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AN OPERATIONAL EFFECTIVENESS ANALYSIS ON MANNED-UNMANNED TEAMING USING WEAPONIZED UNMANNED VEHICLES IN URBAN TERRAIN

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THESIS

AN OPERATIONAL EFFECTIVENESS ANALYSIS ON MANNED-UNMANNED TEAMING USING WEAPONIZED UNMANNED VEHICLES IN URBAN TERRAIN

by

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September 2022

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13. ABSTRACT (maximum 200 words)

In recent years, militaries have strengthened efforts to integrate unmanned technologies to improve manned-unmanned teaming (MUM-T) capabilities. As some countries' fighting-age populations are decreasing, militaries are turning to readily available, cost efficient, and sophisticated unmanned technologies. MUM-T holds great potential not only to alleviate manpower shortages in militaries, but also to improve combat capabilities. This thesis studies the effectiveness of MUM-T at the frontline, down to infantry teams supporting offensive operations in urban terrain. An agent-based simulation is used to model a MUM-T combat operation with and without an unmanned ground vehicle (UGV) to support an infantry company. An analysis was conducted on more than 76,800 simulated battles. It was observed that MUM-T concepts could dramatically increase combat effectiveness, as assessed by increased enemy casualties. The UGV reloading time, weapon accuracy, and own force structure were also observed to significantly impact the infantry's lethality and survivability. This analysis concludes that implementation of MUM-T at the small-unit tactical level has great potential to enhance overall combat performance. Moving forward, combat models could be integrated into future military exercises such that the findings from simulations can be verified and validated.

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Submitted in partial fulfillment of the
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ABSTRACT

In recent years, militaries have strengthened efforts to integrate unmanned technologies to improve manned-unmanned teaming (MUM-T) capabilities. As some countries' fighting-age populations are decreasing, militaries are turning to readily available, cost efficient, and sophisticated unmanned technologies. MUM-T holds great potential not only to alleviate manpower shortages in militaries, but also to improve combat capabilities. This thesis studies the effectiveness of MUM-T at the frontline, down to infantry teams supporting offensive operations in urban terrain. An agent-based simulation is used to model a MUM-T combat operation with and without an unmanned ground vehicle (UGV) to support an infantry company. An analysis was conducted on more than 76,800 simulated battles. It was observed that MUM-T concepts could dramatically increase combat effectiveness, as assessed by increased enemy casualties. The UGV reloading time, weapon accuracy, and own force structure were also observed to significantly impact the infantry's lethality and survivability. This analysis concludes that implementation of MUM-T at the small-unit tactical level has great potential to enhance overall combat performance. Moving forward, combat models could be integrated into future military exercises such that the findings from simulations can be verified and validated.

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LIST OF ACRONYMS AND ABBREVIATIONS

AFV	Armored Fighting Vehicle
AO	Area of Operations
ATGM	Anti-tank Guided Missile
CAPDEV	Capability Development
CONOPS	Concept Of Operations
DOE	Design of Experiment
F2T2E	Find, Fix, Target, Track, and Execute
LER	Loss Exchange Ratio
MAAW	Multi-purpose Anti-armor Anti-personnel Weapon
MANA	Map Aware Non-Uniform Automata
MBT	Main Battle Tank
MOE	Measure of Effectiveness
MUM-T	Manned Unmanned Teaming
MUTT	Multi Utility Tactical Transport
NOB	Nearly Orthogonal Balance
NOLH	Near Orthogonal Latin Hypercube
ORBAT	Order Of Battle
PHIT	Probability of Hit
RCP	Relative Combat Power
TTP	Tactics, Techniques and Procedures
TUGV	Tactical Unmanned Ground Vehicle
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle

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EXECUTIVE SUMMARY

Warfare is increasingly evolving with the use of complex technologies and innovations. Driven by global manpower shortages, nations are turning to unmanned technologies to alleviate such shortages and provide combat capabilities. Hence, there is much potential to leverage unmanned technologies to support frontline infantry soldiers through the adoption of manned-unmanned teaming (MUM-T).

This thesis aims to explore the effectiveness of MUM-T in an offensive urban scenario. The thesis discusses, analyzes, and studies the effectiveness of the tactical employment of unmanned ground vehicles (UGV) in an urban environment at the company level. The research questions guiding this research include the following:

Primary Questions:

1. How lethal and survivable are infantry squads supported with an UGV or UGVs?

2. What are the battle outcomes and analyses of different force structures for a MUM-T force in the simulated scenario?

Secondary Question:

- What is the scope for future research on potential implementation approaches of MUM-T at broader, strategic levels?

Using the agent-based simulation environment Map Aware Non-Uniform Automata (MANA), this thesis studies MUM-T by building a simulation and conducting analysis on operational scenarios for UGVs coupled with factors affecting operational effectiveness of offensive infantry forces in urban terrain.

The combat model comprises two main groups of combat forces modeled after the U.S. Army’s infantry order of battle (ORBAT): (1) A Blue force comprising an infantry company of friendly soldiers equipped with an UGV; and (2) A Red force comprising an

infantry platoon of enemy soldiers acting as the defender. Figure 1 shows the start-state of one of the iterations of the simulated combat operations.

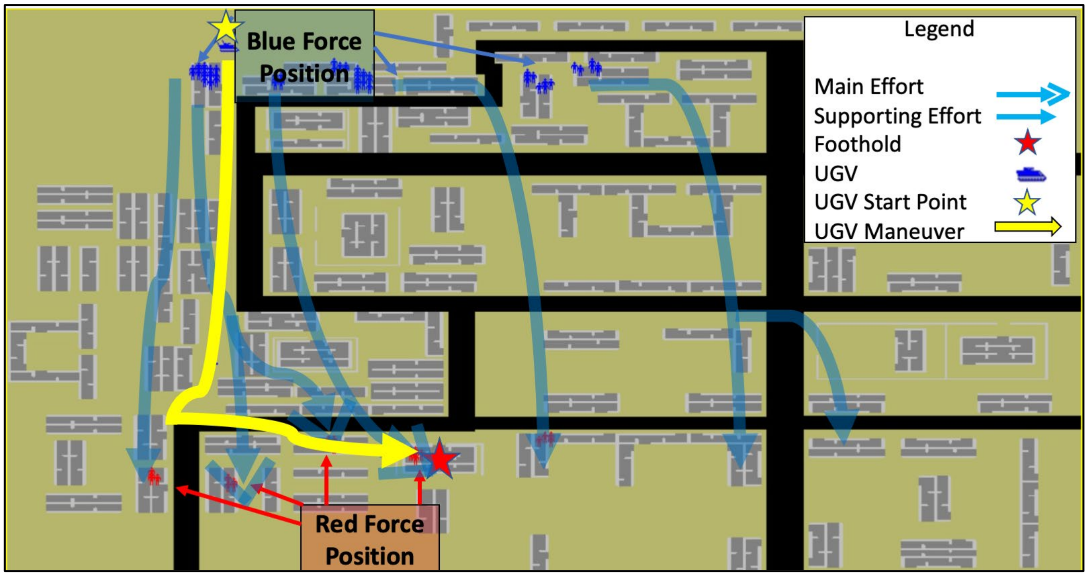

Figure 1. A Screenshot of the Initial State of One Simulation Replication from MANA.

A total of three different design of experiments (DOE) were created to study key combat characteristics and effects from MUM-T capabilities and concepts. The measures of performance focused on mission effectiveness, with an emphasis on identifying factors that correlate to lethality and survivability. The author undertook an iterative approach to each DOE by incorporating some of the findings and analysis from the previous DOE(s) into the next. The first DOE focused on the effects of the initial introduction of MUM-T compared to a baseline infantry ORBAT. The second DOE focused on varying manpower and force structure to study the effects of force sizing in support of MUM-T. The last DOE combined every aspect of the first two DOEs and created a nearly orthogonal and balanced mixed design to enable a more comprehensive and conclusive experiment to conclude the thesis. Nearly 80,000 simulated battles, each covering over eight hours of combat, were run and analyzed.

The study presents evidentiary support that reinforces the benefits and usefulness of MUM-T. In terms of enhancing lethality and survivability, observations from the simulated combat operations saw a 300% increase in Red casualties and 50% decrease in Blue casualties. It also demonstrated the importance of maintaining a sustainable and optimal force structure, where "over-sizing" a combat force could contrarily endanger the soldiers—especially in an urban or other complex operating environment.

In conclusion, it is evident that MUM-T holds potential in warfare operations of the future. Based on the findings from this research, some useful areas recommended for future works include:

1. Exploring other tactics, techniques, and procedures in combat simulations to examine other factors that could support MUM-T concepts to cross-validate and verify the findings.

2. Conducting software and combat modeling across other platforms to capture additional findings or metrics.

3. Leveraging combat simulation findings to support field tests to validate and verify the analyses. The combination of real-world testing and combat simulations could help decision makers make more informed decisions on costly and timely capability development plans.

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I am honored and humbled to pen down my acknowledgements as I close the final chapter of my master's thesis at Naval Postgraduate School.

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I would also like to thank my fellow Singaporeans for walking the path with me for the past one and a half years, juggling assignments, theses, and late nights together.

Most importantly, I would like to thank my wife, Vivian, for always being there during late nights and tough times.

Learning doesn't stop here; this is only the beginning of a lifelong learning journey.

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I. INTRODUCTION

Just as war is too important to leave it to the generals, science and technology are too important to leave in the hands of the experts.

— Sheldon Rampton, 2000

This chapter discusses some of the background and problems associated with emerging technologies and manpower shortages which are causing a capability shift towards the adoption of unmanned technologies in modern combat forces. The chapter also highlights the aims, benefits, research methods, methodology, and organization for this thesis.

A. BACKGROUND AND PROBLEM STATEMENT

Defense is an essential arm of every nation. Reinforced by the recent invasion of Ukraine by Russia, every nation should never take its defense for granted (Atlantic Council 2022). With rapid modernization of industry and emerging technologies in recent years, warfare is increasingly evolving and incorporating complex technologies and innovations. Faced with global manpower shortages, nations are turning to unmanned technologies to alleviate those shortages and provide combat capabilities. By adopting unmanned elements, nations aim to provide combat power to the frontline.

One driver for the adoption of unmanned technologies is the modernization and evolution of combat operations. Over the last decade, key shifts in warfare enabled by technological advances or innovation can be categorized into three essential elements in most armies: The Infantry, Shock, and the Fire Support (Pointon 2003). Today's modernized infantry force boasts sophisticated capabilities, smaller and more lethal Main Battle Tanks (MBT), enhanced lethality and accuracy of fire support, unmanned aircraft, and cruise missiles. While significantly different in characteristics, the three elements of warfare (infantry, armor protection, and fire support) continue to remain relevant—and will likely be so in the near future.

Another development that has driven global interest in unmanned technologies is the issue of alleviating manpower shortages and demand constraints across every industry (Natalitzia, 2022). Over the last five years, reliable market surveys have shown a steep decline in birth rates globally, with an estimated decreasing trend of up to 33% by the year 2030 (Bricker 2021). Major factors contributing to the decline in manpower include COVID-19, urbanization, female education, and change in lifestyles, among others. This manpower shortage is significantly affecting many sectors of society, with the defense sector and militaries most affected.

With approximately 1.3 million active-duty service personnel, the United States military estimates that it needs 150,000 recruits yearly to cope with attrition and retirement (Stelloh 2022). Military recruitment is a stringent process. In 2020, the U.S. Army reduced its recruitment target to 61,200 enlistees, which was an additional 20% reduction from 2019 (Stelloh 2022). Despite expanded government support to increase enlistment bonuses and monetary benefits up to $50,000 USD, the availability of manpower continues to be a concern (Stelloh 2022). The challenge to recruit continues to affect sustainability of manpower in the military, which is further aggravated when at least 70% of young Americans between 17 to 24 are deemed ineligible to undertake active-duty service due to obesity, mental-health issues, drug abuse histories, criminal records, or inadequate academic qualifications (Bloomberg 2021).

In recent years, militaries have been operationalizing and enhancing their unmanned assets and manned-unmanned teaming (MUM-T) concepts of operations (CONOPS). In October 2021, the resident unit at the U.S. Army's Joint Readiness Training Center (JRTC), nicknamed Geronimo, conducted a field exercise where it saw the operationalization of unmanned ground vehicles (UGV) deployment of two Multi-Utility Tactical Transports (MUTT), UGVs, and other tools against a Blue Force Combat Team to deny landing zones (Trevithick 2021). Unlike MUM-T applications in the past, the MUTTs were weaponized and equipped with a 7.62 Machine Gun, an anti-tank guided missile (ATGM) launcher, and a tethered unmanned aerial vehicle (UAV). The UGV was also equipped with several video cameras to provide enhanced surveillance and intelligence updates (Trevithick 2021). Validated at the exercise, the UGV provided enhancement of the survivability and lethality of troops at the frontline and reinforced the value of further development of MUM-T capabilities and concepts.

Furthermore, operationalization of UGVs is becoming increasingly common across militaries around the world. Russia has been field testing different classes of UGVs (some equipped with a 30 mm cannon and ATGM missile launchers), and China has been enhancing its unmanned capabilities, with weaponized wheeled and tracked platforms seen in defense exhibitions and exercises (Trevithick, 2021).

There are two concurrent operational analysis studies related to the capability development (CapDev) applications in an offensive scenario in urban terrains. At the Naval Postgraduate School (NPS), Teo (2022) is studying the effects of soldier performance with improved weapon systems accuracy as a proxy for AI-supported small arms. Meanwhile, another study at NPS, by Tang (2022), is investigating the effect of supporting tank units with UAVs to improve combat effectiveness.

With the increasing demands on and challenges facing militaries over the next few decades, there is potential for growth in MUM-T concepts and applications. This thesis analyzes the employment of MUM-T concepts at the tactical level (up to an infantry company). The goal is to increase the relative combat power (RCP) of troops at the tactical edge to support future force structure development and decision making.

Specifically, this thesis aims to explore the effectiveness of MUM-T in an offensive urban scenario. The thesis discusses, analyzes, and studies the effectiveness of the tactical employment of UGVs in an urban environment at the company level. The research questions guiding this research include the following:

Primary Questions:

1. How lethal and survivable is an infantry squad supported with an UGV or UGVs?

2. What are the battle outcomes and analyses of different force structures of a MUM-T force in the simulated scenario?

Secondary Questions:

- What is the scope for future research on potential implementation approaches of MUM-T at broader, strategic levels?

B. BENEFITS OF STUDY

This study will enable the U.S. Department of Defense (DOD), militaries, and other defense agencies globally to gain deeper insights on: (1) future MUM-T force structure development; (2) the operational perspective to support future CapDev efforts; and (3) strengthening concepts of MUM-T in an offensive scenario. These insights can serve to support future force MUM-T force structure review and CONOPS development.

C. STUDY APPROACH

To answer the research questions, this thesis uses a quantitative method involving agent-based simulation. The effort aims to enhance the lethality of future military forces by conducting qualitative analysis of operational scenarios for UGVs, coupled with the factors affecting operational effectiveness of infantry forces, to study MUM-T. These scenarios are then modeled using the agent-based simulation environment Map Aware Non-Uniform Automata (MANA) for data farming and experimentation. The analysis of the result provides insights on force structure by assessing the various measures of effectiveness to support future CapDev efforts in the domain of MUM-T.

D. METHODOLOGY

In implementing this methodology, the thesis underwent an iterative process to understand and analyze the effects of a MUM-T force in an urban scenario. The following steps were taken to ensure a credible study was conducted:

1. Model each operational context with a suitable modeling parameter or environment to define the measures of effectiveness (MOE) or "Stop" conditions of the model.

2. Develop each of the possible scenarios in MANA and converge in a baseline model.

3. Apply a series of designs of experiments (DOE) based on the operational constraints and tests, coupled with data farming techniques developed by the SEED Center for Data Farming at Naval Postgraduate School (https://harvest.nps.edu).

4. Conduct simulation runs to gather data and results.

5. Leverage statistics to analyze the simulation results using statistical software, both JMP Pro (www.jmp.com) and Microsoft Excel.

6. Apply the findings of the study to the research questions.

7. Provide recommendations on future research and other focal areas.

E. THESIS ORGANIZATION

Chapter II reviews past works on MUM-T applications and modes of operation (including kill chains, simulation, and studies) to help shape the model development. Chapter III describes model development, including the translation of terrain from the geographical data into MANA, defining operational conditions for the model, and presenting the key takeaways from the development of the initial to the baseline model. Chapter IV explains the purpose behind the iterative process of the three DOEs and the changes to the modeling parameters associated with the specific aim of each DOE. Chapter V presents the results and analysis of the DOEs and draws operational lessons, specifically those relevant to the thesis research questions and other additional findings. Chapter VI highlights key takeaways from the analysis and provides alternative perspectives on the study to provide valuable insights and support future research in similar fields.

II. LITERATURE REVIEW ON MUM-T

This chapter examines past research on MUM-T applications and soldier performance relevant to this thesis. This literature review focuses on three areas: (1) MUM-T kill chain for modeling and simulation; (2) past unmanned capability efforts; and (3) MOEs of the infantry force. In regard to the enhancement in lethality of the friendly force, the purpose of the literature review serves to inform readers about the basis and background to support the scenario building, the design of the model and experiment in the next phase of the study, and the operational analysis of MUM-T in an urban environment, as presented in this thesis.

While research on the employment of unmanned technologies has been ongoing and increasing in recent years, there is potential for development in offensive MUM-T concepts.

A. MUM-T KILL CHAIN FOR MODELING AND SIMULATION

From a systems analysis perspective, Lee (2014) used a nine-step process to study the requirements of his analysis of MUM-T kill chains for future strike operations to support his design of experiments. Lee's holistic approach at the start enabled the study to shift from macro to micro, concluding with two main approaches using the U.S. Marine Corps kill chain compared to the Find, Fix, Target, Track, and Execute (F2T2E) kill chain. While this approach was applied at the strategic level in accordance with the Joint Capability Area (JCA) framework of the U.S. DOD, a simpler, similar approach is used to support the design of experiment in this thesis. This early identification of applications (weaponized front scout, firebases, and other possible tactical agents) also provided an alternative perspective in terms of tactics such as deployment and CONOPs for modeling and simulation.

B. PAST UNMANNED CAPABILITY DEVELOPMENT EFFORTS

Based on requirements at the strategic level, in this case, the transformation of Distributed Marine Operations (DMO), Nissen and Gallup (2019) identified three key areas related to MUM-T: (1) technology trajectories for MUM-T based on relevance to DMO; (2) the relationship between existing DMO frameworks against these technology trajectories; and (3) the way ahead to support the CapDev of DMO. Addressing the "known-unknowns and unknown-unknowns," the project highlighted at the onset that a solution may not be available or realistic, which led to the focus on computational modeling since it is the most efficient approach to broadly explore MUM-T capabilities and concepts. The autonomy and interdependence of the agents in the model were identified as the key parameters to be varied to provide a comprehensive analysis scenario. Aiming to provide an overview of the necessary capabilities required for future force transformation, the project concurred that the MUM-T concept of operations was superior to that of fully manned or fully autonomous systems in the proposed DMO scenario.

From a CapDev angle, Harper (2016) conducted a force structure transformation and modeling study to first identify the demands, challenges, and potential for "future-proofing" the U.S. Marine Corps (USMC) force. The results from the combat modeling were then analyzed in terms of the potential application of MUM-T to provide the Blue force with greater lethality. The study was scoped at the onset to address two broad areas: (1) potential concepts of operations (mainly strike operations) and (2) resource requirements to achieve the proposed scenario. The methodology used in Harper's study offered a paradigm for scenario building and modeling in the present research to support a realistic combat model. More importantly, Harper's thesis necessitated the development of good MOEs, especially in a force-on-force scenario. Harper's study concluded with findings and results regarding these MOEs and identified the benefits of MUM-T, which provided improved lethality and survivability, and secured victory. Realistically, Harper's study concluded that the model was a representation for analysis and at no point was a prediction of results.

Regardless of the purpose of simulation and modeling or implementation, there is a need to ensure that the right platforms are selected to meet the operational profile of the user. Kilitci and Buyruk (2011) undertook a system approach to identify the best UGV suitable for the Turkish Ministry of National Defense (MND) by comparing requirements and existing capabilities of the UGVs of the Turkish MND. These requirements and capabilities such as weapon systems and protection helped support the UGV agent design for this study.

Beyond the technical specifications of UGVs in relation to the system requirements, to give credibility to the model, it is paramount to analyze the impacts of the operating environment and possible battle damage that would affect the performance of UGVs. Survivability is one major factor considering the increased complexities of the battlefield. Goh (2014) examined the system design of ground systems, MBTs in a defensive urban scenario, aiming to identify how the following factors contribute to survivability of the platform: (1) vulnerability reduction by passive and active protection; (2) introduction of sensors and mobility enhancements; (3) design factors for consideration; and (4) impacts of emerging technology. These factors would help enhance realism in assessing the protection capabilities of the UGV in a small-scale tactical scenario.

Babilot (2005) conducted a study to determine the effectiveness of a USMC distributed operations (DO) platoon in urban combat when compared to a traditional urban assault force. Babilot’s thesis studied the impact of the intricacies and complexities of terrain on combat operations.

With a variety of research objectives, these theses examined factors and parameters for their respective field of interest related to the combat capabilities and operating environment that would apply to MUM-T operations. As such, this thesis leverages their findings and conclusions to support system and model design in follow-on research.

C. MEASUREMENT OF EFFECTIVENESS OF THE INFANTRY FORCE

The final part of the literature review examines factors affecting the MOEs of the infantry force that will be integrated with MUM-T concepts. To support small arms development in the U.S. Army, Martin, Perez, and Peterman (2017) conducted a study to understand the factors affecting the effectiveness of infantry rifleman in a squad. The project focused on four key measures of performance: (1) lethality; (2) accuracy; (3) mobility; and (4) interoperability. The study concluded with four potential courses of action: (1) status quo; (2) change ammunition; (3) change weapon system; and (4) change weapon system and ammunition. As this thesis aims to study and address the effects of MUM-T on modernization and manpower constraints, the primary focus shall be on enhancing and studying the effects MUM-T on lethality.

Besides increased combat power and capabilities obtained through fire support from the MUM-T Unmanned Aerial System (UAS) concepts, Harper (2016) also illustrated the utility of enhancing the infantry troops' weapon arsenal. Based on his research, he recommended that the individual rifleman would ideally be equipped with at least 2 × rockets and missiles for the Multi-purpose Anti-armor Anti-personnel Weapon (MAAW) gunner and Javelin team, respectively, with each infantry squad equipped with 2 × OPF 1 class 1 systems. These enhancements would provide a probability of kill like that of a tank section (20 targets for a tank versus 16.2 targets for the infantry squad). The infantry squad is also far more mobile and survivable, which emphasizes the usefulness of MUM-T in the scenario. Hence, this advantage would be an important factor in shaping the parameters for modeling efforts in this thesis.

III. MODEL DESIGN

This chapter explains the key considerations for the development of the system model for this thesis. The discussion considers terrain, operational concepts, MOEs, agent characteristics, and model assumptions. It also highlights the key lessons learned during experimentation on the baseline model development, leading to the subsequent designs of experiment (DOE).

A. THE TERRAIN

The terrain of the model used to conduct the analysis in this thesis was adapted from a previous study on distributed operations in urban terrain (Babilot, 2005). The terrain is based on Operation Phantom Fury (commonly known as Operations Al-Fajr), which was a coalition effort led by the U.S. Marine Corps in Fallujah, Iraq, November to December 2004 (Luna, 2014).

With the data and experiences gained from the six weeks in Fallujah, many operational techniques, tactics, and procedures (TTP) could be learned and refined by the U.S. Army and Marine Corps. To enhance the learning modalities, a mock-up of the urban terrain of Fallujah was developed and built as a training facility for the U.S. Marine Corps in 2011 in Twenty-Nine Palms, California. The facility can support urban and coastal operations of up to 15,000 troops (Watson, 2011).

For this thesis, the terrain features of buildings and streets are the most important features in urban MUM-T operations. Hence, in terms of software modeling for this thesis, it is paramount that the terrain be precise to conduct useful operational analysis. To ensure the details of the actual terrain in Fallujah are modeled in accordance with the actual urban terrain, a satellite picture of the facility was obtained before the development of a three-dimensional (3D) model. The 3D model encompasses details necessary to model the urban battlespace accurately (buildings, streets, subterranean, and air), as shown in Figure 1.

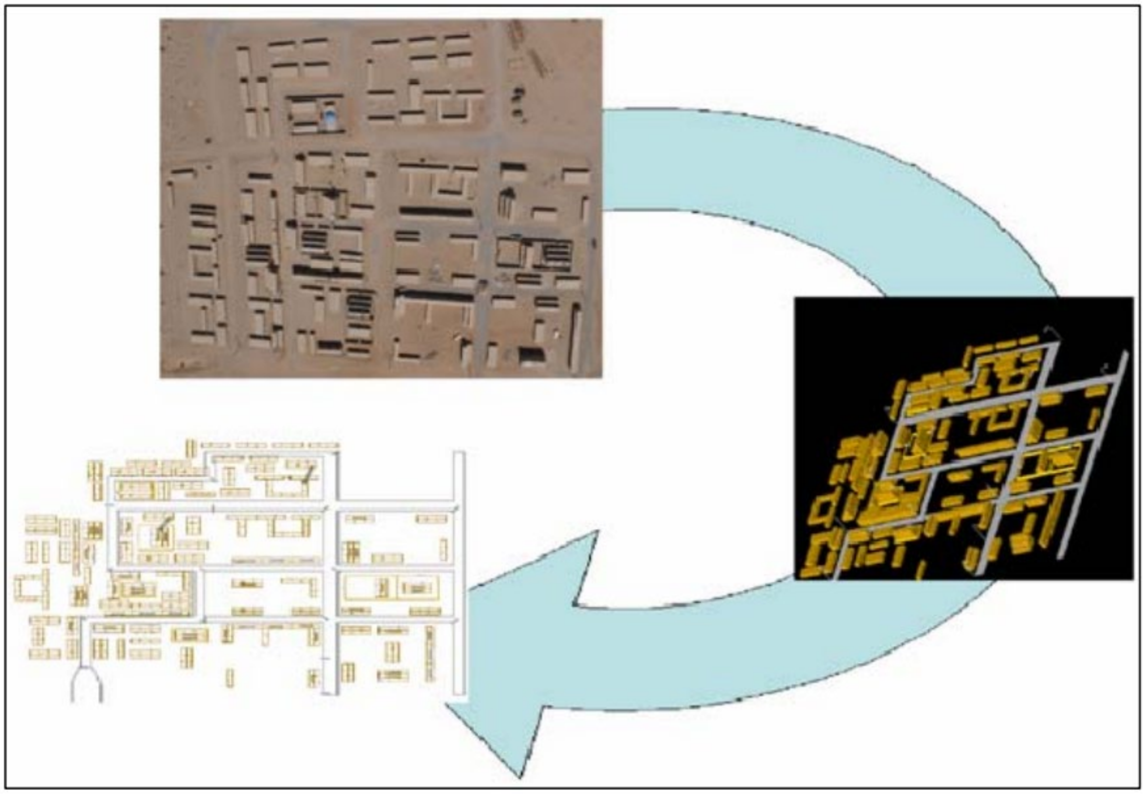

Figure 1. The Process of Obtaining the Software Model from 3D Modeling

B. OPERATIONAL SCENARIO

Current Situation. The Blue force has successfully secured the northern sector of the area of operations (AO). Intelligence updates suggest that sizeable Red forces have been spotted in the southern AO, particularly in the buildings overseeing the T-junction, which will allow them to project forces southwards. Hence, the commanding officer of the Blue force has tasked one of his companies to secure the southern sector and capture the foothold building to enable future operations.

Concept of Operations (CONOPs). The central idea is to conduct a north to south attack onto the southern sector to capture the foothold building and allow follow-on forces to safely project southwards, with the main effort coming from the northwest and supporting efforts from the north and northeast. Leveraging the blind spots and urban terrain to speedily project forces southwards, the commencement of a simultaneous assault on the surrounding buildings of the foothold is critical to enable a decisive fight at the terminal objective, which is shown in Figure 2. The capture of the foothold building intact shall remain necessary for post-conflict operations. The Blue force will be equipped with a UGV in support of its mission.

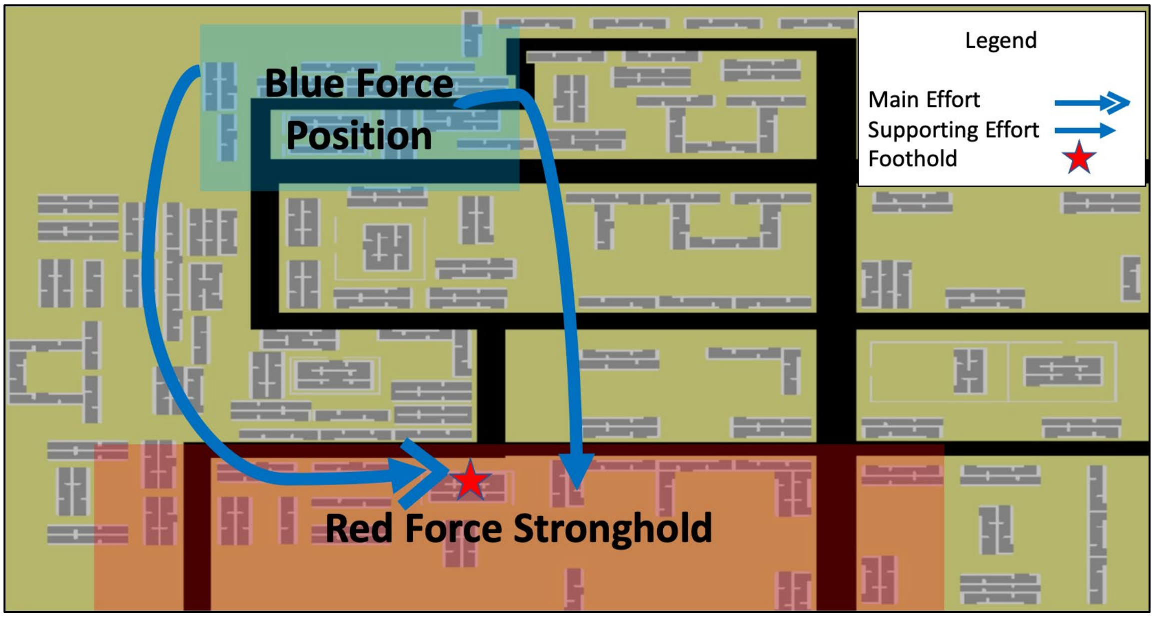

Figure 2. CONOPs of the Model Scenario

C. MEASURES OF EFFECTIVENESS AND OTHER CONSIDERATIONS

Prior to the development of the model, it is necessary to recapitulate the MOEs of the study and understand the operational context motivating these measures to: (1) draw relevant linkages to MANA model design and (2) ensure the operational analysis study would be useful. If the parameters or the end goals are not determined accurately, the results from the model will be irrelevant and unrealistic for analysis.

Four key MOEs have been identified for this study. These MOEs serve to draw operational linkages to the aim of the study to support future MUM-T CapDev efforts.

1. **Total number of Blue casualties (primary MOE)** – Assesses the survivability of the Blue force. In a military context, a ratio of 3:1 (known

as RCP highlighted earlier) is typically used as a benchmark to size the attacking force against the defending force. This is applied for this MOE to create an additional buffer for the attacking force to overcome the advantages that the defending force possesses (largely terrain familiarity and preparation).

2. **Total number of Red casualties** – Assesses the offensive capability or the lethality of the Blue force. In a military context, enemy soldiers killed are usually accounted for in small-units tactical fights to prepare for any counter-offensive actions or clearing of remaining enemy forces in critical terrain.

3. **Mission completion (Blue forces reaching the objective building)** – Assesses whether the Blue force reached its objective. In a military context, once a position or objective has been infiltrated or overrun by the opposing force, the objective would be deemed compromised unless reinforcements are sent to conduct a counteroffensive maneuver.

4. **Mission completion (time taken to achieve mission)** – Assesses the offensive capabilities of the Blue force to complete the mission within a stipulated time. In a military context, failing to meet the mission within the required time would likely render the mission a failure.

The MOEs used to determine the stop condition of the simulation are explained in Tables 1 and 2.

Table 1. Key MOEs with Stop Conditions to Determine Mission Success.

S/N	Key MOEs	Stop Conditions	Remarks
1	Blue Casualties (Primary)	More than 50% Blue Casualties	Mission Fail
2	Red Casualties	More than 75% Red Casualties	Mission Success
3	Mission Completion	Any Blue Agent's arrival at Foothold Building.	Mission Success
4		More than stipulated run time	Mission Fail

Table 2. Operational Context for the Definition of MOEs.

Operational Context
1. The Blue force will be unlikely to continue offensive operations upon 50% combat losses since the RCP of 3:1 for Blue force against Red force is no longer fulfilled.
2. At a 75% casualty rate for the Red force, the Blue force will eventually overwhelm Red's position in a matter of time, forcing the Red force to retreat.
3. Upon the Blue force occupying the foothold objective, the Red force will likely eventually be overwhelmed.

D. AGENT DESIGN

A series of experiments was conducted as part of the development of the baseline model, running tens of thousands of simulation runs to analyze the impact of agent characteristics and experiment factors on model outputs. To ensure that the model could run realistically with minimal interference, each agent "squad" (MANA terminology for a group of entities with the same physical and behavioral properties) was designed to represent four Blue soldiers, modeling a four-man team, and four Red soldiers, modeling a four-man aggressor team. The order of battle (ORBAT) for the scenario was an eightman squad, 24-man platoon. Other key parameters with the relevant operational considerations are shown in Table 3.

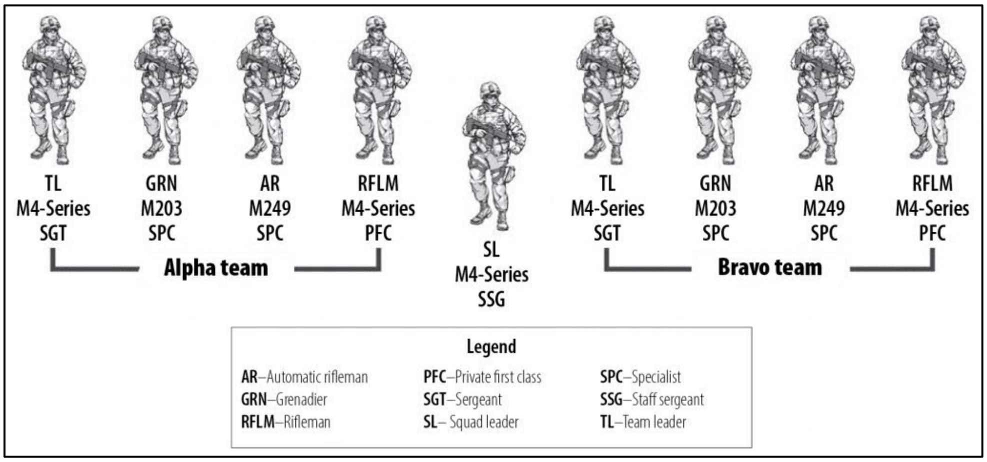

Figure 3. The Modern U.S. Rifle Squad. Source: Army Techniques Publication (2016).

Table 3. Key Parameters for Red and Blue Agents.

S/N	Parameters	Force	Type / Range	Remarks
1.	Weapon Systems	Blue	M4 Rifle	Organic Weapon System
		Red	AK 47	Simulated Aggressor Weapon System
2.	Weapon Performance	Blue	15 shots per second, up to 91% hit at 150 m	Baseline Weapon Data, Varied in DOE
		Red	15 shots per second, up to 90% hit at 150 m	Baseline Weapon Data, Varied in DOE
3.	Ammunitions	Blue	720 total, 180 for each soldier	6 Magazines of 30 Rounds
		Red	450 total, 90 for each soldier	3 Magazines of 30 Rounds
4.	Hits to Kill	Blue	2	Vulnerable to blind spots and fire bases in the urban battlefield
		Red	3	Sufficient battle preparation with terrain advantage

An initial experiment aimed to study the battle outcomes at the tactical level of a Blue platoon against a Red squad (24 against eight soldiers), as shown in Figure 4 and Table 4.

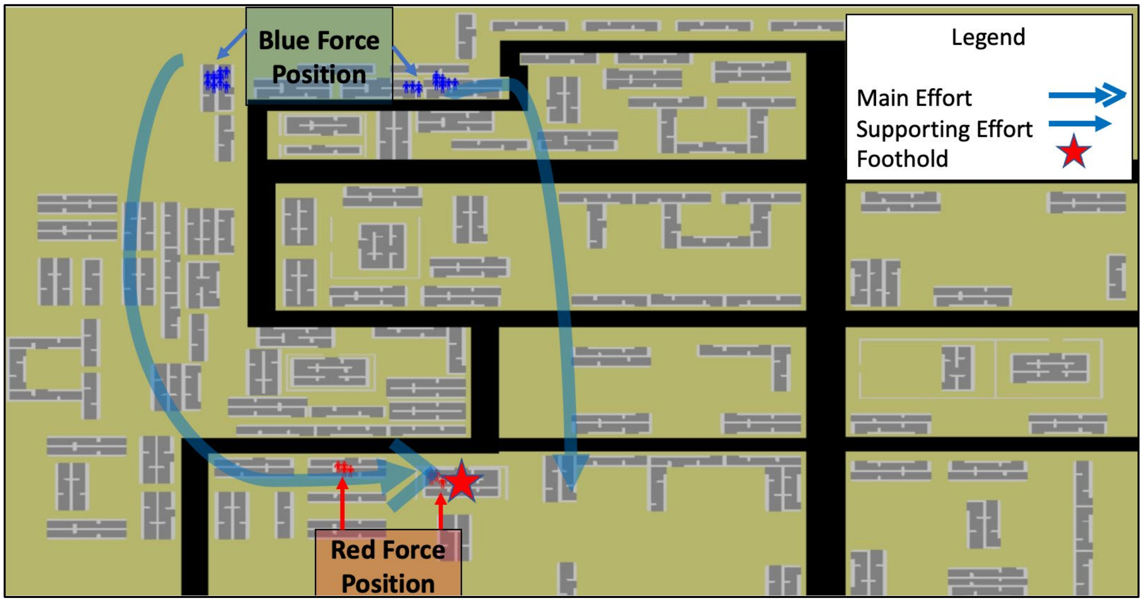

Figure 4. Initial Model (Platoon against Squad)

Table 4. Agent Characteristics of the Initial Model.

S/N	Force	Agent #	Remarks
1.	Blue	2, 3, 5, 6, 7, 8	Represent 6 × 4 Soldiers, 3 Squads of 2 Teams each, forming 1 Platoon.
2.	Red	1, 4	Represent 2 × 4 Soldiers, forming 1 Squad.

Upon completion of the development of the initial model, it was observed that an expansion of the project scope beyond the boundaries of a tactical scenario would help support a more robust and comprehensive study. Expanding the scenario would accommodate more DOE applications and enable a deeper understanding of a variety of factors. As such, the baseline model was revised and increased to the scale of a company-level offensive scenario against a platoon. The revised baseline model included additional Blue and Red forces distributed across the northern and southern AO, respectively, with no additional changes to the CONOPs.

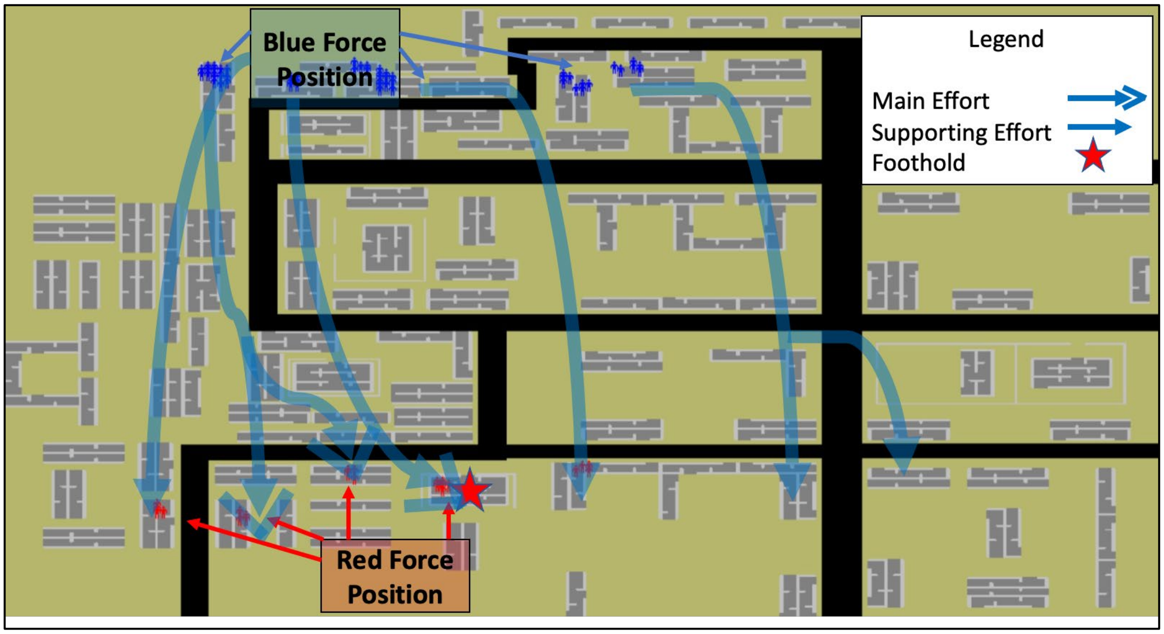

Figure 5. Revised Baseline Model (Company against Platoon)

The force composition of the baseline model after revision is shown in Table 5, with the associated comparison.

Table 5. Agent Characteristics of the Baseline Model.

S/N	Force	Agent #	Remarks
1.	Blue	2, 3, 5, 6, 7, 8, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24	Represent 18 × 4 Soldiers, 3 Platoons of 3 Squads each, forming 1 company.
2.	Red	1, 4, 9, 10, 11, 12	Represent 3 × Squads, forming 1 platoon.

E. ASSUMPTIONS AND KEY TAKEAWAYS

This section explains some of the assumptions made regarding doctrinal military operations considerations for the baseline model, including the key takeaways that led to the model design during the development of the initial model.

Table 6. Assumptions and Key Takeaways from the Baseline Model.

S/N	Assumptions and Key Takeaways
1.	**Direct and Indirect Fires**
	There are no agents designated for the purpose of direct and indirect fires. It is assumed that precision fire support operations had been completed prior to the commencement of the assault.
	Operational Consideration
	It is challenging to conduct simultaneous fire support operations in tandem with assault operations, especially in the same AO since the risks of fratricide is great and must be avoided. Furthermore, artillery operations should be minimized in urban terrain to minimize post-combat interference and restoration efforts, especially when the objective of the mission is to keep the foothold building intact.
2.	**Weapon Matching**
	The characteristics of the weapon systems for Blue and Red forces are the M4 and AK47 rifles, respectively, and serve as proxies for the actual weapon system. This proxy enables a balance in terms of combat power between Blue and Red. In the earlier stage of the baseline model's development, organic weapons such as grenade launchers and section automatic weapons were assigned to both the Blue and Red forces. However, due to the limitation and complexities of the simulation, the outcome of the simulation was heavily affected by the composition of weapon systems, resulting in an annihilation of the Red Force. To maintain equilibrium between both forces for studying the effects of MUM-T, there is a need to ensure minimum disruption. Hence, the baseline model was revised to equip both forces with only organic rifles.
	Operational Consideration
	An arming distance or elevated ground is necessary for successful deployment of any section organic assets, such as grenade launchers or anti-tank missiles. The AO lies within a complex and dense urban terrain with minimal open ground or views to gainfully employ these systems. Furthermore, intelligence did not pick up any armored elements, like AFVs or MBTs, and hence, there is little need for

S/N	Assumptions and Key Takeaways
	anti-tank capabilities since the buildings are to be captured intact. The precision fires conducted prior to the assault provided sufficient fire support.
3.	**Weapon Proxies**
	Whenever necessary, proxies can be used to represent weapon systems in specific scenarios to enhance realism in the simulation. Following the introduction of one light armored UGV as part of DOE #1, the Red forces in the vicinity of the foothold building would be able to target the UGV (Agent Squads 9 and 12 could target the UGV).
	Operational Consideration
	Taking into consideration the terrain features in the model, only Red forces in the foothold building are positioned to be able to target the UGV. As in typical urban battles, the foothold objective (usually a building with many floors) provides greater situation awareness for the setting up of firebases, observation posts, and anti-tank teams to enhance lethality.
4.	**Terrain Consideration**
	It is assumed that the Red forces (defender) would have sufficient time to conduct defense preparation, such as positioning and setting of obstacles. These would hinder the Blue force (attacker) assault, which is further amplified by the urban infrastructure. As a proxy, the model is designed to factor in the difficulty of killing Red forces (3 hits) compared to Blue forces (2 hits), signifying the terrain advantage.
	Operational Consideration
	Typically, the defender has the terrain advantage since they would be prepared and ready while waiting for attacker to commence their assault, which may or may not occur depending on the earlier phases of the fight. Doctrinally, even for hasty defense operations, the defender usually gains the advantage of being in a better position as compared to the attacker, who is venturing into the terrain while fulfilling their mission requirements.

F. CONCLUSION

The baseline model underwent significant modifications to fit the needs of the study while including realistic operational considerations through agent designs and proxies. In the next chapter, a series of DOEs is implemented in the simulation model to study the effects of varying different factors on the MOEs.

IV. DESIGN OF EXPERIMENT

This chapter explains the considerations behind the application of different DOEs to the baseline model, assesses the MOEs, and explains the chosen number of stochastic simulation replications per design point.

A. INTRODUCTION

The research is built on a series of experiments, each of which introduces factor (input variable) changes to the baseline model, designed to study the effects of varying different factors or performance criteria related to combat operations. A specified combination of these factor settings is a design point and a row in the design run matrix. In all, three DOEs were conducted, with emphasis on studying MUM-T Blue force offensive capabilities, MUM-T force structure design, while a comprehensive study encompassing other factors including survivability was also carried out. Each DOE considers and incorporates the results of the previous DOE(s). As such, DOE #1 and DOE #2 are more direct, varying one factor with two to four design points. DOE #3 considers the results from the previous DOEs, varies more factors (six), and utilizes a nearly orthogonal and balanced mixed design with 256 design points. Since MANA is a stochastic simulation, it was also necessary to determine the number of stochastic replications per design point required to credibly assess the effects of the factors.

B. DETERMINING THE IDEAL NUMBER OF RUNS PER DESIGN

The power equation (see Equation 1) was used to ensure the number of simulation replications would be sufficient to make a reasonable statement about the factor effects on the MOE, considering the inherent variability of the model. The notation includes the null hypothesis (μ_o), the alternative hypothesis (μ'), sigma (the standard deviation of the metric of interest), and Z values associated with desired levels of confidence and power (Thompson 2019). The minimum number of replications (sample size) per design point is then calculated by μ_o

$$\left(\frac{\sigma(Z_\alpha + Z_\beta)}{\mu_o - \mu'}\right)^2, \qquad (1)$$

where the respective factors are defined to be the following:

- n refers to the sample size and denotes the number of runs necessary to achieve the desired error rates given model variability.

- σ, refers to the standard deviation (Std Dev) of the response or MOE of interest, in our case, Blue casualties. A set of 1,000 replications was performed on the base case to determine the estimate of σ.

- Z_α refers to the Z value associated with 100×(1–α)% confidence, meaning only an α probability of making a Type I error (i.e., declaring a statistically significant effect where one does not exist).

- Z_β refers to the Z value associated with 100×(1–α)% power, meaning that there is only an β probability of a committing a Type II error (i.e., declaring no statistically significant effect when there is one).

- $\mu_o - \mu'$ refers to the practical difference or precision to be achieved (e.g., a one-soldier casualty difference would mean μ_o - μ' = 1). This accounts for every soldier casualty as part of the survivability MOE.

Table 7 summarizes the minimum and actual number of simulation runs for each of the DOE from #1 to #3, to account for model variability. The minimum was obtained using Equation (1). In all cases, more replications are made than the minimum required, providing additional precision.

Table 7. Comparison between Minimum and Actual Number of Simulation Runs for the Three DOEs.

DOE #	**σ (For Blue Casualties)**	**Z_α, Z_β**	$\mu_o - \mu'$	***n* (Minimum)**	***n* (Actual)**	**Remarks**
1	3.62	1.96, 1.65	1	171	1000	To account for model variability, the actual number of runs, *n*, for all 3 DOEs has to exceed the minimum number required.
2	3.17			131	200	
3	2.44			78	300	

The next three sections elaborate on the three DOEs and highlight the operational considerations behind each DOE.

C. DOE #1: ONE FACTOR WITH TWO LEVELS (TWO DESIGN POINTS) (MUM-T)

As highlighted previously, the thesis adopts an iterative approach to design the experiments, leveraging on the results and analyses of previous DOE(s). DOE #1 starts by studying one of the most important factors in this thesis: the effectiveness of MUM-T.

To examine the operational impacts of MUM-T, an UGV agent (Agent Squad #25) was introduced to the ORBAT of the Blue force. The UGV agent was modeled after a Gladiator Tactical Unmanned Ground Vehicle (TUGV) platform, a light armored, anti-personnel UGV equipped with a M240 Machine Gun. It has been an operational platform since 2004, supporting the U.S. Marine Corps during military operations (Turner 2019). Figure 6 and Table 8 provide a visual representation of the UGV CONOPs and a summary of specific changes made to the baseline model for DOE #1, respectively.

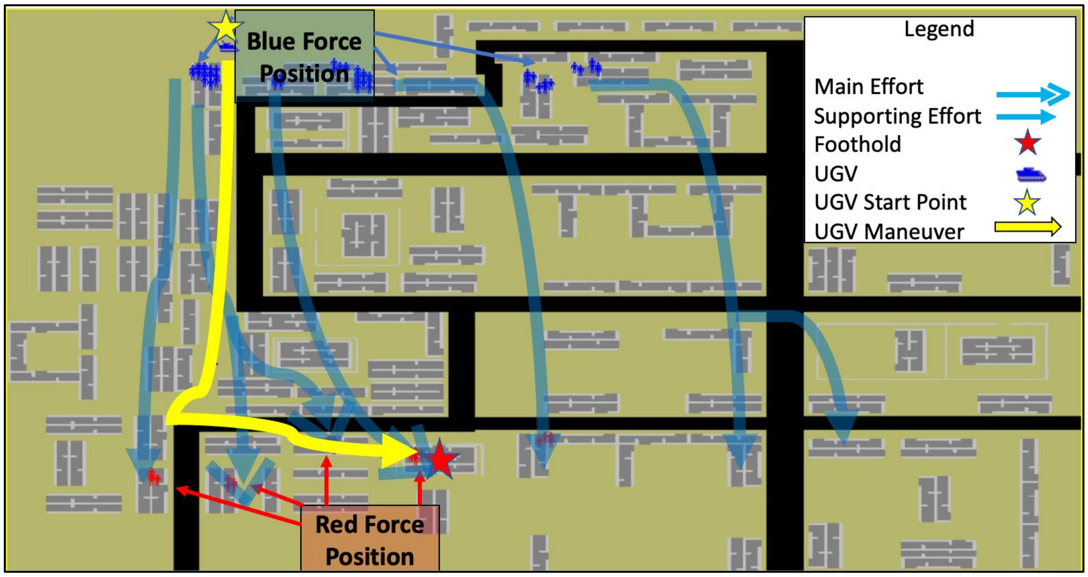

Figure 6. Scheme of Maneuver of the UGV for all Three DOEs

Table 8. Specifications for DOE #1.

Factor	**Design Point Number**	**Blue Force**	**Red Force**	**Operational Context**
UGV Present= No	**#1**	Baseline Model	Baseline Model	Baseline operations modeling infantry force-on-force urban operations
UGV Present= Yes	**#2**	Added 1 × UGV Agent (Squad #25) Maneuver from northwest to the southern AO toward the objective building, and **Agent squad #25 equipped with 7.62 mm weapon capabilities, Light Armour with 8 hits to kill**	Defense positions at foothold building able to conduct anti-tank operations **Agent squads #10 and #12 can target UGV**	Introduction of an UGV to Blue force to model MUM-T operation

Referencing Table 8, to analyze the effects of MUM-T, there were 2,000 simulated runs of combat operations for DOE #1, with 1,000 stochastic replications for each design point.

D. DOE #2: ONE FACTOR WITH FOUR LEVELS (FOUR DESIGN POINTS) (FORCE STRUCTURE)

Enhanced lethality through MUM-T examined in DOE #1 is only one of the areas of interest in the primary research questions. DOE #2 studies the effects on varying force structure through the revision of force allocation in each team.

To examine the operational impacts of the force structure study, the number of soldiers from every team of the Blue force was reduced and re-configured from four per team to one, two, and three per team. It is paramount to highlight that the primary goal of the experiments serves to test the extremities of the force structure study and that these experiments do not intend to support any claims of force reduction to reduce every team to one or two soldiers.

Table 9. Specifications of DOE #2.

Factor	Design Points	Blue Force	Red Force	Operational Context
Number of Soldiers	**#1**	Every Blue Agent reduces to 1 soldier	As per DOE #1	To study the effects on Blue force capabilities limited by the manpower reduction
	#2	Every Blue Agent reduces to 2 soldiers		
	#3	Every Blue Agent reduces to 3 soldiers		
	#4	As per DOE #1		

Referencing Table 9, 800 simulation runs of combat operations were performed for DOE #2, with 200 stochastic replications for each design point, to analyze the effects of force structure on combat capabilities.

E. DOE #3: NEARLY ORTHOGONAL AND BALANCED MIXED DESIGN WITH 256 DESIGN POINTS (MULTI-FACTOR)

After the analyses of DOE #1 and DOE #2 to study lethality and force structure were concluded, DOE #3 was formulated to provide a comprehensive design leveraging the insights from the results of those analyses. Hence, DOE #3 examines multiple factors related to lethality, force structure, and survivability, varying technical specifications such as weapon accuracy, reloading time, and armor penetration of the UGV.

To support this more comprehensive DOE to evaluate operational impacts, 256 design points were used to capture six of the operational factors in the model. Changes in these factors were associated with a brief description of the operational context to ensure the variations were logical and relevant in military operations. Table 10 highlights the summary of the changes for DOE #3, with an explanation of the operational logic behind the variations in design points.

Table 10. Summary of Changes for DOE #3.

ORBAT	Factor	DOE #1 Value	DOE #3 Value (s)	Number of Levels	Operational Context
Red Soldiers	**Probability of Hit (Phit)**	0.9 or 90% at 100 m	0.3–0.7 (Increments of 0.05)	9	Blind spots in urban terrain could pose challenges in human target acquisition; hence, 30% to 70% Phit may be more realistic
Blue Soldiers	**Phit**	0.91 or 91% at 100m	0.3–0.7 (Increments of 0.05)	9	
	Soldiers Per Team	4	1–4 (Increments of 1)	4	Extreme values to explore sensitivity

Blue UGV	**Phit**	0.95 or 95% at 100m	0.5–0.9 (Increments of 0.05)	9	While AI may support target acquisition in urban terrain, the enhanced accuracy of 50% to 90% may be more realistic, superior to manual target acquisition
	Hits to Kill	8	4–8 (Increments of 1)	5	Reducing the hits to kill would allow a fairer fight between Blue and Red forces
	Time Between Shots (Reloading)	1 second	5–15 (Increments of 1)	11	To account for automated weapon reloading and re-acquisition of target, a range of 5 to 15 seconds may be useful to evaluate defensive operations of Red forces

Combat operations are complex and often occur at the expense of precious lives and resources such as time and money. While combat simulations can be useful to approximate combat operations with minimal destruction to achieve resource savings, running combat simulations over changes in numerous factors and levels can become computationally expensive and unattainable beyond a certain threshold. For example, a full factorial DOE of two factors, with two levels each, would require four design points, while a full factorial of two factors, with six levels each, would require 36 design points. The exponential increase is further amplified as the number of factors or levels increases. Table 11 further describes the factors, levels for each, and total number of design points required for a full factorial. A total of 160,380 design points would be required. To run each design point for 300 stochastic replications each, a total of 48,114,000 simulated battles would be required. The completion of approximately 48 million stochastic replications would require many weeks of computation, and we therefore seek an effective and more efficient solution.

Table 11. Description of DOE #3.

Factor	**Low**	**High**	**Levels**	**Number of Levels**
Red Soldier Phit	0.3	0.7	.3, .35, .4, .45, .5, .55 .6, .65 .7	9
Blue Soldier Phit	0.3	0.7	.3, .35, .4, .45, .5, .55 .6, .65 .7	9
Blue Soldiers Per Team	1	4	1, 2, 3, 4	4
Blue UGV Phit	0.5	0.9	.5, .55, .6, .65, .7, .75, .8, .85, .9	9
Blue UGV Hits to Kill	4	8	4, 5, 6, 7, 8	5
Blue UGV Time Between Shots	5	15	5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15	11
Total Number of Design Points for a Full Factorial				160,380

The Nearly Orthogonal Latin Hypercube (NOLH) is a nearly orthogonal space-filling design developed by Cioppa and Lucas (2007) to conduct experiments efficiently. The NOLH design is superior compared to other design choices such as the fractional or full factorial in terms of orthogonality, efficiency, and space filling properties. Figure 7 compares the difference between the space filling properties of: (a) a fractional factorial design that tests at only two levels; (b) a full factorial that tests at four levels; (c) an NOLH design that tests at 17 levels with 17 design points; and (d) an NOLH design that tests at 257 levels with 257 design points.

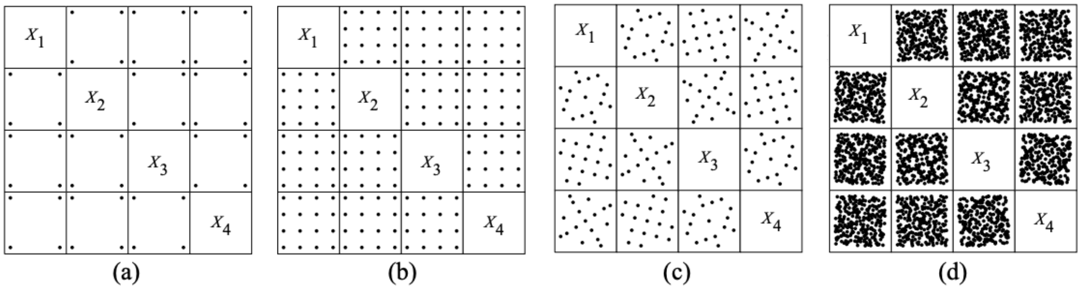

Figure 7. Comparison of Different Types of DOEs. Source: Sanchez and Wan (2015).

DOE #3 uses a design with similar properties and goals as the NOLH, but with more flexibility with respect to the types of factors in can handle. This design is called the NOB (Nearly Orthogonal and Balanced) mixed design. While the NOLH was designed for a set of continuous factors, the NOB design explicitly allows for a mix of factor types (continuous, discrete, and categorical) (Vieira et al. 2013). The use of the NOB allows DOE #3 to be conducted using only 256 design points. In total, 76,800 simulation runs of combat operations (300 stochastic replications for each design point) were executed to analyze the impact of the factors in DOE #3. Figure 8 presents the scatterplot matrix of the NOB design for DOE #3.

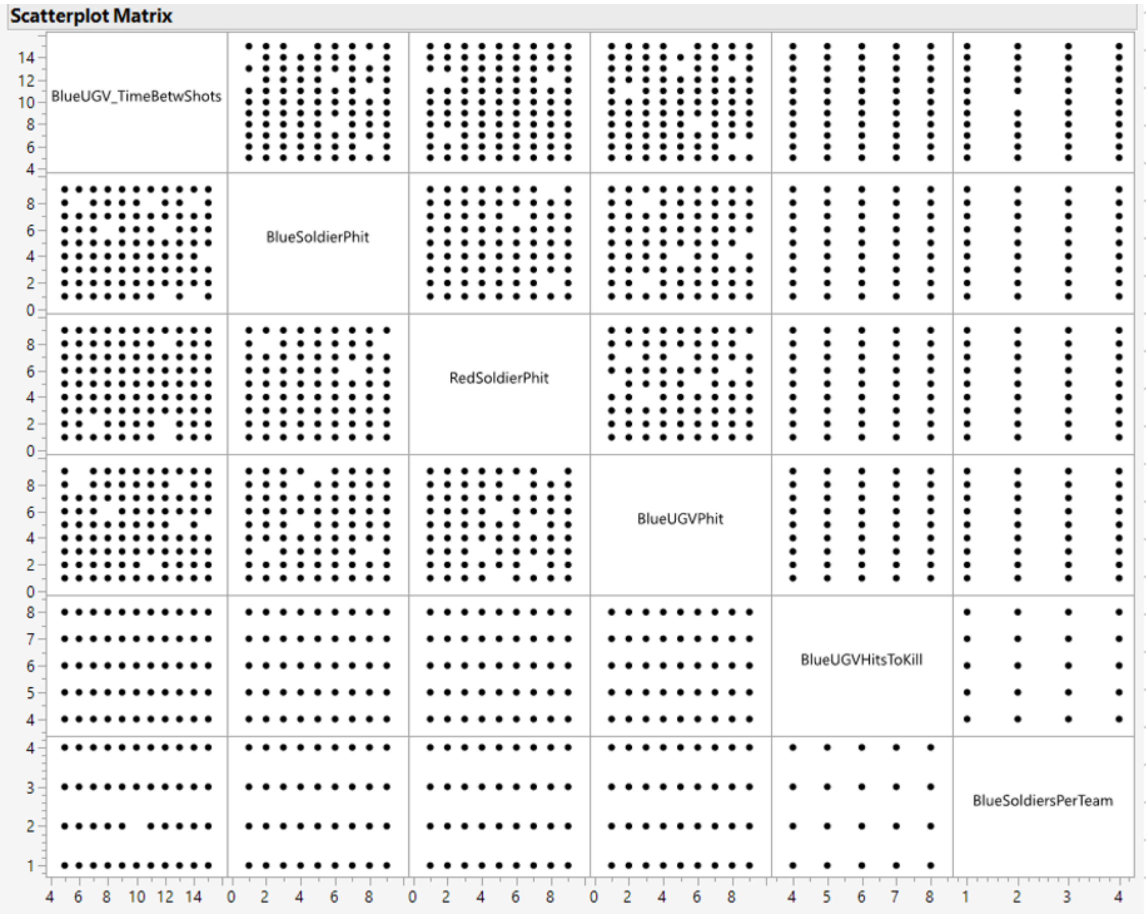

Figure 8. The NOB Scatterplot Matrix for DOE #3

F. CONCLUSION

This chapter has highlighted key operational considerations relevant to the rationale behind each DOE, with emphasis on how an iterative approach was used. It also explained the choices of design and number of stochastic replications to account for the inherent model variability. The next chapter examines the results and highlight operational insights obtained from 80,000 simulation battles.

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V. RESULTS AND ANALYSIS OF MODEL

This chapter analyzes the results obtained from the simulation runs from the three DOEs specified in Chapter IV. After an analysis of the results, this chapter concludes with key takeaways from the experiments. To draw linkages with military operations, the takeaways are associated with relevant operational scenarios.

Approximately 80,000 simulation runs were conducted for the combination of all three DOEs. To harvest the results obtained and draw operational insights to support future CapDev efforts, this research employed statistical and visual methods such as regression, interaction profilers, partition trees, histograms, summary statistics, and plots. It is important to note that more emphasis was placed on DOE #3 as it was more comprehensive and incorporated insights from the first two DOEs.

A. KEY FINDINGS FROM DOE #1: ASSESSING EFFECTS OF MUM-T

Three key insights were obtained from DOE #1, where an UGV was introduced to the Blue ORBAT to support offensive operations. Table 12 summarizes key insights from the model and assesses them from the military perspective. Figure 9 shows the histogram and summary statistics of the three key MOEs: Blue casualties, Red casualties, and time steps at the end of the operations for the baseline model (left) and DOE #1 (right). The number of time steps measures the battle's length, as each time step corresponds to one second.

Table 12. Key Findings from DOE #1: Baseline versus Addition of UGV.

S/N	Simulation Outcome and Operational Perspective
1.	**Enhancement to Blue Force’s Survivability**
	The introduction of the MUM-T saw a significant reduction in Blue force casualties and achieved greater consistency in terms of the results, with the Std Dev decreasing from 4.97 to 3.62 casualties compared to the baseline model. (Unit: Individual Soldier) **Maximum**: From 36 to 22 **Median**: From 19 to 8 **Mean**: From 19 to 8 (rounded to nearest soldier)
2.	**Enhancement to Blue Force’s Lethality**
	The introduction of the MUM-T saw a significant increase in Red force casualties compared to the baseline model. Of note, the minimum number of Red casualties increased from three to 11, supporting the argument that MUM-T is more lethal. (Unit: Individual Soldier) **Minimum:** From 3 to 11 **Maximum**: From 16 to 17 **Median**: From 11 to 16 **Mean**: From 11 to 16 (rounded to nearest soldier)
3.	**Mission Completion in a Shorter Time**
	The introduction of the MUM-T saw a significant decrease in mission completion time. Of note, there is a significant decrease of approximately 21% in terms of the time taken to complete the mission over the 1,000 simulated battles. (Unit: Seconds) **Minimum**: From 5,135 to 4,244 **Maximum**: From 30,000 to 7,605 **Median**: From 6,102.5 to 5,467

<table>
<tr><th>S/N</th><th>Simulation Outcome and Operational Perspective</th></tr>
<tr><td></td><td>Mean: From 6,909 to 5,467 (rounded to nearest second)

The results from the 1000 MUM-T replications also achieved greater consistency, with the Std Dev decreasing from 4,228 to 386 seconds.</td></tr>
<tr><td colspan="2">Operational Perspective</td></tr>
<tr><td colspan="2">The increase in survivability of the Blue forces is due to the enhanced offensive capabilities of MUM-T operations. The increased firepower with the UGV enables more Red forces to be attritted early and throughout the operations, reducing the threats to Blue forces. Red forces would also be compelled to take a more defensive approach when encountering the UGV since the terrain only allows the Red forces in the foothold building to target the UGV. Prioritizing the UGV as the target would also divide the attention on Blue soldiers.

The momentum gained by the Blue force would enable a swift and decisive fight toward the foothold objective, increasing the offensive effect of attriting more Red soldiers. Reinforced by the enhancement offensive capabilities, the overall attrition and casualties of the Blue force decrease while mission completion is achieved in a shorter period.
The overall increase in Red casualties and the reduction in Blue casualties and mission completion time significantly improved the combat capabilities of the Blue force.</td></tr>
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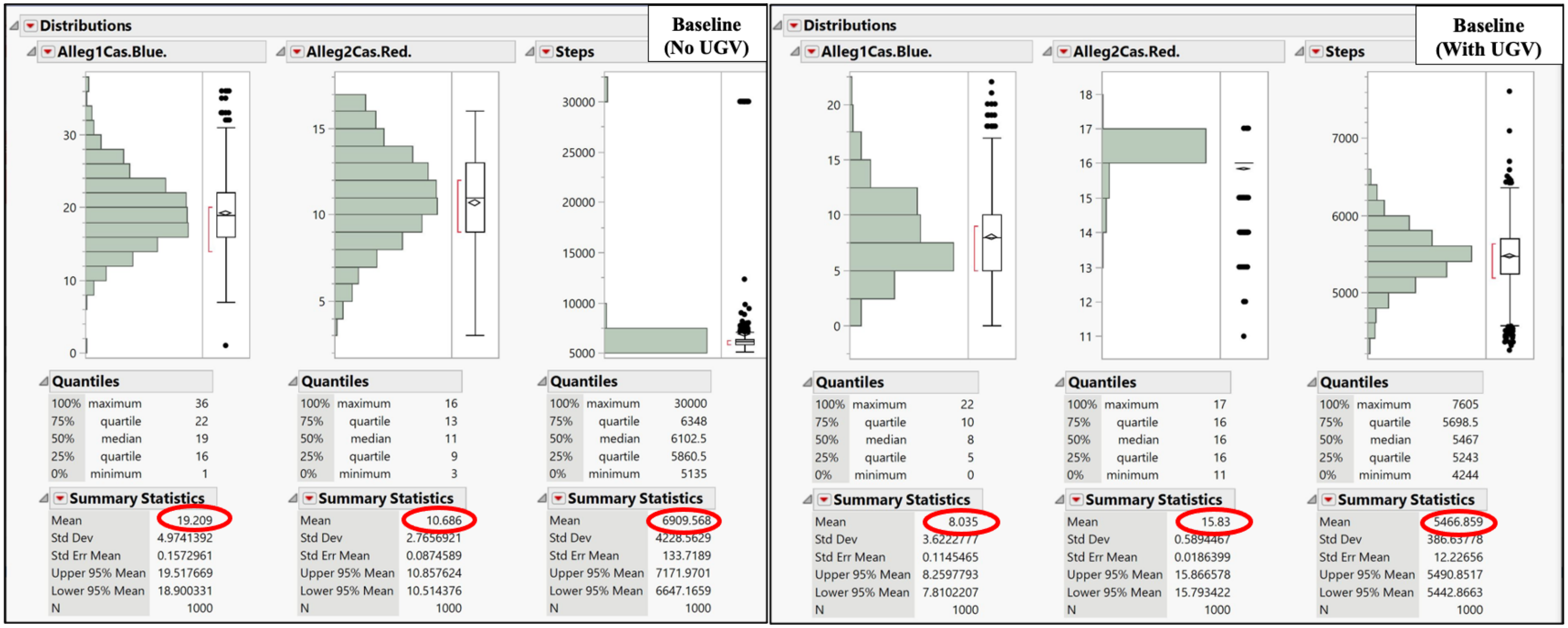


Baseline (No UGV)

Quantiles

		Alleg1Cas.Blue.	Alleg2Cas.Red.	Steps
100%	maximum	36	16	30000
75%	quartile	22	13	6348
50%	median	19	11	6102.5
25%	quartile	16	9	5860.5
0%	minimum	1	3	5135

Summary Statistics

	Alleg1Cas.Blue.	Alleg2Cas.Red.	Steps
Mean	19.209	10.686	6909.568
Std Dev	4.9741392	2.7656921	4228.5629
Std Err Mean	0.1572961	0.0874589	133.7189
Upper 95% Mean	19.517669	10.857624	7171.9701
Lower 95% Mean	18.900331	10.514376	6647.1659
N	1000	1000	1000

Baseline (With UGV)

Quantiles

		Alleg1Cas.Blue.	Alleg2Cas.Red.	Steps
100%	maximum	22	17	7605
75%	quartile	10	16	5698.5
50%	median	8	16	5467
25%	quartile	5	16	5243
0%	minimum	0	11	4244

Summary Statistics

	Alleg1Cas.Blue.	Alleg2Cas.Red.	Steps
Mean	8.035	15.83	5466.859
Std Dev	3.6222777	0.5894467	386.63778
Std Err Mean	0.1145465	0.0186399	12.22656
Upper 95% Mean	8.2597793	15.866578	5490.8517
Lower 95% Mean	7.8102207	15.793422	5442.8663
N	1000	1000	1000

Figure 9. Comparison of Distribution of MOEs for DOE #1. Baseline No UGV (left) and With UGV (right)

B. KEY FINDINGS FROM DOE #2: ASSESSING EFFECTS OF FORCE STRUCTURE

Three key observations were obtained from DOE #2, which varied the number of soldiers conducting offensive operations in each team from one to four. Table 13 summarized the key insights from the model and assesses them from the military perspective. Figures 10 through 12 show the box plots of the three key MOEs: Blue casualties, Red casualties, and time steps to reach the stop condition.

Table 13. Key Findings from DOE #2.

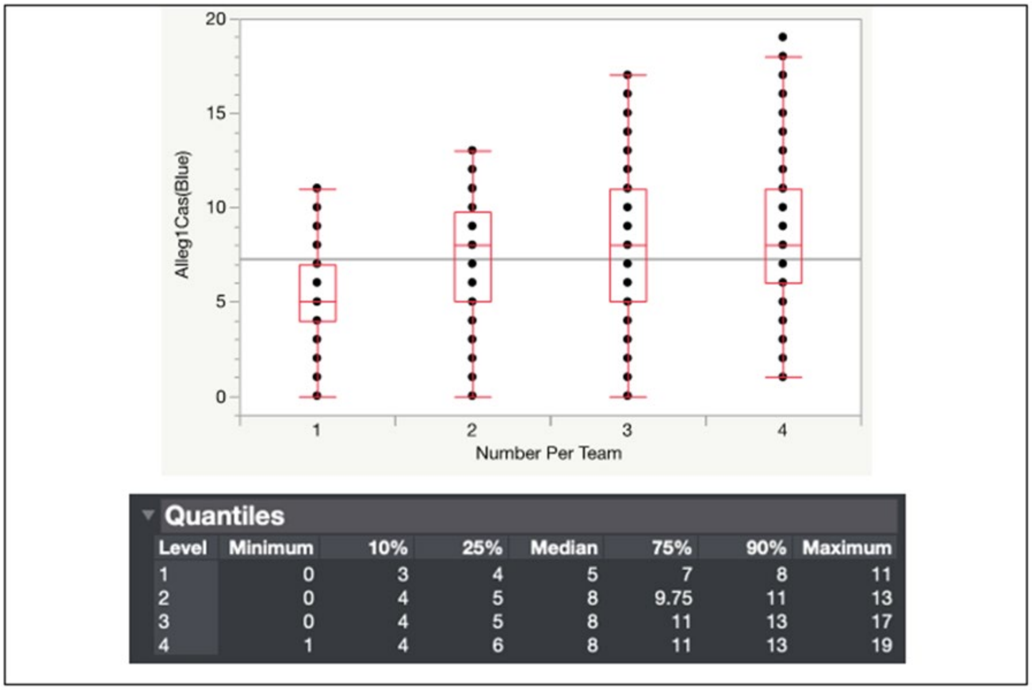
S/N	Simulation Outcome and Operational Perspective
1.	**Vulnerability in Urban Warfare.**
	Based on the results for DOE #2, shown in Figure 10, there is clearly an upward trend in the number of Blue casualties with increases in force size. The maximum number of Blue casualties increased by at least two for every soldier added into each team. The maximum increases from 11 to 19. Intuitively, more Blue soldiers (i.e., targets) have the potential to be more Blue casualties.
2.	**Strength in Numbers**
	Increasing the number of Blue soldiers in each team enhanced the firepower of the Blue force, resulting in an overall increase in Red casualties. It is noted that the effect on Red casualties reaches the "knee in the curve" when the number of soldiers per Blue team is two since the median and upper quartile display similar characteristics for two, three, and four soldiers for every Blue team. This highlights that having more than two Blue soldiers per team corresponds with the 25th percentile for killing all Red soldiers. Essentially, this shows that two soldiers per team is sufficient to attrite greater than 90% of the Red force, on average.
3.	**Similarities in Mission Completion Time**
	Operationally, having more Blue soldiers would provide greater firepower and lethality, which theoretically results in shorter mission completion. This is evident

<table>
<tr><th>S/N</th><th>Simulation Outcome and Operational Perspective</th></tr>
<tr><td></td><td>in Figure 12, where there is greater consistency in shorter mission completion time as the number of soldiers increases per team (e.g., 5,440 seconds to complete the mission when there are four soldiers in each team compared to approximately ~6,000 seconds with one soldier in every team). However, the differences in median time taken for mission completion is deemed not practically significant as the number of soldiers is increased to two, three, and four soldiers in each team. There is only a 2.5% difference from the shortest duration of 5,440 seconds compared to 5,580 seconds, an approximate difference of two minutes for the duration of the combat operations. This is an important finding since the increase of two soldiers per team is a significant resource commitment as opposed to the time savings of two minutes.</td></tr>
<tr><th colspan="2">Operational Perspective</th></tr>
<tr><td colspan="2">The motivating factor behind the study on force structure was the effect on capabilities given the constraints of manpower availability. While the introduction of an UGV serves to push power to the front lines, it also serves to determine whether the same combat operations can be accomplished when facing reductions in manpower.

Theoretically, having more soldiers would mean increased firepower in terms of combat capabilities, which would cause greater damage (increased enemy casualties) in every combat scenario. This was shown in Figure 11, where there was a clear upward trend in Red casualties as the number of Blue soldiers was increased. However, results from DOE #2 also showed that Red casualties leveled off at two soldiers per team. For three or four soldiers in every Blue team, the number of Red soldiers attritted did not increase significantly. One reason could be due to the enhanced firepower provided by the UGV, which already caused significant damage to the Red force in the earlier phases of the operations.

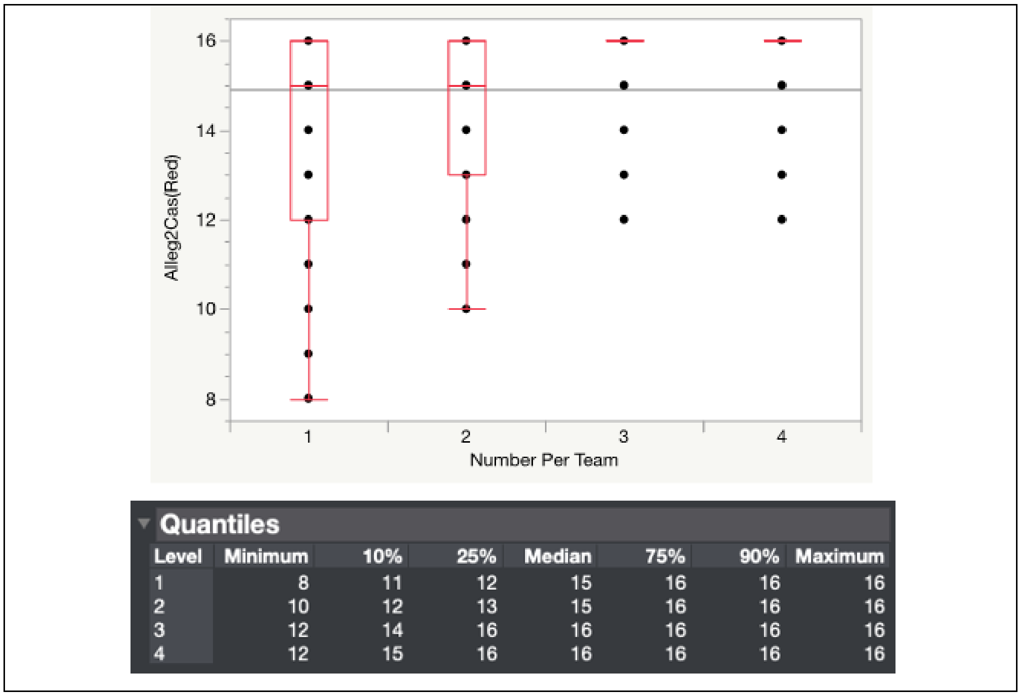
A similar trend was observed in the mission completion time, which showed no practically significant difference in mission completion time for two, three, and four soldiers. The UGV as part of the MUM-T, being the point element of the Blue force,</td></tr>
</table>

S/N	Simulation Outcome and Operational Perspective
would have engaged many more Red forces as it was advancing toward the foothold building. This enabled the Blue force to advance more quickly in the AO, reducing overall mission time. One counter-intuitive finding was observed from DOE #2: the number of Blue casualties that increased with every increase in the number of Blue soldiers per team. This goes against the expectation that increasing lethality leads to more Red casualties, which leads to more Blue soldiers surviving. One main reason for this discrepancy could be due to the terrain features of the AO. With an overwhelming size force (more than the terrain cap or RCP), Blue soldiers may be more susceptible to attacks since the number of targets for the Red force is increased. This is a paramount concern since the life of every soldier counts and must be accounted for. One proposal to overcome the susceptibility would be a change in tactics, where sending reinforcements in smaller groups would help overcome the limitations of the terrain cap. To conclude the analysis for DOE #2, the overall increase in Red casualties and mission completion time has been shown to significantly improve the combat capabilities of the Blue force.	



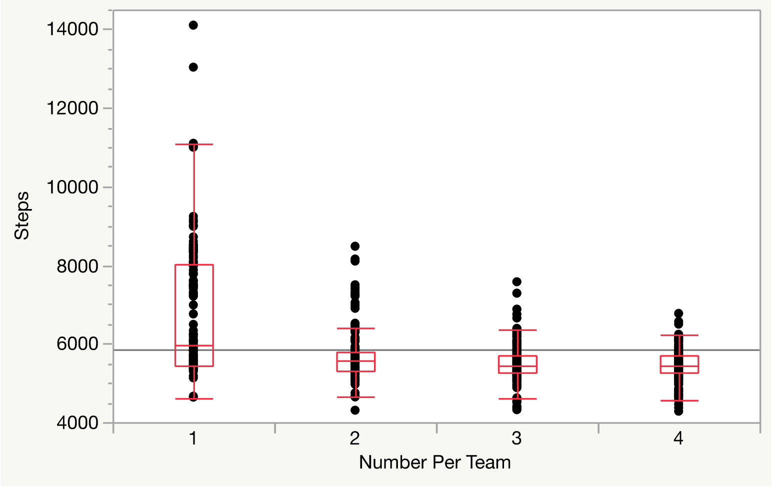
Level	Minimum	10%	25%	Median	75%	90%	Maximum
1	0	3	4	5	7	8	11
2	0	4	5	8	9.75	11	13
3	0	4	5	8	11	13	17
4	1	4	6	8	11	13	19

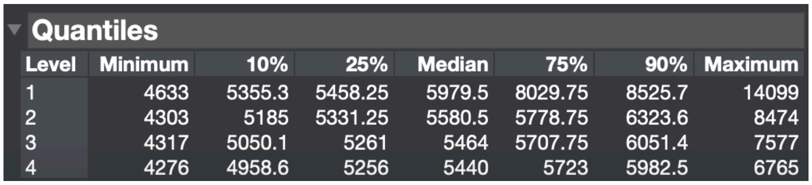
Figure 10. Boxplots and Summary Statistics for Blue Casualties versus Number of Soldiers per Team



Level	Minimum	10%	25%	Median	75%	90%	Maximum
1	8	11	12	15	16	16	16
2	10	12	13	15	16	16	16
3	12	14	16	16	16	16	16
4	12	15	16	16	16	16	16

Figure 11. Boxplots and Summary Statistics for Red Casualties versus Number of Soldiers per Team



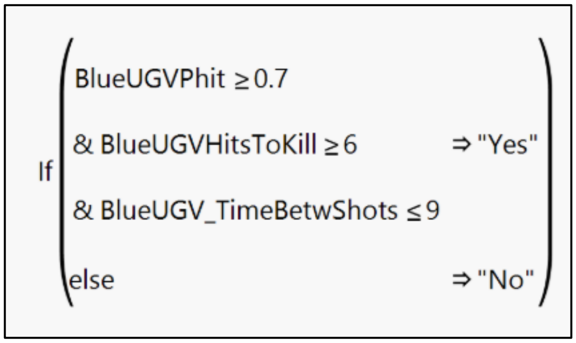


Level	Minimum	10%	25%	Median	75%	90%	Maximum
1	4633	5355.3	5458.25	5979.5	8029.75	8525.7	14099
2	4303	5185	5331.25	5580.5	5778.75	6323.6	8474
3	4317	5050.1	5261	5464	5707.75	6051.4	7577
4	4276	4958.6	5256	5440	5723	5982.5	6765

Figure 12. Boxplots and Summary Statistics for Time Steps versus Number of Soldiers per Team

C. KEY FINDINGS OF DOE #3: MULTI-FACTOR NOB DESIGN

In DOE #3, the features of the UGV were varied to simulate the effects of different technical capabilities. To better support the key findings of DOE #3, a new indicator variable was created. The variable, named ‘HigherCapabilityUGV,’ is defined to be a more powerful and protected UGV (shown in Figure 13) comprising all three capabilities as follows: (1) Phit or accuracy of at least 0.7 (to define UGV weapon accuracy); (2) the ability to take at least six hits from the Red force (to define survivability); and (3) a reloading time of nine seconds or less (to define UGV lethality). A “Yes” value denotes that the UGV fulfills all three criteria and is classified as a ‘HigherCapabilityUGV’; otherwise, it receives a value of “No.” The variable takes the mid-point of all three capabilities as a benchmark to classify cases where the Blue force is equipped with a more capable UGV with improved performance, as compared to the Blue force operating with a less capable UGV.



$$\text{If}\begin{pmatrix} \text{BlueUGVPhit} \geq 0.7 & \\ \&\ \text{BlueUGVHitsToKill} \geq 6 & \Rightarrow \text{"Yes"} \\ \&\ \text{BlueUGV\_TimeBetwShots} \leq 9 & \\ \text{else} & \Rightarrow \text{"No"} \end{pmatrix}$$

Figure 13. Definition of the New Indicator Variable: “HigherUGVCapability”

Another new metric, the loss exchange ratio (LER) was also introduced in this section. LER, shown in Equation (2), is simply the ratio of Red casualties to Blue casualties, where 1 is added to the denominator to protect against division by zero. A higher LER value equates to a more ideal combat outcome for the Blue force.

$$\text{Loss Exchange Ratio, LER} = \left(\frac{\text{Red casualties}}{\text{Blue casualties} + 1}\right) \tag{2}$$

The analysis of the results is conducted using regression analysis, interpretation of the regression profilers, partition tree analysis, and graphical displays.

Regression Analysis

Figure 14 shows the predicted plots of regression analysis conducted on both Blue casualties (left) and Red casualties (right) as a function of the experiment factors. It is observed that the RSquared values for both regression models are high, indicating that at least 99% and 96% of the variation can be explained by the fitted regression models, respectively. Visually, there are no extreme outlier data points, and most of the data points fall within proximity of the best fit model.

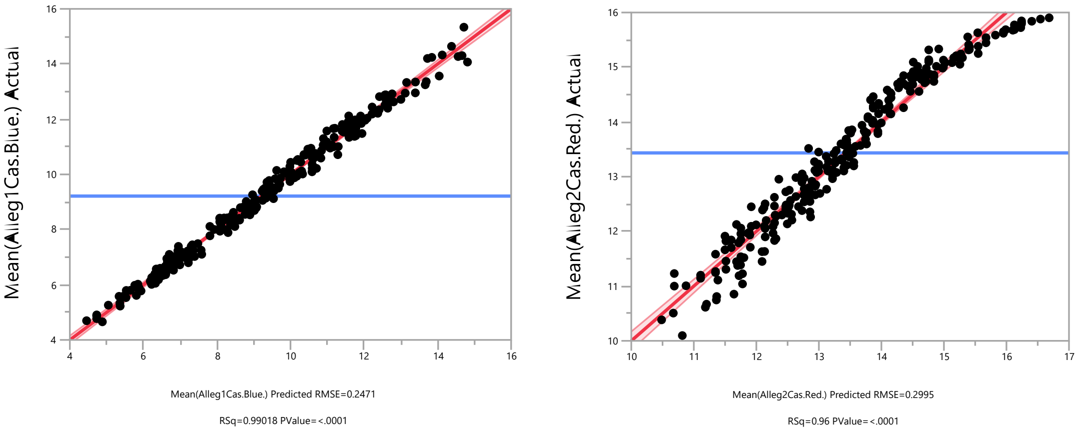
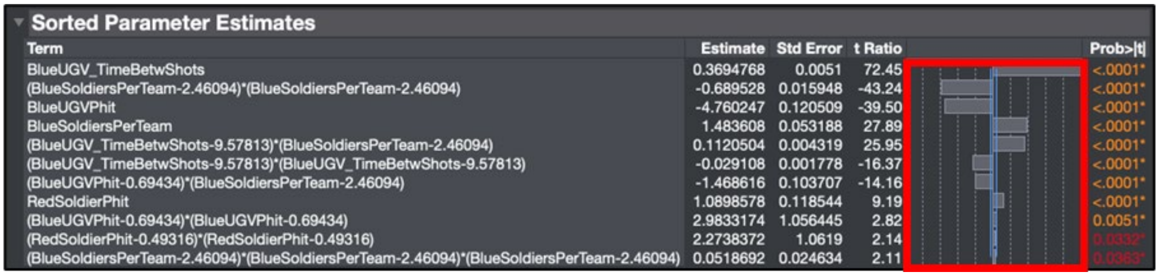


Figure 14. Predicted Plots for Regression Models for Mean Blue (left) and Red (right) Casualties

Parameter Estimates and Prediction Profilers (Mean Blue & Red Casualties)

The tornado plot in Figure 15 highlights the relative strength of different factors with the UGV time between shots (commonly referred to as reloading time) as the most significant factor for Mean Blue Casualties. A total of four main effects from, in order of significance, UGV Reloading Time, UGV Phit, Blue Team Size, and Red Team Phit, as well as a few quadratic terms and two-way interactions are observed as significant predictors. This is supported by the prediction profiler, shown in Figure 16, which provides a visual reference of the influence of the main effects on the response.


Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
BlueUGV_TimeBetwShots	0.3694768	0.0051	72.45	<.0001*
(BlueSoldiersPerTeam-2.46094)*(BlueSoldiersPerTeam-2.46094)	-0.689528	0.015948	-43.24	<.0001*
BlueUGVPhit	-4.760247	0.120509	-39.50	<.0001*
BlueSoldiersPerTeam	1.483608	0.053188	27.89	<.0001*
(BlueUGV_TimeBetwShots-9.57813)*(BlueSoldiersPerTeam-2.46094)	0.1120504	0.004319	25.95	<.0001*
(BlueUGV_TimeBetwShots-9.57813)*(BlueUGV_TimeBetwShots-9.57813)	-0.029108	0.001778	-16.37	<.0001*
(BlueUGVPhit-0.69434)*(BlueSoldiersPerTeam-2.46094)	-1.468616	0.103707	-14.16	<.0001*
RedSoldierPhit	1.0898578	0.118544	9.19	<.0001*
(BlueUGVPhit-0.69434)*(BlueUGVPhit-0.69434)	2.9833174	1.056445	2.82	0.0051*
(RedSoldierPhit-0.49316)*(RedSoldierPhit-0.49316)	2.2738372	1.0619	2.14	0.0332*
(BlueSoldiersPerTeam-2.46094)*(BlueSoldiersPerTeam-2.46094)*(BlueSoldiersPerTeam-2.46094)	0.0518692	0.024634	2.11	0.0363*

Figure 15. Sorted Parameter Estimates for Regression Fit to Mean Blue Casualties

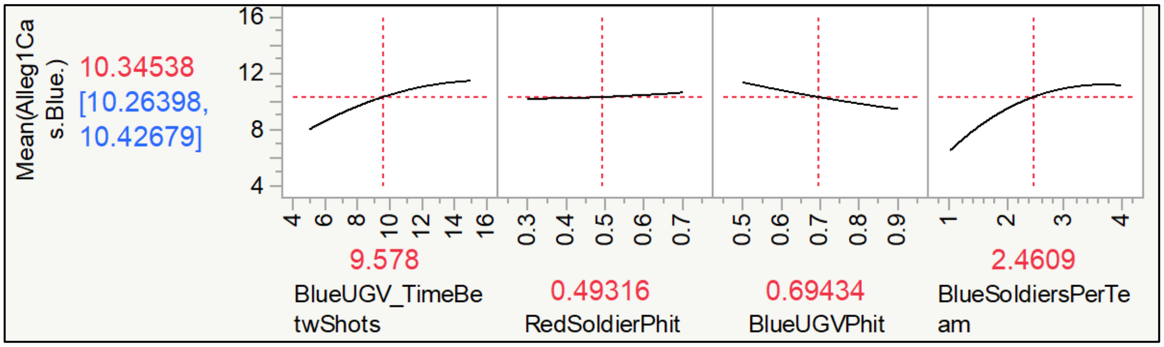
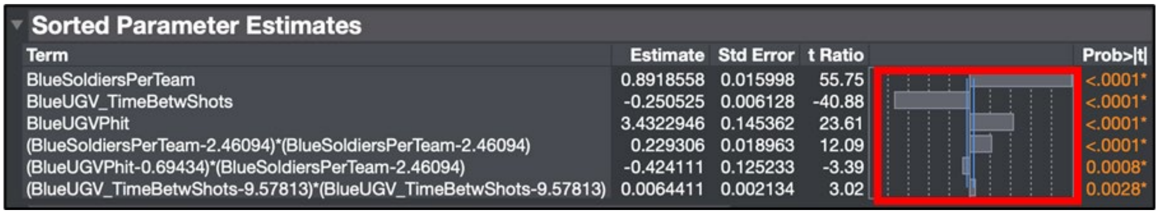


Figure 16. Prediction Profiler for Main Effects of Regression Fit to Mean Blue Casualties

Similarly, Figure 17 shows the relative strength of different factors, with the UGV time between shots (commonly referred to as reloading time) as the most significant factor for the mean Red casualties. A total of three main effects of, in order of significance, UGV Reloading Time, UGV Phit, Blue Team Size, and a few two-way interactions were observed. This is supported by the prediction profiler, shown in Figure 18, which provides a visual reference of the influence of the main effects on the response.



Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
BlueSoldiersPerTeam	0.8918558	0.015998	55.75		<.0001*
BlueUGV_TimeBetwShots	-0.250525	0.006128	-40.88		<.0001*
BlueUGVPhit	3.4322946	0.145362	23.61		<.0001*
(BlueSoldiersPerTeam-2.46094)*(BlueSoldiersPerTeam-2.46094)	0.229306	0.018963	12.09		<.0001*
(BlueUGVPhit-0.69434)*(BlueSoldiersPerTeam-2.46094)	-0.424111	0.125233	-3.39		0.0008*
(BlueUGV_TimeBetwShots-9.57813)*(BlueUGV_TimeBetwShots-9.57813)	0.0064411	0.002134	3.02		0.0028*

Figure 17. Sorted Parameter Estimates for Regression Fit to Mean Red Casualties

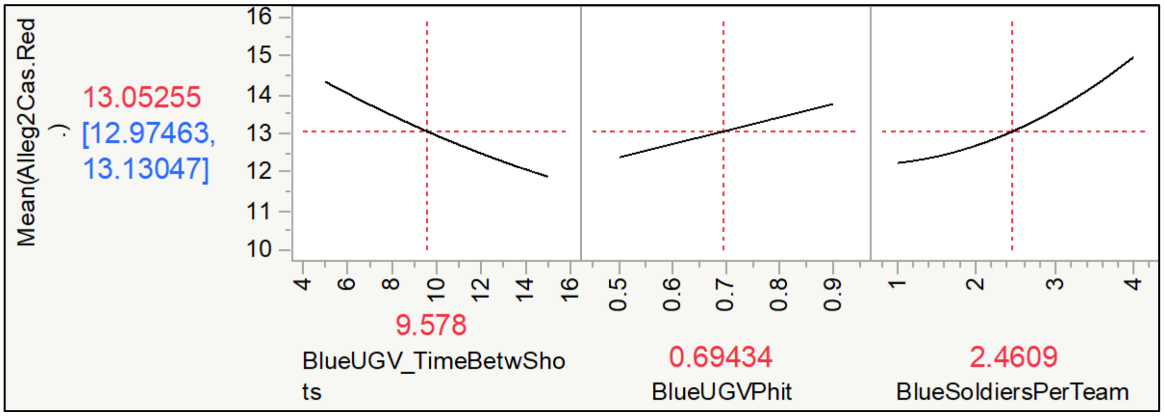


Figure 18. Prediction Profiler for Main Effects of Regression Fit to Mean Red Casualties

Interaction Profile (Mean Blue Casualties)

Figure 19 shows the interactions among a few of the factors for the regression model fit to Blue casualties. Of note, there are two key findings.

1. **Reloading Time & Number of Blue Soldiers**: An UGV with a longer reloading time and an increased number of Blue soldiers per team results in more Blue casualties. This is logical since the delay during UGV reloading means a reduction in firepower, increasing the Blue casualties from eight to 13 soldiers when there are four soldiers in each Blue team. The increase in Blue soldiers per team would also result in the amplification of Blue casualties when coupled with the longer UGV reloading time; Blue casualties increase from seven (one soldier per team) to 14 (four soldiers per team) when the reloading time is 16 seconds, likely influenced by the susceptibility of the urban terrain.

2. **UGV Weapon Accuracy & Number of Blue Soldiers**: An UGV that is less accurate (assessed by low Phit) coupled with the increased force size of the Blue soldiers results in more Blue casualties. This is logical since an

UGV that is less accurate would be unable to destroy Red forces as effectively, increasing the overall risk to Blue soldiers. Additionally, an important takeaway from an interaction plot is how the slope of the impact of one factor changes as a function of the other effect in an interaction. For example, looking at the plot in the last row, third from the left, it is apparent that the impact of increased Phit is much greater as the number of soldiers per team increases. However, it is noted that this point does not take into consideration the effect on Red casualties.

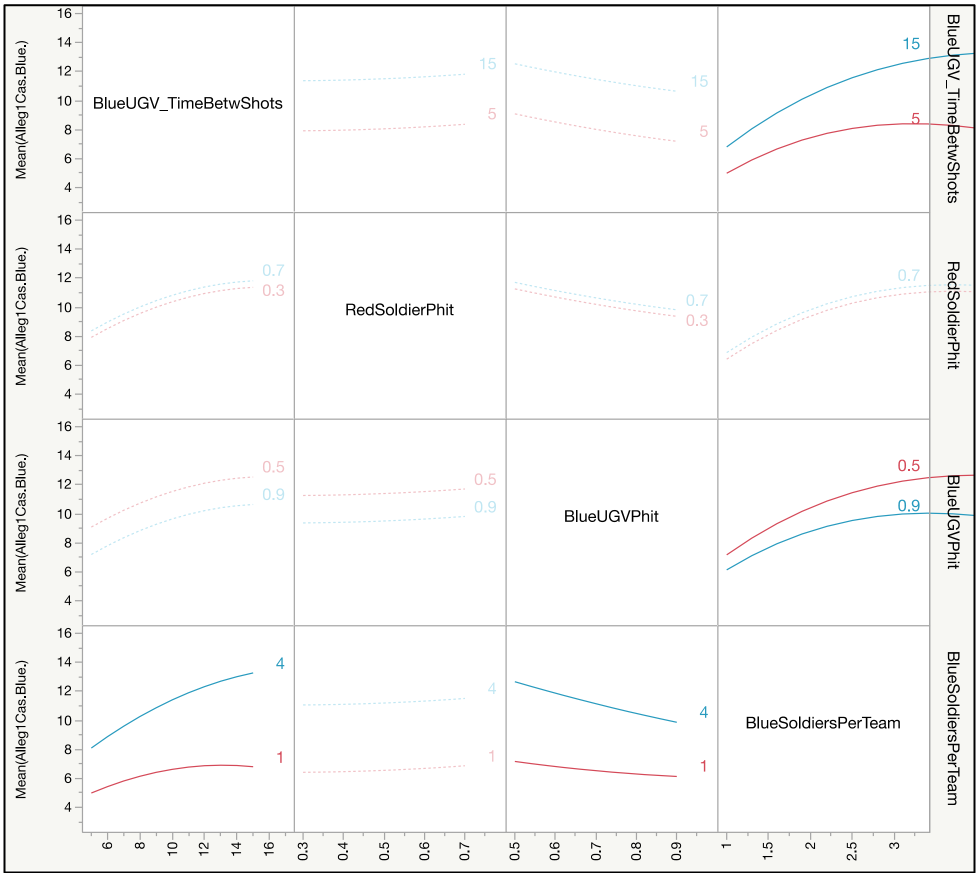


Figure 19. Interaction between Factors Affecting Mean Blue Casualties

Plot of Metrics versus HigherCapabilityUGV and Number of Blue Soldiers per Team

To complement the findings from the regressions, and to seek further insight into how increasing the number of Blue soldiers per team affects Blue survivability, a graphical representation of three metrics versus UGV capabilities and number of Blue soldiers per team is shown in Figure 20. This chart illustrates the effects of the MUM-T on: (1) mean Red casualties in (colored in red); (2) mean Blue casualties (colored in blue); and (3) time steps to complete the mission (colored in green). Three findings were obtained and are summarized in Table 14 with corresponding operational perspectives.

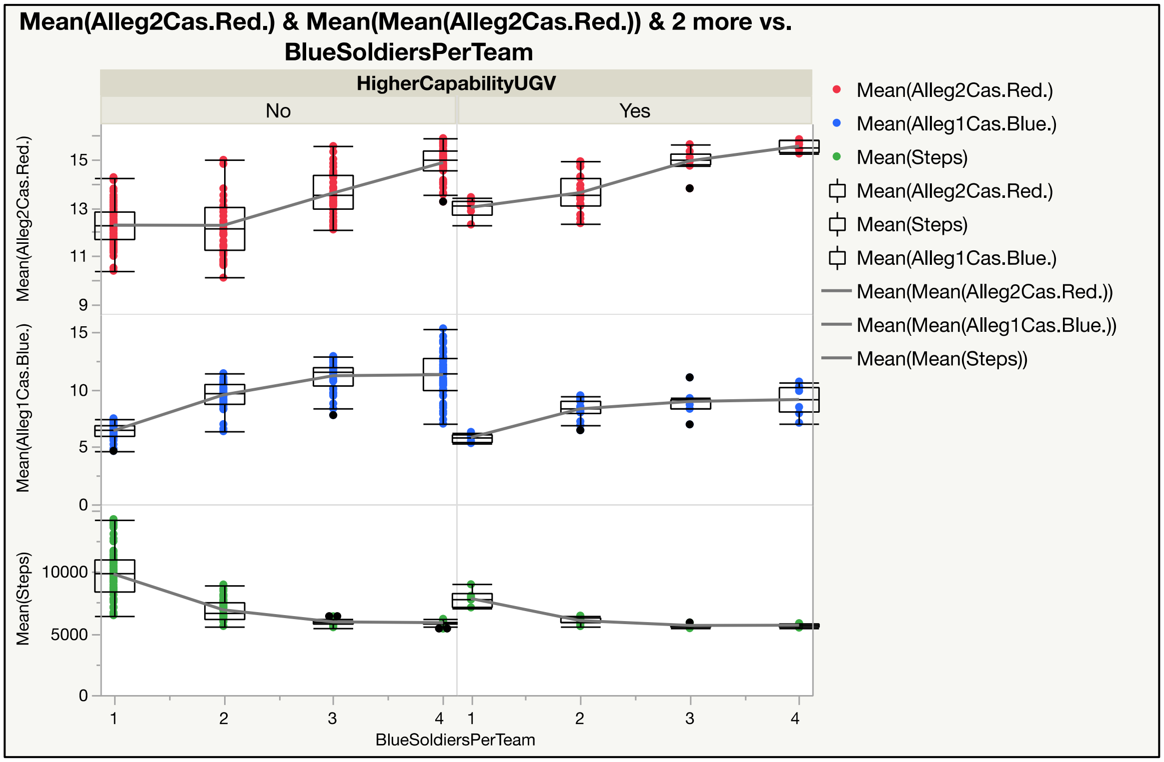


Figure 20. Graphs of MOEs versus UGV Capability and BlueSoldiersPerTeam

Table 14. Key Findings from DOE #3.

S/N	Simulation Outcome and Operational Perspective
1.	**Improvement in UGV Enhances Lethality**
	With a more capable UGV, the lethality of the Blue force is enhanced, increasing the overall number of Red soldiers killed throughout the mission. It is observed that coupled with the force structure of the Blue force, an increase in Blue soldiers per team results in increased Red casualties, and further, a team size of four Blue soldiers equipped with such a UGV would achieve an average of 15 to 16 Red casualties every battle. Additionally, the combination of a more capable UGV and additional Blue soldiers per team reduces variability. The differences between minimum and maximum values were much smaller when the Blue force was equipped with a capable UGV. This improvement in consistency further reinforces the improved capability of the Blue force.
2.	**More Does Not Always Mean Better**
	An increasing trend in Blue casualties was observed as the number of soldiers per team was increased beyond one per team. However, the increase in Blue team size also saw a significant increase in Red casualties and a shorter mission completion time. When mission completion is prioritized, Blue casualties can be reduced or mitigated by equipping the Blue force with a more capable UGV, changing tactics or equipment.
3.	**Improved Mission Completion Time**
	The observation on the mission completion time for both UGV categories was expected; that is, a shorter mission completion time and greater consistency were achieved when Blue force was equipped with a more capable UGV. Like the other findings, a crucial factor in terms of the overall performance would be the team size of the Blue force; more soldiers help with achieving a quicker mission completion. Similarly, it is also noted that the change in mission completion time becomes less substantial as the team size increases, likely due to the

<table>
<tr><th>S/N</th><th>Simulation Outcome and Operational Perspective</th></tr>
<tr><td></td><td>overcommitment of resources (in this case the Blue forces) to complete the mission.</td></tr>
<tr><td colspan="2">Operational Perspective</td></tr>
<tr><td colspan="2">DOE #3 served to identify critical factors that impact the study’s metrics. To conclude the key findings on the distribution for DOE #3, it is evident that the enhanced UGV capabilities proved to be useful in improving the overall combat capabilities of the Blue force. With that in mind, it follows that the null hypothesis that ‘varying multi-factors do not affect the performance’ can be rejected.</td></tr>
</table>

Partition Tree Analysis (Loss Exchange Ratio)

In the last part of this chapter, a partition tree analysis is conducted to complement and reinforce the findings identified in the previous analyses. The mean LER is chosen as the response for the partition tree analysis since it captures both Red and Blue casualties and is a measure of overall performance of the mission. A partition tree is a nonparametric data analysis technique that complements the use of regression. The output might loosely be interpreted as a “decision tree” that explains good versus bad outcomes. From the partition tree shown in Figure 21, four key findings are observed.

1. A larger Blue team size (three or four) reduces the mean LER to 1.37, indicating a poorer performance as compared to a team size of 1 and 2, where the mean LER is higher at 1.73. The combat power offered by more Blue soldiers is outweighed by the risks sustained in the urban environment, reducing the effectiveness once the threshold is reached.

2. A capable UGV with a reloading time of less than nine seconds increases the LER by approximately 41%. This is a significant finding and could be considered in the design of future platform replacements or upgrades.

3. Accuracy is another critical factor in the technical design of an UGV. By improving the accuracy of the platform to at least .7 Phit, the mean LER increased by 20%. As such, there is value in emphasizing accuracy in weapon design specifications.

4. On the right-hand side of the partition tree (i.e., cases where team size was one or two soldiers), it is evident that reducing the UGV's reloading time to less than eight seconds increases LER by 33%, from 1.56 to 2.07. When the cutoff is shortened to reload in less than six seconds, the mean LER would yield an increase of 28%, from 1.89 to 2.43. This further reinforces the importance of the UGV weapon reloading speed as part of the weapon design specifications.

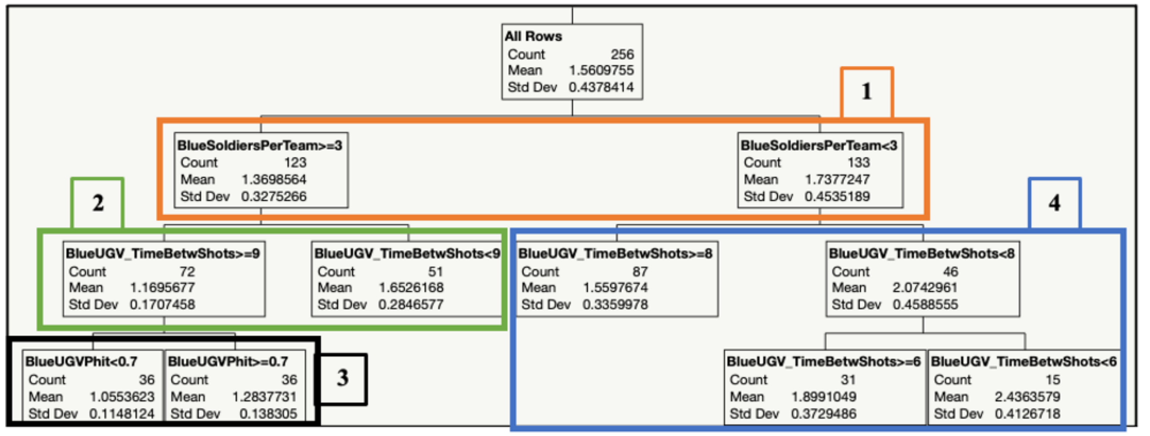


Figure 21. Partition Tree of the Mean (LER) Factor in DOE #3

VI. CONCLUSION AND FUTURE WORKS

A. RESEARCH FINDINGS AND SUMMARY

This thesis involved approximately nine months of intensive research, experimentation, and analysis. During this time, the author proceeded from conceptualization and implementation of the simulation model to experimentation and analysis that have helped shape recommendations. The use of iterated design and analysis of experiments, starting with DOE #1 and concluding with DOE #3, allowed for knowledge to build cumulatively. Before concluding the thesis, this chapter revisits the research questions, to ensure they have all been addressed. A summary of the findings pertaining to each research question is presented in Table 15.

Table 15. Summary of Findings to Address Research Questions.

S/N	Research Questions
Primary Questions	
1.	**How lethal is an infantry squad supported with an UGV or UGV(s)?**
	MUM-T has proved effective and lethal. The introduction of a single UGV in DOE #1 resulted in an increase of Red casualties by 300%, while reducing the mission completion time and enhancing Blue survivability.
2.	**What are the battle outcomes and analysis of different force structures of a MUM-T force in the proposed scenario?**
	Force structure of Blue team size had a significant impact on the outcome of the battle. DOEs #2 and #3 reiterate the importance of identifying the optimal team size or “knee in the curve” since “over-equipping” in terms of team size could potentially result in increased vulnerabilities (more Blue casualties). Operational factors such as TTPs and equipment are also important factors to be considered to overcome the limitations or constraints caused by varying team sizes.

Secondary Questions	
3.	**How can MUM-T help alleviate manpower shortages in militaries through force structure development?**
	Through the conceptual implementation of MUM-T, mission completion time and overall Blue casualties were reduced. While the analysis may be insufficient to fully solve manpower issues without a suitable set of constraints or requirements to model every exact environment, the conclusions from the analyses can encourage further MUM-T studies, which hopefully could help resolve manpower issues in the near future.
4.	**What is the scope for future research on potential implementation approaches of MUM-T at broader, strategic levels?**
	Some areas would include focusing on other specific MUM-T capabilities to study other CONOPs requirements and on involving MUM-T early in the development of future CONOPs. There is also value in exploring real world testing and evaluation upon completion of combat modeling and simulation.

Having broadly summarized and addressed the research questions, the project concludes with two key takeaways on the implementation of MUM-T:

1. Increased Lethality and Survivability: The implementation of MUM-T significantly reinforced the lethality of the Blue force, as evident across the different DOEs. Using a simple and credible model representation of an operational platform, it was possible to observe that the destruction of the Red force increased by 300%. This finding encourages further development of experimentation where similar proxies or even actual prototypes could be used to conduct future MUM-T force structure studies.

2. Maintaining a Sustainable and Operational Force Structure: While the implementation of MUM-T in this scenario effectively increased Blue force capabilities, it presented an unexpected impact on RCP, where increasing the team size of the Blue force beyond a certain number would contrarily endanger the Blue force, also known as the point of diminishing returns. This anomaly was attributed to the feature of the urban terrain, which was one of the key findings from the DOEs. Early identification of the point of diminishing returns (if any) from commitment of resources is critical to military operations, especially for future CapDev initiatives, considering the increasing need to prioritize the dwindling manpower resources over the next few decades.

B. USEFUL AREAS FOR FUTURE WORK

While this study concluded that applications of MUM-T can be effective in urban operations, it is evident that MUM-T has potential in many other areas. These areas include modularizing upgrades of platform capabilities, integration with modern systems, and even innovation in the development of future CONOPs.

This study adopted a combat modeling method to simulate combat operations in an attempt to conduct operational testing. As such, future work could leverage this study and continue research and development on MUM-T concepts in the following areas:

1. Other Scenario Testing: There is room to explore the impact of different TTPs, CONOPs, or operational injects to the various scenarios. Such exploration would make the study more robust. Concepts such as swarming, land-air linkages, and introduction of unmanned armored platforms are areas of CapDev interest. Further, use of a different simulation could be explored to capture behaviors or metrics that MANA could not.

2. Real World Testing: Beyond software simulation, field tests could be conducted using the actual platform or proxies. To enhance the realism of the field tests, experiments could be embedded within part of military exercises and training courses.

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