

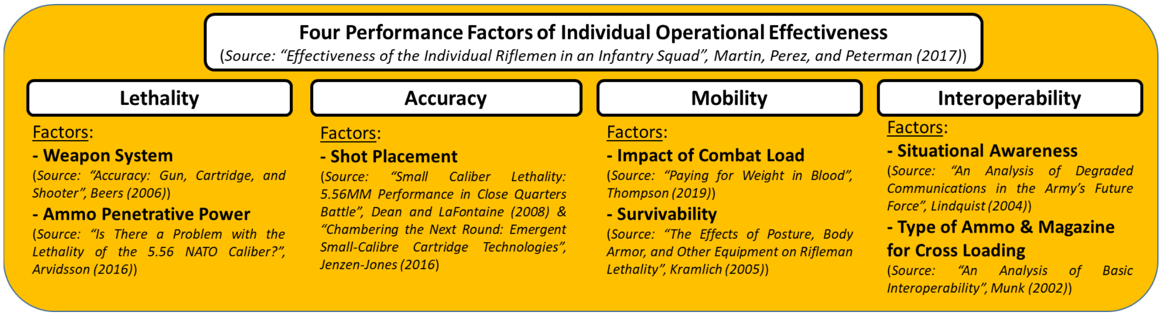
Concurrently, two other NPS theses are studying the enhancement of combat effectiveness by introducing unmanned elements in support of the frontline combatants in urban terrain. Phua (2022) is examining the effectiveness of inter-operability between ground combat forces and supporting Unmanned Ground Vehicles (UGV), while Tang (2022) is investigating how unmanned aerial vehicles (UAV) can support the employment of armored combat units in urban combat. The combination of these three analyses clarifies expected benefits and considerations for future improvements in combined arms combat within the urbanized battlefield.

## E. THESIS ORGANIZATION

Chapter II summarizes past research efforts done on individual operational effectiveness that are leveraged in this thesis. Chapter III presents an overview of Map Aware Non-Uniform Automata – Five (MANA-V), the simulation software used, and the scenario model in this thesis. Chapter IV goes through the Design of Experiments (DOE) and details of the experiments conducted. Chapter V highlights the data collected from data farming and the analysis performed. Chapter VI concludes the thesis and provides recommendations for future work.

# II. LITERATURE REVIEW

This literature review explores the performance factors of an individual's operational effectiveness. In 2017, a team of three U.S. Marine Corps officers studied individual riflemen's operational effectiveness in an infantry squad to establish a framework to support the decision-making process for the acquisition of a new individual combat rifle system. In the framework, the four factors evaluated to improve operational effectiveness of the squad were lethality, accuracy, mobility, and interoperability (Martin et al. 2017). Figure 1 frames this literature review by synthesizing the factors identified with the other supporting sources.



**Four Performance Factors of Individual Operational Effectiveness**
(*Source: "Effectiveness of the Individual Riflemen in an Infantry Squad", Martin, Perez, and Peterman (2017)*)

| **Lethality** | **Accuracy** | **Mobility** | **Interoperability** |
|---|---|---|---|
| Factors: | Factors: | Factors: | Factors: |
| **- Weapon System**<br>(*Source: "Accuracy: Gun, Cartridge, and Shooter", Beers (2006)*)<br>**- Ammo Penetrative Power**<br>(*Source: "Is There a Problem with the Lethality of the 5.56 NATO Caliber?", Arvidsson (2016)*) | **- Shot Placement**<br>(*Source: "Small Caliber Lethality: 5.56MM Performance in Close Quarters Battle", Dean and LaFontaine (2008) & "Chambering the Next Round: Emergent Small-Calibre Cartridge Technologies", Jenzen-Jones (2016)*) | **- Impact of Combat Load**<br>(*Source: "Paying for Weight in Blood", Thompson (2019)*)<br>**- Survivability**<br>(*Source: "The Effects of Posture, Body Armor, and Other Equipment on Rifleman Lethality", Kramlich (2005)*) | **- Situational Awareness**<br>(*Source: "An Analysis of Degraded Communications in the Army's Future Force", Lindquist (2004)*)<br>**- Type of Ammo & Magazine for Cross Loading**<br>(*Source: "An Analysis of Basic Interoperability", Munk (2002)*) |

Figure 1. Framework for Literature Review

## A. LETHALITY

Lethality is the combined ability of the weapon system and ammunition to inflict damage to incapacitate and stop the enemy from performing military tasks. While it is key for weapon systems to have low dispersion as well as sufficient effective range for engagement, heavy recoil might also hinder shooting performance, especially for long-distance and multi-shot engagements. The *Small Arms Defence Journal* (Arvidsson 2012) highlights the two ways to incapacitate an enemy: (1) by a shot to the central nervous system or (2) by causing loss of blood pressure through massive bleeding. Arvidsson also studied the penetrative power of the 5.56mm North Atlantic Treaty Organization (NATO) caliber and its supporting NATO weapon systems. He concluded that "NATO nations are confident with the lethality of their 5.56mm and 7.62mm rounds in terms of performance and penetrative power." Hence, it became clear that the lethality of weapon systems and ammunition are unlikely the main factor hindering the improvement of individuals' operational effectiveness.

## B. ACCURACY

Accuracy, in the context of small arms weapons, is the "ability to hit what one is aiming at" in a repeatable fashion (Beers 2006). In 2008, the Joint Services Wound Ballistics Integrated Project Team (JSWB IPT) studied the terminal mechanics of small caliber, high velocity bullets (NATO 5.56 mm) fired by military assault rifles onto frontal exposed targets and found that at close ranges (0-50 meters) with exposed frontal targets, variations between different shots and rounds are negligible. Furthermore, there appear to be no advantages to using a larger caliber round at close range. Another observation is that while projectile design can boost the efficiency of a good shot, a critical hit to a critical region on the enemy's human body is still required. If instant effectiveness or incapacitation is expected, then there is only a narrow area where the shot must land on the human body. Hence, the JSWB IPT concluded that shot placement trumps all other variables (Dean and LaFontaine 2008). Similarly, "a NATO Workshop on Small Arms Lethality hosted by United Kingdom in February 2009 also concluded that shot placement is the most important parameter" (Arvidsson 2012). Although Subject-Matter Experts (SME) have placed much emphasis on accuracy and shot placement, there are limitations to what we can do to account for design flaws or incompetence.

## C. MOBILITY

Mobility is defined as soldiers' ability to move freely and easily on the battlefield. With the emphasis on providing the latest technology to improve protection and effectiveness of warfighters, an unintended consequence is the increase in individual combat load (Thompson 2019 and Thompson et al. 2020). To provide protection from enemy gunfire, soldiers don body armor designed to protect their vital organs. Although the benefits of body armor usually outweigh the cost of shouldering its load in combat, body armor inevitably adds to the combat load of a soldier, which would in turn reduce the soldier's combat mobility. Hence, it is clear that there is a need to find a balance between mobility and survivability. With combat loads ranging from 42 to 64 pounds, Peoples et al. (2010) concluded that increased combat load will reduce soldiers' speed, increase task completion time, and quicken the onset of fatigue during repetitive actions. Ultimately, additional combat load negatively impacts the combat mobility of combatants.

According to Martin et al.'s 2017 NPS thesis, "Effectiveness of the Individual Riflemen in an Infantry Squad," a U.S. Army study concluded that small weapon accuracy improves as system weight decreases. The riflemen's mobility and effectiveness are hampered by the system's weight, which comprises the weapon and ammunition. In Kramlich's 2005 NPS master's thesis, "The Effects of Posture, Body Armor, and Other Equipment on Rifleman Lethality," a study was done on the effects of body armor and posture on a soldier's marksmanship. Kramlich concluded that soldiers were shooting more accurately while wearing body armor than without when shooting at targets closer than 150 meters. Nonetheless, when soldiers were shooting at targets further than 200 meters, shooting performance declined when the soldiers were wearing body armor. An Australian study similarly concluded that across all shooting distances, on average, there is a 1.5 % performance decrement for every kilogram of combat load added. The lack of mobility, of course, can mean the difference between life and death, which may in turn affect the outcome of a battle (Peoples et al. 2010). Consequently, there has been increased effort in recent years to actively reduce the loads combatants bring to battle (Thompson 2019 and Thompson et al. 2020).

## D. INTEROPERABILITY

On a tactical level, interoperability refers to the ability of squad members to exchange information and equipment. Successful and efficient cooperation for information exchange such as enemy location and captured areas "is founded on continuous harmonization of goals and situational awareness, coordinated planning, and execution" (Munk 2002, 125). On the other hand, interoperability is also the ability for squad members to exchange magazines and ammunition between one another. Hence, standardization of ammunition calibers within an infantry squad provides significant tactical, logistical, and economical advantage via the interoperability of ammunition and magazines (Jenzen-Jones 2016). In addition, various command, control, and communications efforts seek to exploit technology to enhance interoperability of ground troops and maneuver forces.

## E. KEY EMPHASIS AREA

Moving into the information age, researchers have turned to data-driven analytics and combat modeling to improve the accuracy of studies (Meehan 2020). In 2021, the MANA-V agent-based simulation program was used to replicate different force structures of an infantry company based on the Force Design 2030 (United States Marine Corps 2020) proposals and attempts to determine how the changing composition of a Marine infantry company affects the "lethality, survivability and employment of the future force" (Harper 2021).

With considerable emphasis on shot placement, coupled with the lack of external levers to improve shooting accuracy, this thesis analyzes the impact of small arms shooting precision in close-quarters combat through the use of MANA-V.

# III. THE MODEL

*"All models are wrong, but some are useful."*

— George Box 1976

This chapter introduces the simulation engine used, the battlefield scenario simulated, and the assumptions made when designing the thesis model. It also discusses the model development and limitations encountered in the thesis journey.

## A. MODELING ENVIRONMENT (MANA-V)

This thesis used MANA-V, which is "an agent-based, time stepped, stochastic modeling environment" intended for "quick turn," mission-level analysis (Lucas et al. 2015). New Zealand's Defense Technology Agency (DTA) created this version of the agent-based modeling environment to incorporate essential real-world aspects of combat, such as situational adaptation to an evolving battle (McIntosh et al. 2007). An important aspect of MANA is that it is data farmable. That is, it has been developed to allow analysts to run it in parallel using sophisticated DOE that generates data with the appropriate pedigree to use traditional statistical methods.

Instead of having to conduct physical experiments, simulation provides substantial advantages by being able to cost-effectively conduct multiple runs to provide better understanding of how inputs to a system or process can affect the outcome. Given the improvements in technology and experimental methods, simulation has become the preferred method for the analysis of many complex, real-world problems (Lucas et al. 2015).

## B. BATTLEFIELD SITUATION

The battlefield terrain simulated is a dense urban terrain with 100 single level buildings based on a section of Range 200 (185 m x 165 m), at the U.S. Marine Corps Base in Twentynine Palms, CA, that was designed to simulate the Jolan District, Al-Fallujah, Iraq. This terrain map was created first in the MANA-III environment by Babilot (2005) and was converted to the MANA-V format for usage in this thesis with the assistance of Mary McDonald, a Research Associate at the Simulation Experiments and Efficient Designs (SEED) Center for Data Farming (https://harvest.nps.edu) at NPS. Refer to Figure 2 for the battlefield model.

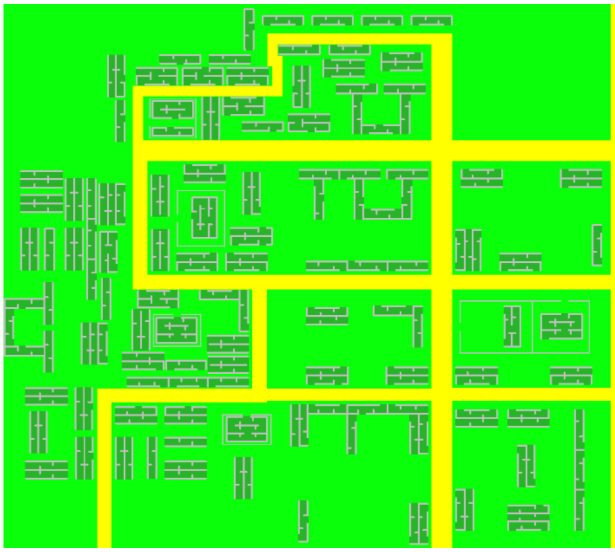


Figure 2. Model Battlefield Terrain of Part of Range 200 (185 m x 165 m)

To enhance the realism of the effects in urban terrain, general characteristics such as movement speed, cover, and concealment are taken into consideration. Cover protects agents from enemy fire. Concealment protects agents from enemy detection and identification. On open areas like roads, the terrain offers no cover nor concealment for agents. The interiors and exteriors of buildings were assumed to have rubble and obstacles, offering up to 15 % cover and concealment to slow the agents' movement speeds. Terrain effects on agents are summarized in Table 1.

Table 1. Terrain Effects on Agents in MANA

| **Terrain Characteristics** | **Movement Speed** | **Cover** | **Concealment** |
|---|---|---|---|
| Road | Fast (4 km/h) | None | None |
| Rubble | Slow (2 km/h) | Some (15%) | Some (15%) |
| Building Walls | NA | 100% | 100% |
| Building Interior | Slow (2 km/h) | Some (15%) | Some (15%) |

A platoon of insurgents (red force) composed of non-uniformed, non-state actors is defending in a central location within the area of operations. Three key buildings are defended by the three insurgent squads, with one static team within each key building and one mobile team patrolling in the vicinity of the respective buildings. Red patrol lines surrounding the respective key buildings depict the route taken and limit of exploration when patrolling. Refer to Figure 3 for the red force platoon's defensive deployment. The intent of the red force insurgents is to terrorize the community while blending in with the local populace. Their primary means of communication is cell phones. They are armed and have the ability to attack and defend anywhere within the urban terrain. Intelligence indicates that they are unlikely to be reinforced. Hence, their likely course of action is to secure and defend their area by performing surprise attacks and fighting to their deaths to inflict maximum casualties.

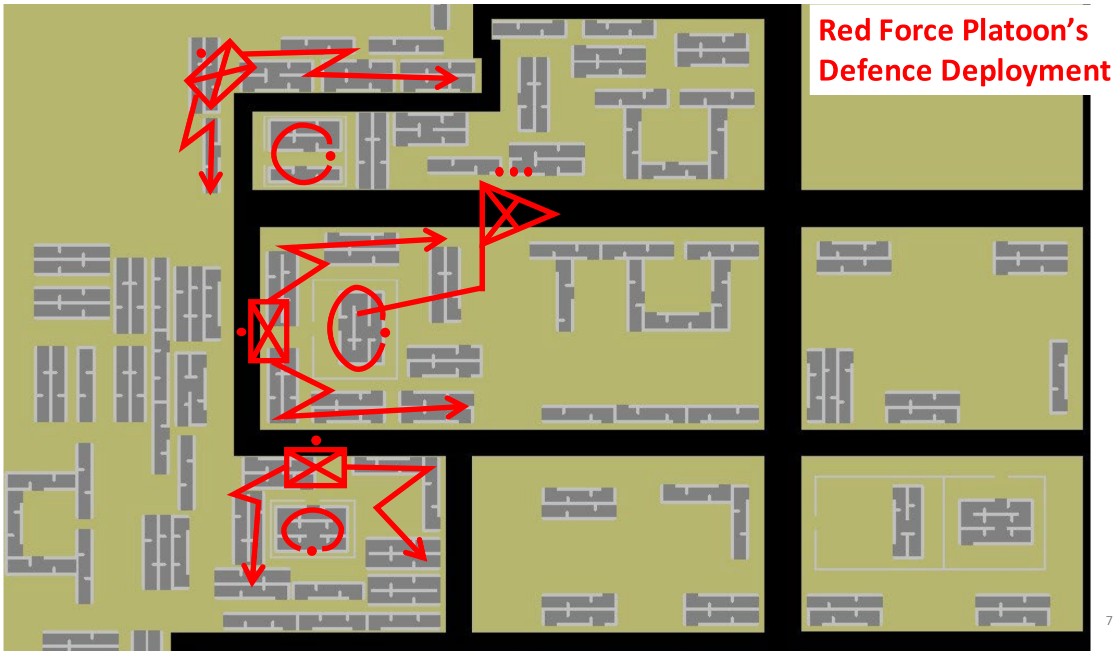


Figure 3. Red Force's Defense Deployment

A coalition company (blue force) is deployed to maneuver from east through west in the area of operations in a bid to eliminate all threat (red force) to reinstate peace and stability. As part of the company's attack maneuver, each platoon is tasked to secure a key building. The blue arrow lines establish the route of advancement for the three platoons maneuvering towards their respective objectives. Refer to Figure 4 for the blue force coalition company's attack maneuver plan. The intent of the blue force dismounted coalition company is to secure the urban terrain and ensure the safety of the local populace by denying the red force the ability to inflict harm.

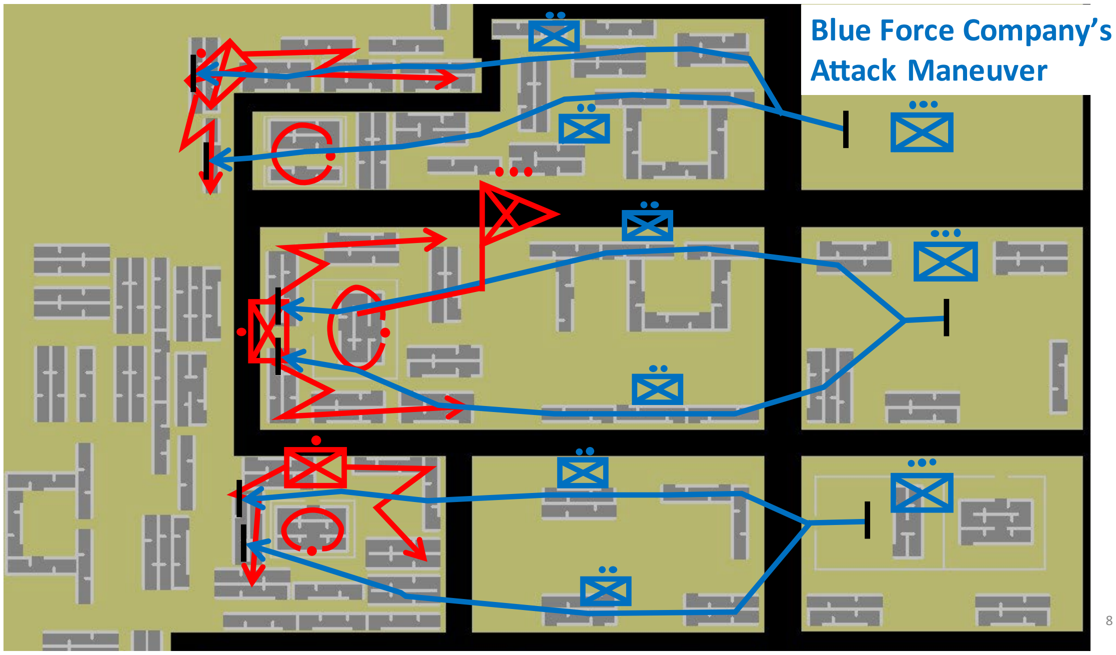


Figure 4. Red Force's Defense Deployment and Blue Force's Attack Maneuver

The simulation's stopping condition and mission completion for each scenario is determined by the elimination of 90% of the agents in either force. Based on a typical dismounted company-level assault on a platoon, a time limit of 50,000 time steps or seconds, which equates to nearly 14 hours was implemented. The time limit was implemented in the event of a standoff where the stop condition of agents' elimination was not triggered. Standoff scenarios are taken into consideration during results analysis where possible.

## C. SCENARIO IN MODELING ENVIRONMENT

### 1. Assumptions Made

Many scenario details were omitted to simplify the model and to allow exploration of factors that the author posited as significant to the study. Within the terrain scenario, visibility remained constant throughout the simulation runs. The effects of windows and multiple level effects were deemed insignificant and were therefore neglected. In terms of agents' characteristics, fatigue was not modeled and the slew rates for agents were fixed at

10 degrees per second. This study did not model operational concepts, resupply, air or ground vehicles, booby-traps and non-kinetic means such as electronic warfare.

### 2. Red Agent Characteristics

In MANA, a squad is a set of agents that have identical initial properties. A MANA squad can consist of any number of agents and should not be confused with a traditional infantry squad. Therefore, the author modeled each red squad as a four-man insurgent team. Two MANA squads form an insurgent section (see Figure 5). Each section is tasked with defending a key building in its sector. Within each section, a team of insurgents remains static defending its respective key building in its area of operations while another insurgent team patrols in the vicinity.

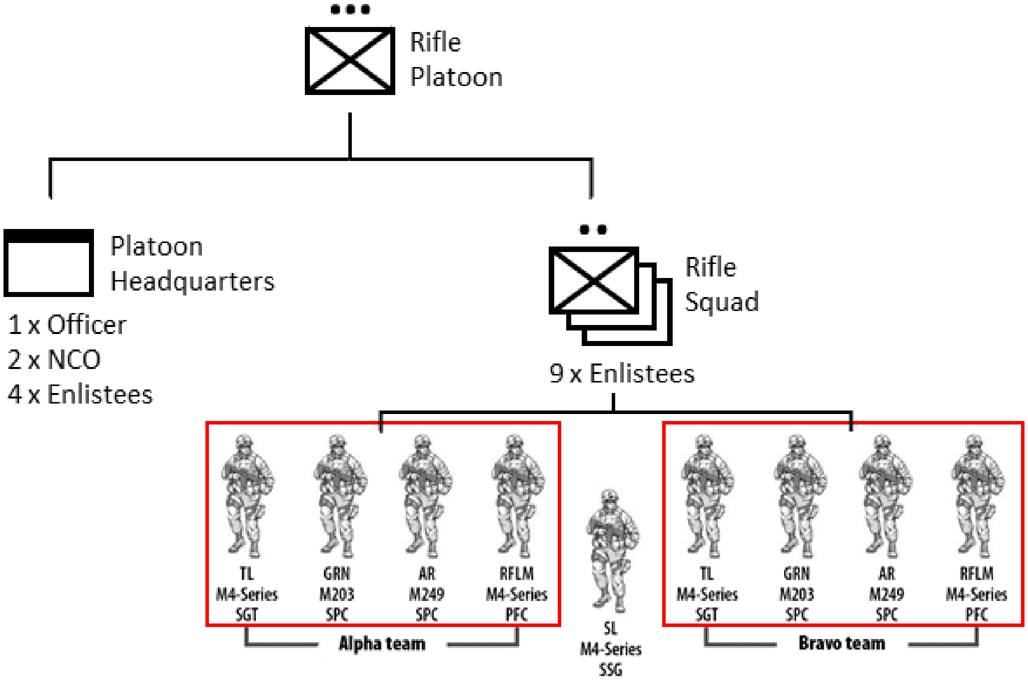


Figure 5. Red Force Platoon's Organization Chart. Adapted from HQ Department of the Army (2016).

Due to the modeling limitation explained in Section D later in this chapter, an insurgent platoon was modeled without its command elements. The command elements' tactical decision making was circumvented by the implementation of patrol waypoints to cover the key buildings. Each MANA squad consisted of a four-man insurgent rifle team. Hence, a total of six MANA squads with four agents each were modelled to represent three insurgent rifle squads as part of an insurgent rifle platoon. Figure 5 shows the red force platoon's organization chart.

### 3. Blue Agent Characteristics

Each blue MANA squad is modeled as a four-man infantry rifle team, with two MANA squads forming an army infantry section. This configuration is used to control the maneuver of the organic infantry rifle teams, and situational awareness is also shared instantaneously within the MANA squad. If every individual agent was modeled as its own MANA squad, it would not be possible to ensure the formation of assault at the team or squad level. This model configuration lacks the ability to control individual shooting P-hit, which can only be modified at MANA squad-level. Similar to the red force, the blue force coalition company is also modelled without its command elements. This limitation was circumvented by the implementation of maneuver waypoints for the assault in accordance with the maneuver plan shown in Figure 4. A total of 18 MANA squads with four agents each were modeled to represent nine rifle squads as part of the three rifle platoons within the blue force coalition company. Refer to Figure 6 for the blue force coalition company's organization chart.

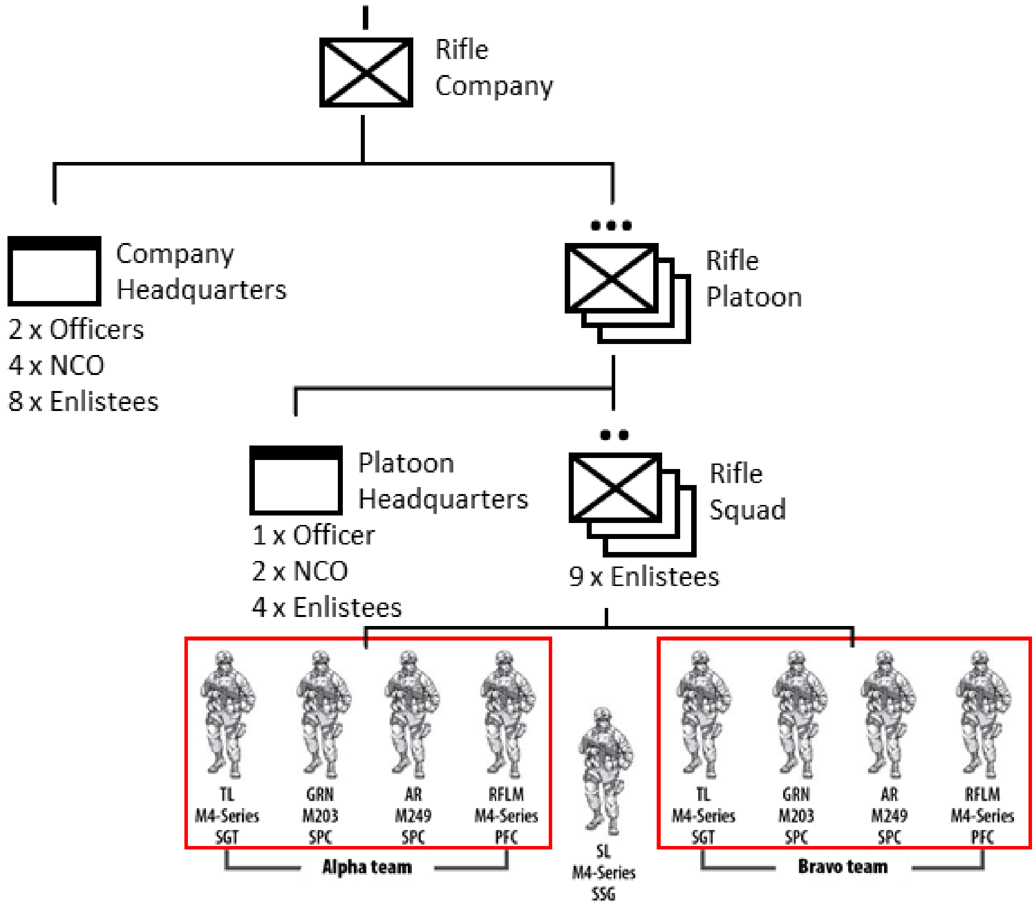


Figure 6. Blue Force Company's Organization Chart. Adapted from HQ Department of the Army (2016).

In a typical scenario of urban terrain assault, internal reserve forces were also allocated as part of the blue force assault maneuver plan. The assigned reserve forces were artificially made to delay their assault by 300 seconds at their starting location while following the waypoints of the main assault force. This artificial delay was employed to mimic realistic deployment of reserve forces on the ground where the reserve forces are following closely behind the main assault to ensure timely reinforcement when the situation arises. Company and platoon-level anti-tank weapons were also not modeled in this scenario as the key characteristic of interest is the individual force-on-force combat. The rest of the details in a typical operations order are omitted for simplicity.

## D. LIMITATIONS

As with any simulation environment, MANA has limitations. In this section, we highlight some of the more important ones relevant to this thesis.

Command elements within the simulation model. MANA is unable to explicitly model command elements for tactical decision making and control to change maneuver, etc. In a typical assault plan, the main assault force would assault up to a certain boundary before allowing the reserve force passage through to assault the next bound. However, the timing and sequence of this maneuver is dynamic and often left to the commander on the ground to decide and control the tactical fight. As MANA is unable to explicitly model the command element to make tactical decisions, this leap and bound maneuver was omitted from the model. This omission inevitably removes the ground tactical commanders' dynamic decision making during the assault phase.

Modeling squad weapons. Squad weapons such as grenade launchers are usually held only by one member of the team. Due to the design of MANA squads, however, grenade launchers modelled as a secondary weapon can be accessed by every member of the squad. This model configuration would suggest that every member in the MANA squad can fire the grenade launcher as his or her secondary weapon. In order to mitigate this limitation, there was a need to divide the firing rate and total number of grenades by the total number of agents within the MANA squad. This mitigation would provide a realistic count of the number of grenades launched although there is still a possibility of all agents firing the grenade launcher at the same time.

Through the process of building the desired model in the MANA-V environment, a new bug was found. When the formation parameter of the MANA-V squads was activated within a scenario file, certain runs produced an invalid floating point operation error before ceasing the entire simulation run. This was discovered to be caused by an unintentional divide by zero operation under certain conditions. The most straightforward solution was to simply set the formation perimeter to zero for all squads in MANA-V; this was not deemed to have an adverse effect on scenario development. The NPS SEED Center research team informed the MANA developers of this issue and resolution.

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# IV. DESIGN OF EXPERIMENTS

This chapter highlights the full factorial DOE methodology used to generate data from which analysis would address the research questions. The number of design points is the number of distinct input combinations that are tested. The first step is to identify inputs, called factors, that may affect the outcome. The factors may be nominal, discrete, or continuous over a specified range. The individual values (called levels) each factor can take is determined by the factor type and the type of design used. Depending on the number of factors, levels, model run time, and computing resources, a full factorial set of experiments, which tests every possible combination of inputs in a brute force manner, could take a prohibitive amount of time, perhaps many years to complete.

To address the research questions, a sequential analysis approach was devised involving a base case analysis followed by three sets of experiments. Each experiment set in the analysis campaign was designed to inform the subsequent experiment. This was done to scope the analysis and funnel the huge possibilities in combat into valuable insights. Insights from the previous experimental sets were taken into consideration when designing the subsequent set of experiments in order to sharpen the desired scenario and reduce the design space.

## A. BASE MODEL ANALYSIS

In the base model scenario, all red and blue agents have a 0.5 P-hit with their primary weapons, and the blue force has a 3:1 Relative Combat Power (RCP) advantage over the red force. The base model scenario was replicated 1,000 times to develop a better understanding of the random variability associated with the thesis scenario. The three primary Measures of Effectiveness (MOE) studied in this experiment are (1) the amount of time for the model to reach terminating conditions, (2) total casualties suffered by the blue force at the end of the simulation, and (3) the total ammunition expended by the blue force.

These results act as a reference for the interpretation of results for the subsequent experiments. These results were also used to determine the expected scenario run times and the variance of the MOEs. The variance of MOEs was used in power calculations to determine the sample size required to identify statistically significant differences. Two methods were used to determine the number of replications to run per design point, one based on the desired confidence level precision and one based on the requirement of hypothesis testing:

Method 1: Calculate the required sample size based on the desired level of precision and 99% confidence level.

$$n = \left( \frac{2Z_{\alpha/2}\sigma}{E} \right)^2 \tag{1}$$

In Equation (1), *n* is the number of replications per design point to be determined. *E* defines the precision and is the margin of error set to be +/- one blue casualty. The z score is based on the desired 99% confidence level. Sigma (σ) is the estimated standard deviation for the total casualties suffered by blue force. This leads to the result of the sample size (*n*) required.

Method 2: Calculate the required sample size for hypothesis testing to achieve the desired resolution of one casualty suffered with a type I error rate of $\alpha$ and a type II error rate (for one casualty) of $\beta$. The type I error rate $\alpha$ is the probability we reject the hypothesis that $\mu_0 = \mu'$ when it is in fact true. The type II error rate $\beta$ is the probability we fail to reject the hypothesis that $\mu_0 = \mu'$ when in fact we should have.

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

As before, *n* is the number of required replications per design point. Sigma (σ) is the estimated standard deviation for the total casualties suffered by the blue force. The militarily significant difference, $\mu_0 - \mu'$, was set to be +/- one blue casualty suffered. The error rates $\alpha$ and $\beta$ were set at 0.01. Therefore, both the level of power and confidence were 99%.

Both calculations were done explicitly on blue casualties suffered, with the desired resolution of up to one casualty, as it was deemed to be the most useful MOE selected. Both equations recommended that just under 1,000 replications were required; thus, to be conservative, 1,000 replications per design point were used.

## B. EXPERIMENT SET 1 – IMPACT OF BLUE P-HIT

With the intention to determine the impact of the blue force's P-hit on the MOEs, Experiment Set 1 was used to explore the current operational context where all red agents have a 0.5 P-hit with their primary weapons and the blue force have a 3:1 RCP advantage over the red force. While keeping the environment and the red force's variables constant, the blue force's P-hit was varied between 0.05 to 1 in steps of 0.05, forming 20 equally-spaced design points (DP). Each DP was replicated 1,000 times, totaling 20,000 simulated battles. The DPs are depicted in Table 2.

Table 2. Summary of Design Points for Experiment Set 1

| Design Points | Blue P-Hit | Red P-Hit |
|---|---|---|
| 1 | 0.05 | 0.5 |
| 2 | 0.1 | |
| 3 | 0.15 | |
| 4 | 0.2 | |
| 5 | 0.25 | |
| 6 | 0.3 | |
| 7 | 0.35 | |
| 8 | 0.4 | |
| 9 | 0.45 | |
| 10 | 0.5 | |

| Design Points | Blue P-Hit | Red P-Hit |
|---|---|---|
| 11 | 0.55 | |
| 12 | 0.6 | |
| 13 | 0.65 | |
| 14 | 0.7 | |
| 15 | 0.75 | |
| 16 | 0.8 | |
| 17 | 0.85 | |
| 18 | 0.9 | |
| 19 | 0.95 | |
| 20 | 1 | |
| Design points = 20 | | |
| Simulated battles per design point = 1,000 | | |
| **Total: 20 × 1000 = 20,000 simulated battles** | | |

The four primary MOEs studied in this experiment were (1) the amount of time for the model to reach terminating conditions, (2) total casualties suffered by the blue force at the end of the simulation, (3) total casualties suffered by the red force at the end of the simulation, and (4) the total ammunition expended by the blue force. The results from Experiment Set 1 provide the operational context for subsequent experiments.

## C. EXPERIMENT SET 2 – BLUE P-HIT VS. SCALE OF IMPLEMENTATION IN BLUE FORCE

Experiment Set 2 considered the limited number of marksmen in a company of soldiers. Experiment Set 2 studied the impact of the number of marksmen and their P-hit in the blue force. By keeping the environmental variables and red force variables constant, it is possible isolate the effect of the number of blue marksmen and P-hit on the MOEs.

Kramlich (2005) measured the performance of the average U.S. Army infantry rifleman when shooting in a standing posture at a range of 15 meters. He found the average

P-hit to be 0.61 against various targets in a non-combat scenario. Building on Kramlich's results, the standing posture and range of 15 meters were credible proxies for a typical fire fight within an urban terrain. Hence, with the intent of mimicking combat stress, the baseline P-hit of the blue force was halved to 0.3. The defending red force, in a static prepared position, was assumed to have a P-hit of 0.5.

Given the consideration of a limited number of marksmen in the company, with one marksmen squad available to be chosen to be deployed in any of the 18 squads, 18 design points would be needed. With two marksmen squads available to be chosen to be deployed in any of the 18 squads, 18 choose two, denoted as 18C2 in Table 3, or 153 DPs would be needed. By continuing these calculations up to the case of 18 available marksmen squads, it can be seen in Table 3 that a total of 262,143 DPs would be needed if explicitly testing every possible deployment.

To observe the impact and effectiveness of P-hit in detail, improvements in P-hit were scaled across different size forces within the blue force. However, with the 20 DPs for blue P-hit from Experiment Set 1 and a total combination of 262,143 DPs for the 18 blue teams, this would lead to a total of 20 × 262,143 = 5,242,860 DPs. Replicating each DP 1,000 times would therefore require more than five billion simulated battles.

Table 3. Combination Calculation for Full Factorial Implementation in Experiment Set 2

| No. of Squads | Combinations | No. of Design Points |
|---|---|---|
| 1 | 18C1 | 18 |
| 2 | 18C2 | 153 |
| 3 | 18C3 | 816 |
| 4 | 18C4 | 3060 |
| 5 | 18C5 | 8568 |
| 6 | 18C6 | 18564 |
| 7 | 18C7 | 31824 |
| 8 | 18C8 | 43758 |
| 9 | 18C9 | 48620 |
| 10 | 18C10 | 43758 |
| 11 | 18C11 | 31824 |
| 12 | 18C12 | 18564 |

| No. of Squads | Combinations | No. of Design Points |
|---|---|---|
| 13 | 18C13 | 8568 |
| 14 | 18C14 | 3060 |
| 15 | 18C15 | 816 |
| 16 | 18C16 | 153 |
| 17 | 18C17 | 18 |
| 18 | 18C18 | 1 |
|  | **Total DPs:** | **262143** |

With reasonable simplifications, however, it was possible to reduce the 262,143 combinations to just nine carefully chosen combinations. This was done by the logical assignment of marksmen (soldiers with higher P-hit) as the key consideration in forming teams for their primary task. The order of decreasing priority that was determined follows: first priority to the main assault force, then to the flank assault force, and then to the reserve force, as shown in Table 4.

Table 4. Blue Squad's Primary Task to Squad Number (in MANA-V) Reference

<table>
<tr><th></th><th>Type of Squad</th><th colspan="2">Blue Main Assault Force (Priority 1)</th><th colspan="2">Blue Flank Assault Force (Priority 2)</th><th colspan="2">Blue Reserve Force (Priority 3)</th></tr>
<tr><td rowspan="2"><b>Platoon 1</b></td><td>Actual Squad</td><td colspan="2">Squad 1</td><td colspan="2">Squad 2</td><td colspan="2">Squad 3</td></tr>
<tr><td>MANA-V Squad</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td></tr>
<tr><td rowspan="2"><b>Platoon 2</b></td><td>Actual Squad</td><td colspan="2">Squad 1</td><td colspan="2">Squad 2</td><td colspan="2">Squad 3</td></tr>
<tr><td>MANA-V Squad</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td></tr>
<tr><td rowspan="2"><b>Platoon 3</b></td><td>Actual Squad</td><td colspan="2">Squad 1</td><td colspan="2">Squad 2</td><td colspan="2">Squad 3</td></tr>
<tr><td>MANA-V Squad</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td></tr>
<tr><td colspan="8">*Note: Every four-agent MANA-V squad represents a four-man team. Two four-man teams form one squad.</td></tr>
</table>

Following the priority scheme, the options for assigning marksman soldiers were determined. In a scenario where there are only sufficient marksmen to form three teams (three MANA-V squads), the priority would be to assign them to one team in each platoon's main assault squad. This constitutes two options. With sufficient marksmen to form six teams, the priority would be to assign all six teams within the main assault squad in each platoon. By extrapolating this principle, nine levels of implementation were determined, as shown in Table 5.

With the blue force baseline P-hit starting from 0.35 onwards, the number of blue P-hit DPs was reduced from 20 to 14. Coupled with this logical marksman prioritization allocation methodology, the DPs executed in this experiment set were reduced from 5,242,860 to just 126, as shown in Table 6. Each DP was replicated 1,000 times, resulting in 126,000 simulated battles (instead of five billion).

Table 5. Summary of Design Points for Blue Force's P-hit Scale of Implementation

| **Total no. of Marksmen Squads** | **Variants (Marksmen Squads #)** | **Reference to Blue Force's Squad Primary Task** | **Total # of Levels** |
|---|---|---|---|
| 3 | 7, 13, 19 | 50% Blue Main | 2 |
| | 8, 14, 20 | | |
| 6 | 7, 13, 19,<br>8, 14, 20 | 100% Blue Main | 1 |
| 9 | 9, 15, 21 | 100% Blue Main + 50% Blue Flank | 2 |
| | 10, 16, 22 | | |
| 12 | 9, 15, 21,<br>10, 16, 22 | 100 Blue Main + 100% Blue Flank | 1 |

| **Total no. of Marksmen Squads** | **Variants (Marksmen Squads #)** | **Reference to Blue Force's Squad Primary Task** | **Total # of Levels** |
|---|---|---|---|
| 15 | 11, 17, 23 | 100 Blue Main + 100% Blue Flank + 50% Blue Res | 2 |
| | 12, 18, 24 | | |
| 18 | 11, 17, 23,<br>12, 18, 24 | 100 Blue Main + 100% Blue Flank + 100% Blue Res | 1 |

Table 6. Summary of Design Points for Experiment Set 2

| **Factor** | **Min** | **Max** | **Increment** | **Type** |
|---|---|---|---|---|
| **Red P-Hit** | Constant at 0.5 P-Hit | | | |
| **Blue P-Hit** | 0.35 | 1 | 0.05 | Discrete |
| **Scale of Implementation** | 1 | 9 | 1 | Categorical |
| Design points: 14 × 9 = 126<br>Simulated battles per design point = 1,000<br>**Total: 126 × 1,000 = 126,000 simulated battles** | | | | |

The three primary MOEs studied in this experiment were (1) the amount of time for the model to reach terminating conditions – i.e., mission length, (2) the total casualties suffered by the blue force at the end of the simulation, and (3) the total ammunition expended by the blue force. The results and insights from Experiment Set 2 were considered and implemented for Experiment Set 3.

## D. EXPERIMENT SET 3 – BLUE P-HIT VS. BLUE MANPOWER

Experiment Set 3 studies the effect of blue P-hit for the entire blue force and manpower requirements. The author sought to determine a potential reduction in requirements of manpower and ammunition to achieve the same successful mission outcome. By keeping the environmental variables and red force variables constant, it is possible to isolate the effect of the experiment factors on the MOEs.

To determine the maximum manpower reductions that could be realized, improvement in blue P-hit was varied along with two factors representing manpower, number of teams [i.e., MANA-V squads] and number of soldiers [i.e., agents per team]. If a full factorial experiment were to be sought, however, the 20 DPs for blue P-hit from Experiment Set 1, the combinations of 18 blue teams (refer to Table 3 for the combination calculation), and one to four soldiers per blue team, would lead to a total of 20 × 262,143 × 4 = 20,971,440 DPs. Replicating each design point 1,000 times would require almost 21 billion simulated battles.

To scope the problem in a logical manner, manpower options were reduced based on their organic force structure. Three options for the number of teams were used, and for each option, the number of simulated soldiers per team was varied from one to four. The first level for number of teams retains the full 18 teams. The second level removes all six of the teams primarily tasked as the reserve force, leaving 12 teams in play. The third level retains one team tasked as the main assault force and one team tasked as the flank assault force in each platoon. For each of these three options or levels, the number of soldiers is varied between one and four. The summary and details of each scenario can be seen in Table 7. The teams (i.e., MANA-V squads) to be removed and their assigned primary task can be seen in Table 4.

Table 7. Summary of Design Points for Blue Size Force (Manpower)

| Agents | | Reduce Manpower per Squad | | | | No Reserve Squads | | | | Half Squads with No Reserve | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Red** | 4 men per team (24 combatants with 0.5 P-Hit) | | | | | | | | | | | | |
| **Blue** | **No. of Teams** | 18 | | | | 12 | | | | 6 | | | |
| | **Pax per Team** | 4 | 3 | 2 | 1 | 4 | 3 | 2 | 1 | 4 | 3 | 2 | 1 |
| | **Total Pax** | 72 | 54 | 36 | 18 | 48 | 36 | 24 | 12 | 24 | 18 | 12 | 6 |
| | **RCP** | 3 | 2.25 | 1.5 | 0.75 | 2 | 1.5 | 1 | 0.5 | 1 | 0.75 | 0.5 | 0.25 |
| | **Manpower Savings** | 0% | 25% | 50% | 75% | 33.33% | 50% | 66.67% | 83.33% | 66.67% | 75% | 83.33% | 91.67% |
| | **Squads # Removed** | - | - | - | - | 11, 12, 17, 18, 23, 24 | 11, 12, 17, 18, 23, 24 | 11, 12, 17, 18, 23, 24 | 11, 12, 17, 18, 23, 24 | 8, 14, 20,<br>10, 16, 22,<br>11, 12, 17, 18, 23, 24 | 8, 14, 20,<br>10, 16, 22,<br>11, 12, 17, 18, 23, 24 | 8, 14, 20,<br>10, 16, 22,<br>11, 12, 17, 18, 23, 24 | 8, 14, 20,<br>10, 16, 22,<br>11, 12, 17, 18, 23, 24 |
| **Levels** | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |

Based on the results from Experiment Set 2, which concluded that a minimum P-hit of 0.6 was to be implemented across the blue force in order to achieve the lowest average blue casualties, the blue P-hit was therefore set to 0.6. Hence, with the blue force baseline P-hit starting from 0.6 onwards in Experiment Set 3, the blue P-hit number of levels was reduced from 20 to 9. The DPs for this experiment are shown in Table 8, and each DP was replicated 1000 times, resulting in 108,000 simulated battles (instead of 21 billion).

Table 8. Summary of Design Points for Experiment Set 3

| Factor | Min | Max | Increment | Type |
|---|---|---|---|---|
| **Red P-Hit** | Constant at 0.5 P-Hit | | | |
| **Blue P-Hit** | 0.6 | 1 | 0.05 | Discrete |
| **Manpower (No. of Teams)** | 1 | 3 | 1 | Discrete |
| **Manpower (Soldiers per Team)** | 1 | 4 | 1 | Discrete |
| Design points: 9 x 3 x 4 = 108<br>Simulated battles per design point = 1000<br>**Total: 108 × 1000 = 108,000 simulated battles** | | | | |

The three primary MOEs studied in this experiment are, as before, (1) the amount of time for the model to reach terminating conditions, (2) total casualties suffered by the blue force at the end of the simulation, and (3) the total ammunition expended by the blue force. The MOEs from Experiment Set 3 are then compared with those of the base model analysis and experiment.

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# V. DATA ANALYSIS AND EXPERIMENT RESULTS

This chapter presents the analysis of the data collected from each of the experiment sets specified in Chapter IV. The chapter first describes the analytical methods used before describing the results of each experiment set sequentially.

## A. ANALYTICAL METHODS

Through the use of a data post-processor, custom metrics were defined and collected from the raw data produced by the simulation model runs. Nevertheless, further data processing was still necessary to prepare the data for specific analysis. Hence, the first step in the analysis was to process and organize the data into relevant information before presenting the insights gleaned from this information that may hopefully influence decisions and drive changes to improve operational effectiveness. Figure 7 illustrates the methodology used to transform data into insights. Data analysis develops information through the use of statistical summaries and the identification of trends, patterns, and relationships. Insights are based on the set of information as well as contextual understanding of the scenario developed in the simulation model, and its inherent limitations.

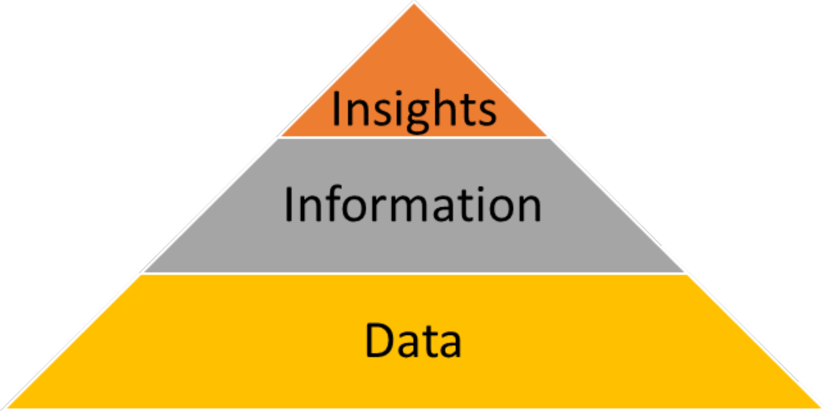
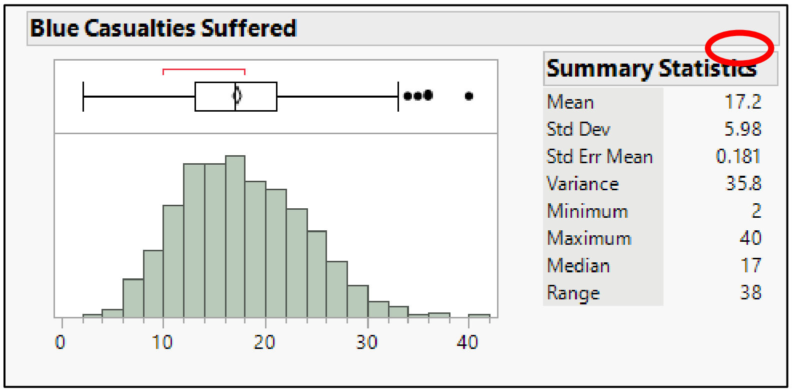


Figure 7. Repackaging Data Collected. Adapted from Dykes (2016).

One example of producing information is the use of histograms, boxplots, and other plots to highlight details such as the shape and spread of the responses and the presence of outliers. Another example of information comes through the use of metamodels to capture the relation between inputs (experimental factors) and the MOEs, e.g., partition tree and linear regression. Insights are derived from the collection of these products and information.

## B. SENSITIVITY ANALYSIS OF THE BASE MODEL

The purpose of the analysis of the base model is to determine the random variability in each of the MOEs. The base model simulated 1,200 battles with the red force P-hit of 0.5 and blue force P-hit of 0.3, with the blue force having a 3:1 manpower advantage. Out of 1,200 simulated battles, 100 battles did not reach the stopping conditions before 50,000 time steps and were therefore discarded from this analysis. The high variance in the number of blue casualties, seen in Figure 8, evinces the fairness and randomness of the model. We see that out of 72 soldiers, the number of blue casualties ranges from two to 40 soldiers even though none of the simulation inputs were changed. The same can be said for the other two MOEs, shown in Figure 9 and Figure 10. Knowing that a battle executed in the real world would lead to a single outcome, the ability to quantitatively capture inherent uncertainty is valuable, as is the ability to use computer experimentation to understand how changes in model inputs might affect the outcome, with no real-world loss of lives.



**Blue Casualties Suffered**

**Summary Statistics**

| | |
|---|---|
| Mean | 17.2 |
| Std Dev | 5.98 |
| Std Err Mean | 0.181 |
| Variance | 35.8 |
| Minimum | 2 |
| Maximum | 40 |
| Median | 17 |
| Range | 38 |

Figure 8. Histogram and Summary Statistics of Blue Casualties Suffered

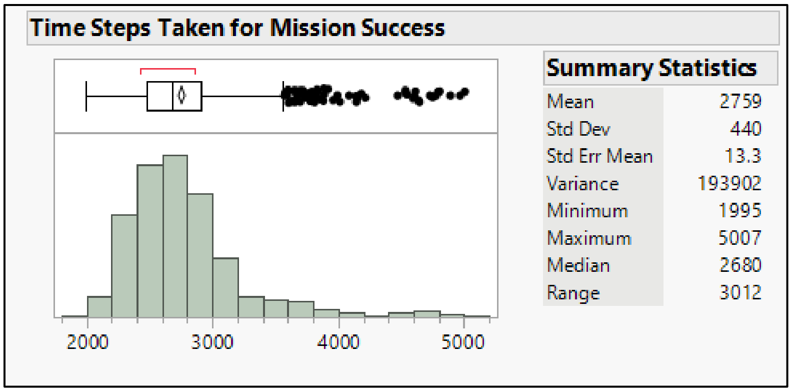


Figure 9. Histogram and Summary Statistics of the Amount of Time for the Model to Reach Terminating Conditions

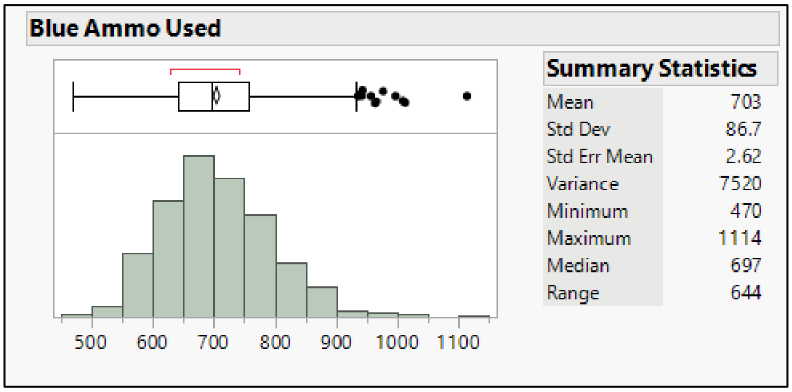


Figure 10. Histogram and Summary Statistics of Blue Ammunition Utilization

With the standard deviation of 5.98 based on the average blue casualties suffered (seen in Figure 8 demarcated with a red circle), two methods, described in Chapter IV.A, were utilized to determine the sample size required to achieve the desired resolution of one casualty:

1. <u>Method 1</u>: Uses Equation 1 to calculate the sample size required based on the desired level of precision and 99% confidence level. This method results in a sample size, *n,* of approximately 953.
2. <u>Method 2</u>: Uses Equation 2 to calculate the sample size required for hypothesis testing with both type-I and type-II error accounted for. This method results in a sample size, *n*, of approximately 861.

Both calculations were performed on blue casualties suffered with the resolution of up to one casualty as it was deemed as the most important MOE selected. With the results from these methods at 953 and 861, respectively, it was decided that the sample size, or the number of simulated battles (replications) for each DP, would be rounded up to 1,000.

## C. ANALYSIS AND RESULTS OF EXPERIMENT SET 1 (IMPACT OF P-HIT)

To better understand the impact of the P-hit of the blue force, the time steps taken for mission completion were recorded. The blue smoother curve for mean time steps taken versus blue force P-hit, which ranged from 0.05 to 1.0, is shown in in Figure 11. In general, it can be seen that the average time taken for the model to reach end conditions decreases as the blue force P-hit increases. Simply put, a more lethal blue force is able to attrite the red force more quickly and reach their objective sooner.

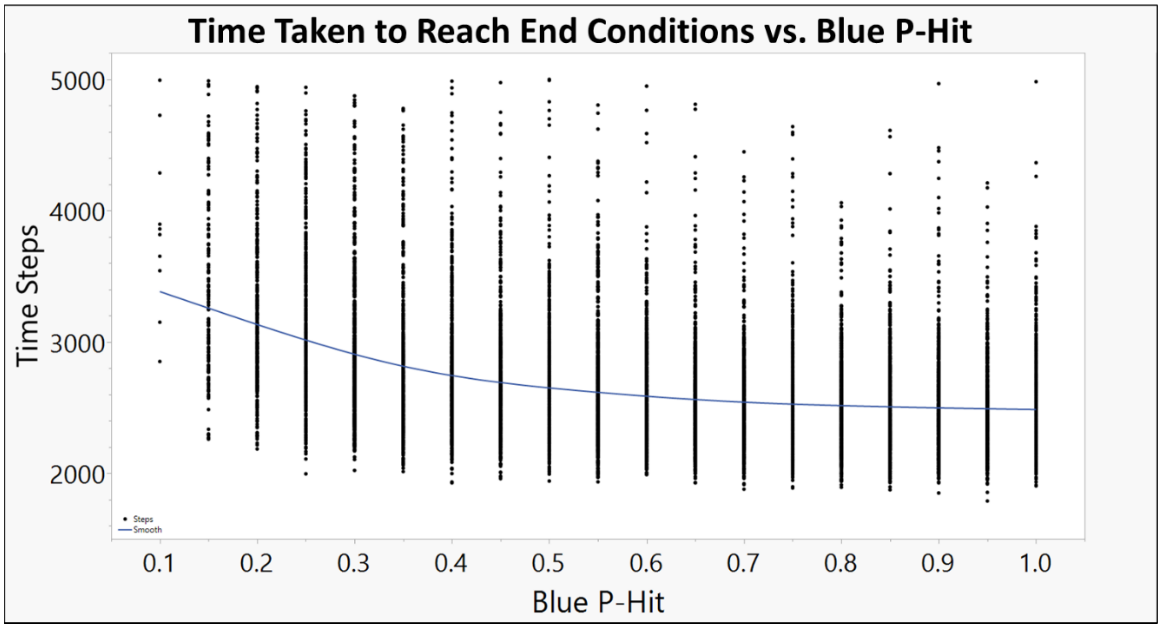


Figure 11. Results for Average Time Taken for Model to Reach End Conditions vs. Blue P-Hit

Red casualties suffered were also measured for Experiment Set 1 to form a holistic view. It can be seen in Figure 12 that the average red casualties peak at 22 casualties (out of a total of 24 red simulated soldiers) when blue force P-hit reaches 0.3 or greater. With a blue force P-hit of less than 0.3, the outcome of the battle might not be favorable to the blue force.

Correspondingly, the impact of improvement in blue force P-hit on the various MOEs is exhibited most strongly when the blue force P-hit improves from 0.05 to 0.3. At a blue force P-hit of 0.3, the knee of the curve is observed in the graph for average blue casualties in Figure 12. In addition, the results shown in Figure 12 also indicate that the blue force's mission ammunition requirement may potentially be slightly reduced when blue P-hit improves. Since the amount of ammunition significantly adds to the combat load of each soldier, this MOE is studied more deeply in the next experiments.

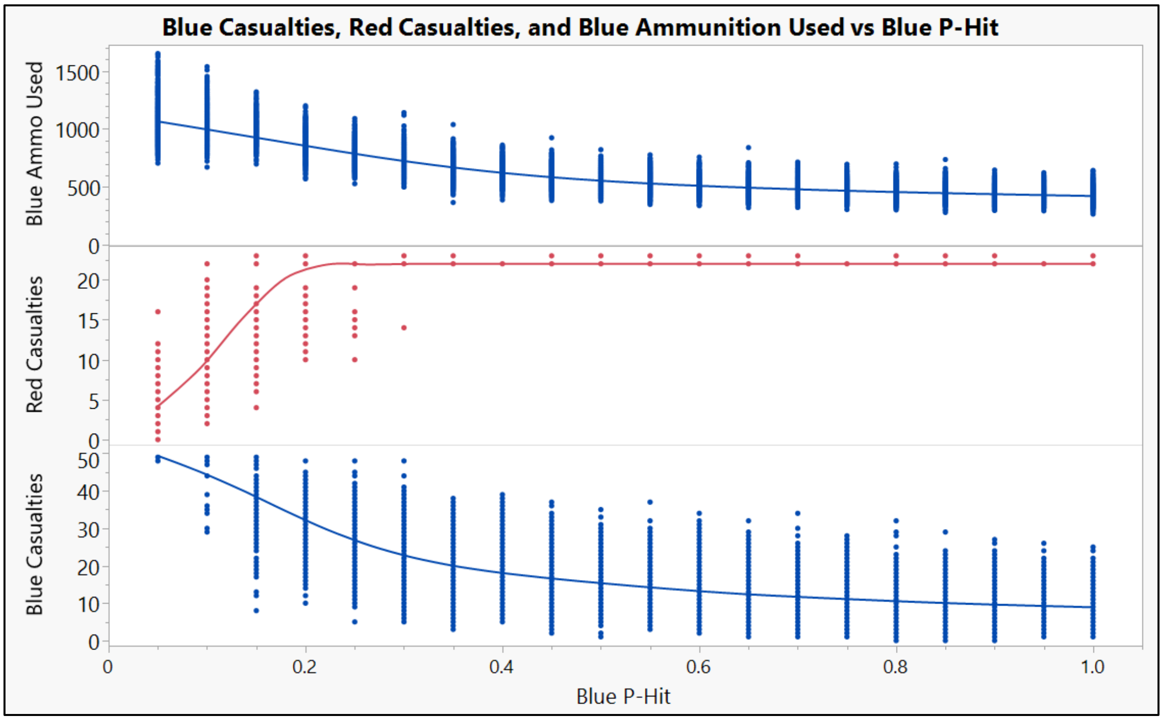


Figure 12. Results for Average Blue Casualties, Average Red Casualties, and Average Blue Ammunition Used vs. Blue P-Hit

In summary, for Experiment Set 1, the red force P-hit remained constant at 0.5, and the blue force always had a 3:1 manpower advantage over the red force. Under these conditions, the blue force dominated the battlefield when its P-hit was 0.3 and above.

## D. ANALYSIS AND RESULTS OF EXPERIMENT SET 2 (BLUE P-HIT VS. SCALE OF IMPLEMENTATION IN BLUE FORCE)

From Experiment Set 1, a minimum blue force P-hit of 0.3 was determined necessary to ensure mission success. With a baseline of 0.3 P-hit and no change in the blue force structure, the effectiveness of the scale of implementation coupled with the increase in P-hit were measured by (1) the amount of time for the model to reach terminating conditions, (2) total casualties suffered by the blue force at the end of the simulation, and (3) the total ammunition expended by the blue force.

The results of the three MOEs were strongly correlated (as shown in Figure 13). Therefore, the analysis of one MOE (total blue casualties suffered) is sufficient to explain these findings.

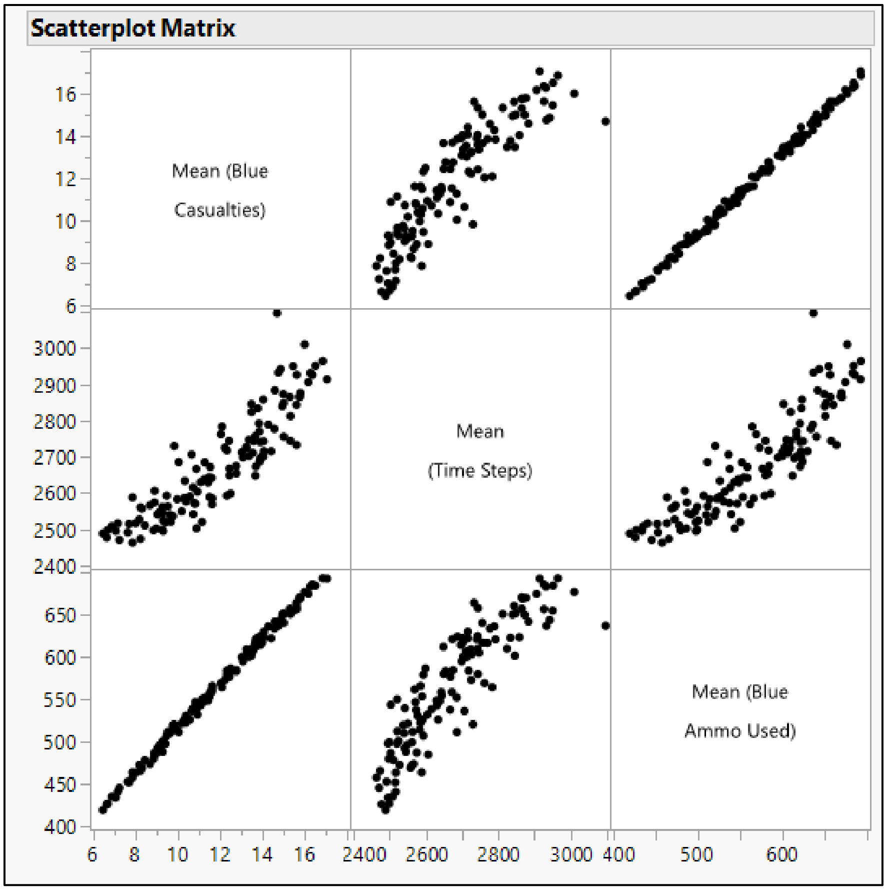


Figure 13. Scatterplot of the Three MOEs for Experiment Set 2

A regression plot can be used to visualize the impact of blue force P-hit and the scale of improvement on the average blue casualties suffered. The slopes of the curves in Figure 14 depict the impact of blue P-hit on blue casualties suffered. Each curve represents the best fit for one marksmen squad configuration where, for example, the 3a curve represents the first combination of three marksmen squads employed; the 3b curve represents the second combination of three marksmen squads employed; and so on. The specific marksmen squads employed can be seen in Table 5. The fitted curves become steeper, and thus, the blue P-hit becomes more impactful with the increase in number of marksmen squads.

The largest impact seen in Figure 14 is the substantial drop in average blue casualties from approximately 14 to 11 when six marksmen squads were employed instead of three marksmen squads. This substantial drop in blue casualties is due to the accuracy and volume of fire available to overwhelm the enemy. Hence, it is deemed essential to always have at least six marksmen squads, and the priority is to assign them to fulfill the primary task as the main assault force (shown in Table 4). Intuitively and as evident in Figure 14, the average blue force casualties suffered are lowest when the entire company is staffed with marksmen.

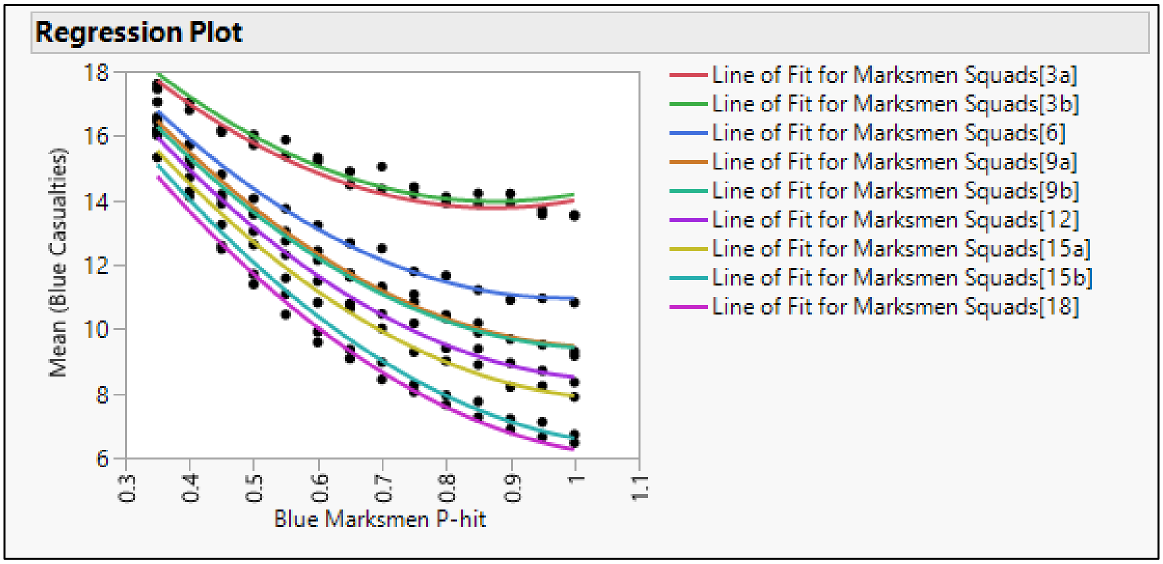
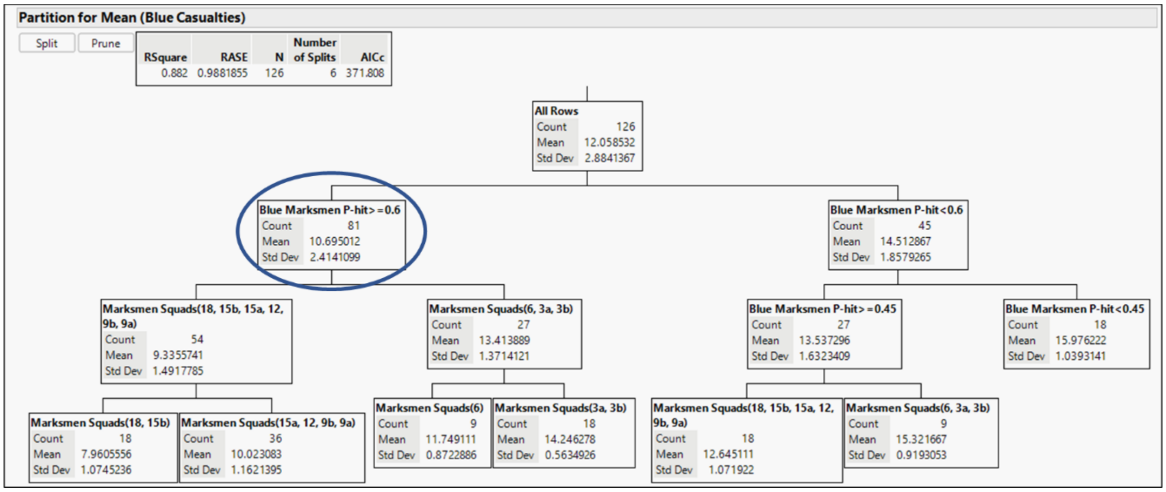


Figure 14. Regression Plot for Average Blue Casualties vs. P-Hit and Scale of Improvement

To further analyze the results based on average blue casualties suffered, a partition tree analysis was used. A partition tree algorithm, which is a nonparametric approach that complements the use of regression, recursively splits the set of factors at determined cutpoints that best separate values of the response, i.e, more favorable versus less favorable. In this case, as seen in Figure 15, the first split occurs on blue P-hit, at the cut value of 0.6. When the blue force P-hit is greater than 0.6 (demarcated in the blue circle), the average blue casualties is approximately 10.7, as compared to 14.5 when the P-hit is less than 0.6. When blue force P-hit is below 0.6, the scale of implementation factor is less significant.



| RSquare | RASE | N | Number of Splits | AICc |
|---|---|---|---|---|
| 0.882 | 0.9881855 | 126 | 6 | 371.808 |

Figure 15. Partition Tree for Average Blue Casualties Suffered

In summary, for Experiment Set 2, the red force P-hit remains constant at 0.5, and the blue force always has a 3:1 manpower advantage over the red force. Under these conditions, a minimum P-hit of 0.6 should be implemented in almost all squads to achieve lowest average blue casualties. Furthermore, there should be at least six marksmen squads (i.e., one third of the force).

## E. ANALYSIS AND RESULTS OF EXPERIMENT SET 3 (BLUE P-HIT VS. BLUE MANPOWER)

Incorporating a key finding from Experiment Set 2, the blue force P-hit was varied from 0.6 to 1.0 in Experiment Set 3, while the red force P-hit remained constant at 0.5.

Three MOEs were utilized to measure the effectiveness of increase in P-hit against the decrease in manpower available to accomplish the same mission. The first MOE is an estimate of the probability of mission accomplishment. Being a probability, it is bounded below by zero and above by one. Mission accomplishment is determined by the condition that the blue force is not eliminated before the time steps reach 50,000. This time limit is based on a typical dismounted company-level assault on a platoon, which equates to nearly 14 hours. The second MOE is the percentage of blue casualties suffered, keeping in mind that the total number of blue soldiers is varied in Experiment Set 3. The author understands that to a military commander every soldier counts, and casualty rates should never be quantified simply as a percentage. However, this method was selected for the ease of comparison between DPs, and every effort in this thesis aims to generate actionable insights for commanders to reduce casualty count during combat. The third MOE is the average amount of time for the model to reach terminating conditions.

To study the interactions among all these factors, the interaction profiler from a regression model fit to the probability of mission accomplishment MOE was generated, and this is shown in Figure 16. There is minimal difference in the probability of mission accomplishment between three or four soldiers per team when there are 18 teams, and between having 12 or 18 teams with four soldiers each. Thus, with larger teams, fewer teams are needed.

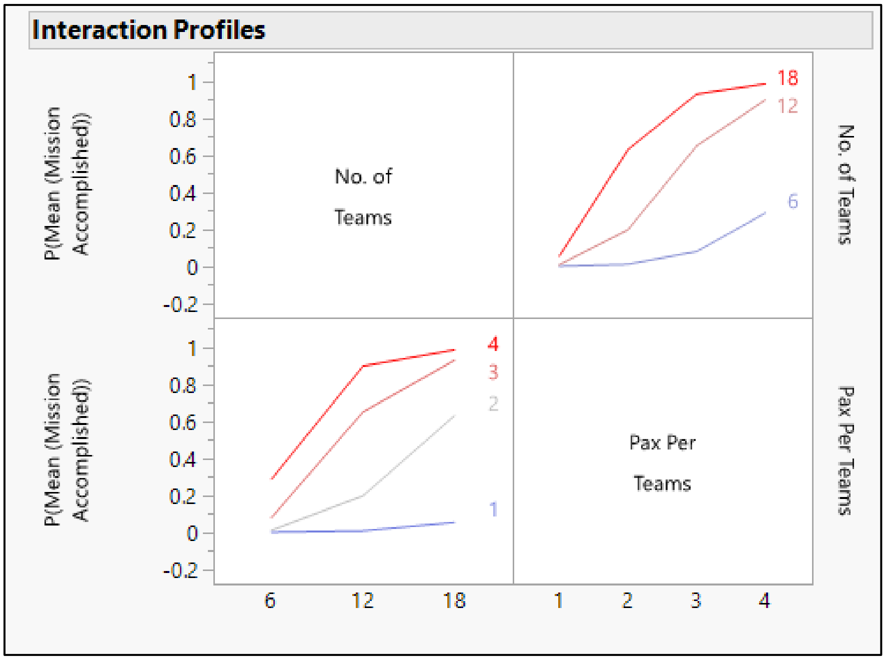


Figure 16. Interaction Profiles for a Regression Model of Probability of Mission Accomplishment

To study the impact of blue force P-hit on the probability of mission accomplishment, a plot of the response versus all three factors was generated, shown in Figure 17. It can be seen that when P-hit is above 0.9 and with at least three soldiers in a team, there is minimal difference between having 12 or 18 teams. Any further increase in blue force P-hit from 0.9 onwards only minimally improves the probability of mission accomplishment. We also see that having 12 or more teams of three or more soldiers per team results in much higher probabilities of mission success (see red box in Figure 17).

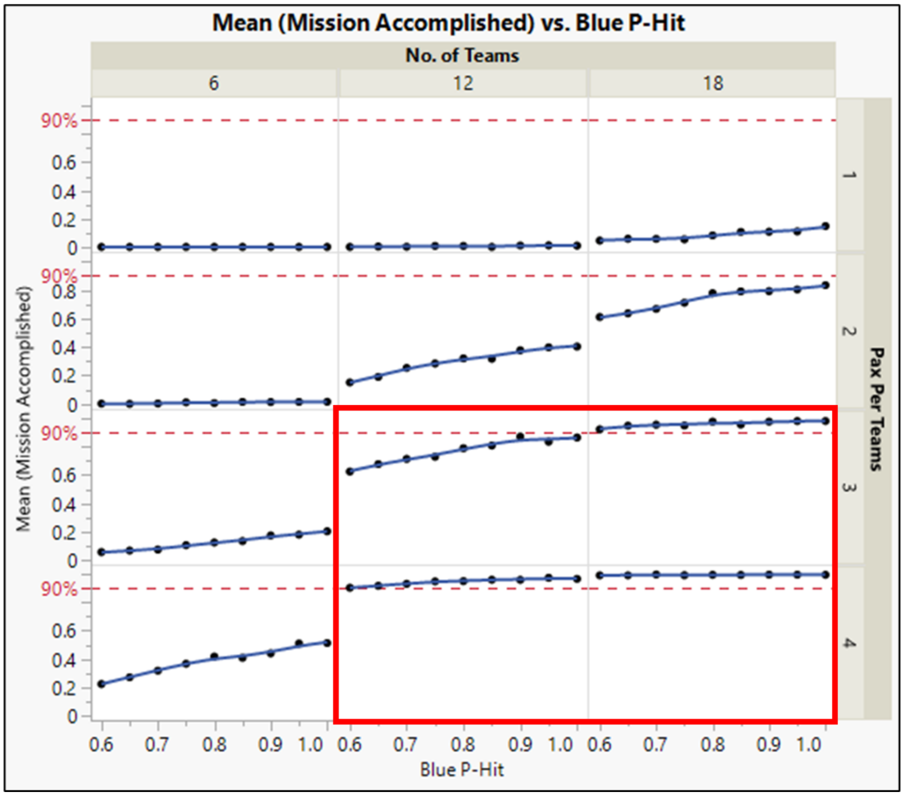
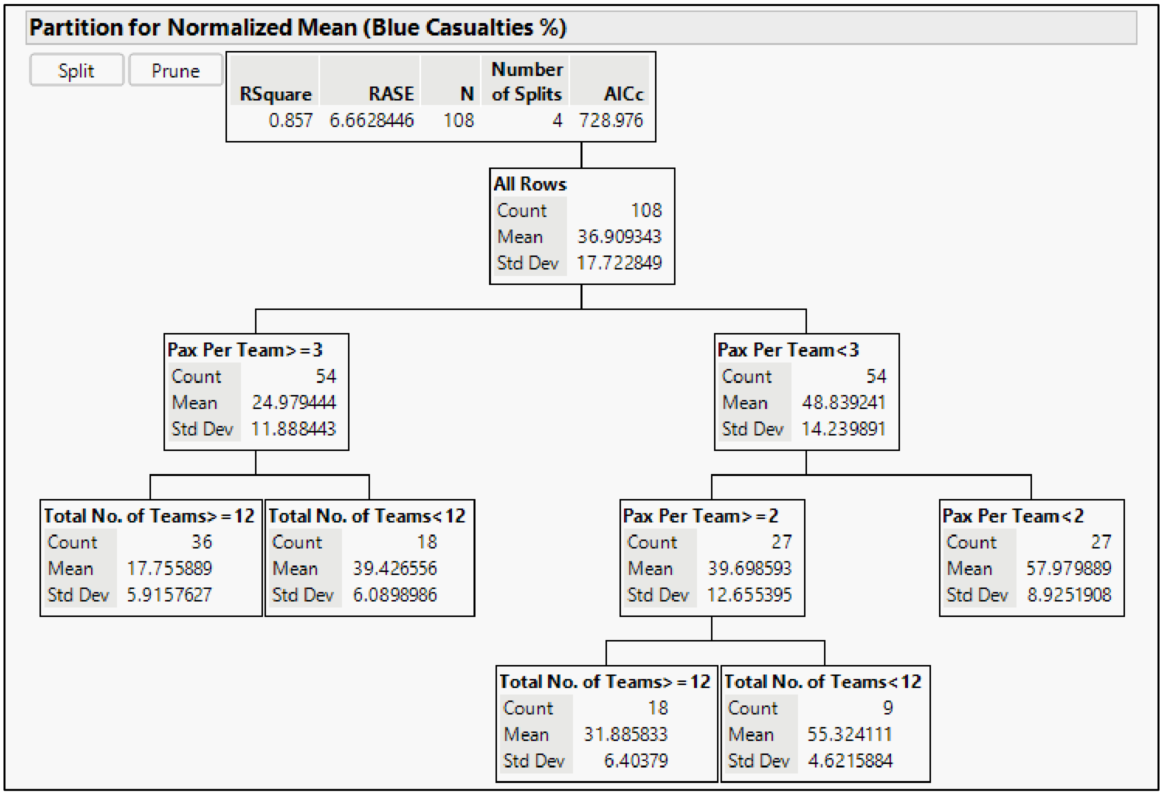


Figure 17. Plot of Probability of Mission Accomplishment vs. All Factors

A partition tree analysis was used to further analyze the results based on the percentage of blue casualties suffered, shown in Figure 18. Based on the tree splits in the left-most boxes, there must be at least 12 teams, with three soldiers at minimum in each team in order to achieve the lowest percentage (approximately 18 %) of casualties. This reinforces what was observed earlier for mission success. Based on the tree splits in the right-most boxes, with reduced manpower in the blue force, that is, fewer soldiers in fewer teams, the percentage of blue casualties increases dramatically.



**Partition for Normalized Mean (Blue Casualties %)**

| RSquare | RASE | N | Number of Splits | AICc |
|---|---|---|---|---|
| 0.857 | 6.6628446 | 108 | 4 | 728.976 |

**All Rows**

| | |
|---|---|
| Count | 108 |
| Mean | 36.909343 |
| Std Dev | 17.722849 |

**Pax Per Team>=3**

| | |
|---|---|
| Count | 54 |
| Mean | 24.979444 |
| Std Dev | 11.888443 |

**Pax Per Team<3**

| | |
|---|---|
| Count | 54 |
| Mean | 48.839241 |
| Std Dev | 14.239891 |

**Total No. of Teams>=12**

| | |
|---|---|
| Count | 36 |
| Mean | 17.755889 |
| Std Dev | 5.9157627 |

**Total No. of Teams<12**

| | |
|---|---|
| Count | 18 |
| Mean | 39.426556 |
| Std Dev | 6.0898986 |

**Pax Per Team>=2**

| | |
|---|---|
| Count | 27 |
| Mean | 39.698593 |
| Std Dev | 12.655395 |

**Pax Per Team<2**

| | |
|---|---|
| Count | 27 |
| Mean | 57.979889 |
| Std Dev | 8.9251908 |

**Total No. of Teams>=12**

| | |
|---|---|
| Count | 18 |
| Mean | 31.885833 |
| Std Dev | 6.40379 |

**Total No. of Teams<12**

| | |
|---|---|
| Count | 9 |
| Mean | 55.324111 |
| Std Dev | 4.6215884 |

Figure 18. Partition Tree Analysis based on Percentage of Blue Casualties

Next, the MOE of average time taken for the model to reach the end conditions is plotted versus the experiment factors, and this is shown in Figure 19. Additionally, boxes are overlaid to indicate DPs with the same total number of soldiers, to facilitate comparison. DPs with the same total number of soldiers are boxed using the same color. Overall, it can be seen that the number of soldiers in a team has a higher impact than the number of teams. It is also observed that for the boxes of the same color (same number of soldiers), the box in the upper right corner is preferable to the box in the lower left. This corresponds to fewer teams with larger team sizes.

This finding substantiates the hypothesis that, given the same total number of soldiers, a company will be more effective having fewer teams with more soldiers each compared to having more teams with fewer soldiers in each team. This could be due to the synergy in having numbers in a team with direct communication linkage and the ability to instantaneously focus fire on the enemy when one of the soldiers on the team identifies threats.

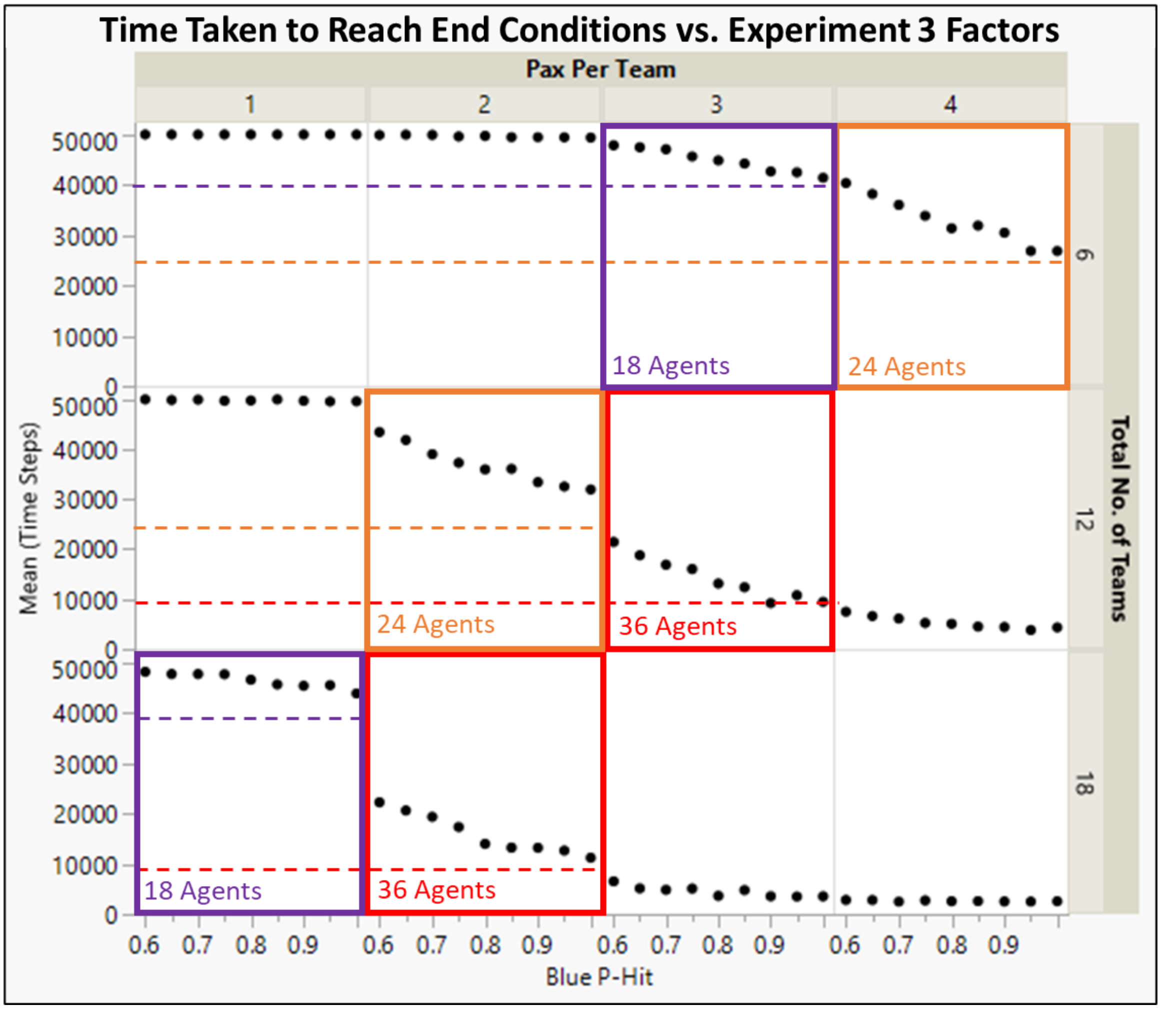


Figure 19. Plot of Mean (Time Steps) vs. All Factors, with Comparison of DPs with the Same Total Number of Soldiers

In summary, given the experimental conditions of this research, to achieve the lowest average blue casualties, a company should have at least 12 teams with at least three soldiers in each team, trained to achieve a minimum level of proficiency of 0.6 P-hit. To reduce manpower requirements, emphasis should be placed on creating larger teams instead of more teams with fewer soldiers each. Moreover, any improvements to P-hit beyond 0.9 bring marginal returns.

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# VI. CONCLUSION AND FUTURE RESEARCH

This chapter summarizes the findings and insights gathered from the experiments performed with the simulation model. The chapter then provides conclusions and recommends potential future follow-on work to collectively improve the developmental efforts for our soldiers.

## A. SUMMARY OF FINDINGS

The findings from this thesis can be divided into two categories, each capturing its respective scenario and purpose:

Improving Status Quo. Given the 3:1 RCP advantage when facing a platoon of red force soldiers with P-hit 0.5, it is essential to ensure that all blue force soldiers in the company deployed are trained to meet the standard of a P-hit of 0.6 under combat conditions. Furthermore, efforts should be made to deploy the best marksmen to the squads tasked as the main assault force. These efforts will increase the probability of mission accomplishment and decrease the average number of blue force casualties suffered.

Reducing Manpower Combat Requirements. To reduce manpower requirements within the same combat scenario, the blue force soldiers must be trained or supported by technology to achieve a P-hit of 0.9 under combat conditions. The blue force company should have at least 12 teams with at least three soldiers in each team. The emphasis should be on creating larger teams instead of additional smaller teams. Any further improvement to P-hit beyond 0.9 brings marginal returns.

## B. CONCLUSION AND RECOMMENDATIONS

After more than 250,000 simulated battles conducted on the MANA-V model developed, the output generated was able to provide sufficient data to address the research questions of this thesis. Though future work could examine the impact of red force characteristics, keeping those characteristics fixed for these thesis runs facilitated ease of comparison across experiments.

It can be concluded that with an improvement in individual shooting accuracy in close-quarters combat, there is the potential to attain a 50% reduction in manpower requirements and a 50% reduction in blue casualties, as shown in Table 9. While this linear reduction is not ideal, it is also not surprising, as there were no efforts made in this model to improve the protection or body armor of the combatants. However, with the reduced manpower, the time taken for the smaller combat force to explore and cover the same area of operations would be tripled. Ammunition requirements would also increase, as the smaller combat force would be exposed to additional enemy fire and would need to focus fire to cover maneuvering team members.

Table 9. Conclusion Comparison

| **Factors & MOEs** | **Baseline Model from Experiment 1** | **Improved Baseline Model from Experiment 2** | **Manpower Saving Model from Experiment 3** |
|---|---|---|---|
| **Blue Force P-hit** | 0.3 | 0.6 | 0.9 |
| **No. of Teams** | 18 teams | 18 teams | 12 teams |
| **No. of Soldiers per Team** | 4 soldiers per team | 4 soldiers per team | 3 soldiers per team |
| **Total No. of Soldiers** | 72 soldiers (3:1 RCP) | 72 soldiers (3:1 RCP) | 36 soldiers (1.5:1 RCP) |
| **Average Blue Casualties Suffered** | 17.2 casualties | 9.6 casualties | 8.1 casualties |
| **Average Time Taken for Model to Reach End Conditions** | 2,759 time steps | 2,848 time steps | 9,235 time steps |
| **Average Ammunition Expended by Blue Force** | 703 rounds expended | 512 rounds expended | 3953 rounds expended |

When considering the requirements of unmanned or artificial intelligence-enabled weapon systems to support future close-quarters combat, it is essential to include the shooting accuracy of P-hit 0.9 as one of the requirements. Further resources should be put to better use and not be invested in trying to improve the shooting accuracy beyond P-hit 0.9.

## C. FUTURE FOLLOW-ON WORK

The framework introduced by Martin et al. in 2017 was used in Chapter II of this thesis. Table 10 summarizes the efforts done by previous NPS students who have utilized agent-based modelling to study a piece of the overall problem. These efforts contribute to a collective effort to acquire insights on how to improve the effectiveness of individual combatants. Work on the study of the effectiveness of combatants in urban and conventional terrain is incomplete.

Table 10. Summary of Efforts on the Study of the Combatants' Operational Effectiveness in Urban and Conventional Terrain

| Four Performance Factors of Individual Operational Effectiveness | Thesis Authors and References | |
|---|---|---|
| | **Urban Terrain** | **Conventional Terrain** |
| **Lethality** | Sanders, 2005 | Harper, 2021 |
| **Accuracy** | Teo, 2022 (This Thesis) | Kramlich, 2005 |
| **Mobility** | - | Thompson, 2019 |
| **Interoperability** | Babilot, 2005 | Lindquist, 2004 |

And we thank the giants whose shoulders we stood on today. It is envisaged that the time and effort put in by these students in the past on the models can be amalgamated to establish a larger model incorporating the various considerations to gain clarity and further insights for the collective improvement and development of our soldiers. Future research could also leverage special-purpose Latin hypercube designs if the size of the scenarios increases or more factors are supported (Hernandez et al. 2012).

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