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ANALYSIS OF BALLISTIC MISSILE DEFENSE STRIKE OPERATIONS USING STOCHASTIC SIMULATION MODELING OF A LEFT-OF-LAUNCH NETWORK

by

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With the proliferation of hostile theater ballistic missiles (TBMs), the Department of Defense has focused on attack operations as a means of ballistic missile defense (BMD). This thesis develops a stochastic simulation of a network for analyzing and comparing BMD strike operations. Applying knowledge of mobile launch site procedures, we construct a TBM left-of-launch network (LLN) model using discrete-event simulation software. This comprehensive network models system components from the storage phase, transportation phase, and launch phase. The simulation model integrates congestion effects after strikes are executed on the LLN. We conduct simulation experiments representing various strike combinations to quantify and compare system metrics focused on increasing the delay of TBM launches. We demonstrate BMD strike effectiveness by analyzing time-valued metrics such as the mean TBM time in system and mean time to complete launches. Increasing the delay in TBM launches grants more time for strategic decision making and prepositioning of retaliatory forces. We present this notional model and experimentation method as a guide for determining the best locations for BMD strike operations.

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LIST OF ACRONYMS AND ABBREVIATIONS

AO	attack operations
BMD	ballistic missile defense
BMDS	ballistic missile defense system
DoD	Department of Defense
GMD	ground-based midcourse defense
ICBM	intercontinental ballistic missile
ISR	intelligence, surveillance, and reconnaissance
JSTARS	Joint Surveillance Target Attack Radar System
LLN	left-of-launch network
MDA	Missile Defense Agency
MDAA	Missile Defense Advocacy Alliance
PAC-3	PATRIOT Advanced Capability-3
SAC	Strategic Air Command
SDI	Strategic Defense Initiative
SM-3	standard missile-3
TAC	Tactical Air Command
TBM	theater ballistic missile
TEL	transporter-erector-launcher
THAAD	Terminal High Altitude Area Defense
TIS	time in system
TMD	theater missile defense
TTC	time to complete launches

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EXECUTIVE SUMMARY

Theater ballistic missiles (TBMs) are an increasing threat against the United States and its allies. Snodgrass (1993) explains the effectiveness of these weapons against the United States during the Gulf War, in which Saddam Hussein's ballistic missile capabilities led to significant losses of life and posed major challenges against a technologically advanced United States Air Force. Rising hostile groups took notice of the effectiveness of the ballistic missiles because they were easy to produce, highly mobile, and powerful. Iran, North Korea, terrorist organizations, and other foreign threats all realized they did not need an air force to compete on a global scale; they needed regional missile capabilities.

Consequently, the United States began improving its ballistic missile defense (BMD) systems. Subsequent research and investments focused mainly on post-launch active defense, which entails constantly locating, tracking, and predicting the TBMs trajectory in order to kinetically interdict the missile. Though feasible, post-launch ballistic missile interdiction is a formidable and uncertain task. Only recently has the Department of Defense (DoD) investigated a multi-layered BMD approach involving attack operations (AO). BMD AO involves striking the enemy's "left-of-launch" network (LLN) to prevent TBMs from launching. The LLN is the network composed of installations and infrastructure designed to facilitate the transportation and launch of mobile ballistic missiles. Current BMD AO analysis, however, can benefit from additional methods to identify the best locations to strike an adversary's LLN given a certain level of uncertainty about that network's capabilities.

To enhance our analytical approaches in assessing alternative BMD strike targets while addressing uncertainty in an adversary's support network, we employ simulation modeling techniques. Simulation is a flexible tool that is capable of modeling network interactions and activity over time. Unlike linear models and equations, simulation can model the stochastic effects inherent in complex system behavior.

Over the course of this research, we outline the quantitative method we hope will guide future decision makers. Using discrete-event simulation software, we construct an enemy's standard LLN and implement the appropriate logic to model the flow of TBMs. In this network, we include missile manufacturing facilities, storage units, maintenance facilities, fuel depots, and several routes to access the different launch sites. Input parameters and distributions are notional and can be altered to tailor analysis to a specific network of interest. Next, we determine feasible targets and model the effects of striking these locations. These effects include congestion, which represents the increase in service and transit times across the network.

The objective of our LLN strike analysis is to maximize the delay of a finite set of TBM launches. Increasing the delay in TBM launches grants more time for strategic decision making and prepositioning of retaliatory forces. To measure this objective, we quantify time-based metrics including mean TBM time in the system (TIS) and mean time to complete launches (TTC). Then, we design a set of experiments that include 20 different strike combinations to execute on LLN targets. Over 4,000 replications are performed to identify statistical differences between the strike alternatives. Finally, we analyze the output by comparing the resulting metrics of the different strike operations.

The LLN used in this research is an unclassified placeholder for the LLNs of particular countries of interest. In turn, the conclusions we draw from our experimentation cannot be directly generalized. Though we identify a superior strike scenario in our notional LLN, the main contribution of this research is the analytical simulation modeling process with which we use to compare potential solutions. We introduce a method to assist military strategists in making decisions about strike operations to minimize foreign ballistic missile threats.

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I. INTRODUCTION

In the modern world, the United States maintains adversarial relationships with nations of ranging military capabilities. Technologically advanced nations and small rogue terrorist groups alike pose threats to the United States and its foreign allies. While enemies of the United States speak several languages, the language of war is universal. Interested countries observe and learn about the effectiveness of different weapon systems used against the United States. The disadvantage for impoverished countries, however, is that they must be able to reproduce these most-effective weapons. In turn, adversaries have converged to the ballistic missile as a common weapon of choice to inflict physical damage. The mobility, simplicity, and cost-effectiveness of such a weapon appeals to adversaries regardless of economic class. Global advancements in missile capabilities require the United States to be at the forefront of effective ballistic missile defense (BMD).

While the United States constantly steps up to the challenge, more inventive solutions should be explored. Current BMD solutions involve destroying the incoming missiles in the air. The volume of research and investments in post-launch missile defense implies that this is the only approach to BMD. The need for additional analytical research regarding ballistic missile activity prior to launch motivates this study. We seek to discover how attacks can be employed on an enemy’s assets to interrupt hostile missile launches. Taking advantage of vulnerabilities in supply and logistics networks is not original; however, there are limited ways to model the resultant effects on missile behavior. This research uses simulation modeling techniques to characterize pre-launch ballistic missile activity and quantify the effects of offensive BMD measures while considering uncertainty in our knowledge of enemy support networks. Such an analytical approach will help military strategists to identify key locations to strike in an enemy’s ballistic missile network and to compare alternative strike combinations.

A. BALLISTIC MISSILE BACKGROUND

Prior to analyzing proper defense, foundational knowledge of a theater ballistic missile (TBM) is required. In general, TBMs have a short to intermediate range, generally below 2200 miles. The range of flight is equivalent to the distance between Moscow and Madrid. Universally, ballistic missiles also have three phases to their flight. Phase one is the boost phase, corresponding to the initial launch and continuous thrust in order to attain the velocity required to reach its target. The second phase is the mid-course phase, when the missile free falls after leaving Earth's atmosphere. This is the longest and most predictable phase of the missile flight; however, countermeasures are often employed by the missile when provoked. The final phase is the terminal phase in which the missile rejoins the atmosphere and homes in on the target, usually in less than one minute (Nuclear Threat Initiative 2004).

Indeed, the ballistic missile is the entity that inflicts the kinetic damage upon a target, though a platform is still necessary for launching the missile. While stationary missile launchers are prevalent in enemy arsenals, this paper focuses on mobile launchers. Relevant mobile launchers are platforms such as the M270 Multiple Launch Rocket System, M142 High Mobility Artillery Rocket System, transporter-erector-launcher (TEL), etc. These agile vehicles are versatile enough to carry, transport, and launch up to approximately 12 ballistic missiles. After a launch, these mobile missile launchers are quick enough to escape and travel to a new site to initiate more launches.

Technological specifications of different missiles and missile launchers are not requisite information for this research paper. Prior to examining current methods toward BMD and their respective disadvantages, we acknowledge the relevancy of effective BMD in modern warfare.

B. MISSILES IN WARFARE

Although the ballistic missile appears as an obvious weapon in a nation's armament, we observe the conflicts that led to the rise of ballistic missile implementation. The global conflict that gave rise to the missile age was the Cold War. The main weapon of interest was the intercontinental ballistic missile (ICBM). These missiles had a much longer range than a TBM and generally contained nuclear warheads, and the intent and threat of these missiles could not be ignored. As a result, smaller countries sought to scale ballistic missiles to a regional level. Enemies sought a more affordable, convenient, and rapid process of launching missile rounds. In fact, the Soviet Union directly aided one of these hostile countries, Iraq, prompting future armed conflict (Snodgrass 1993).

Shortly after the Cold War, in 1990, the United States went to war with Iraq. Throughout the Gulf War, Saddam Hussein used Soviet-influenced WWII German-inspired Scud missiles to his advantage. Flexible and rapid deployment of Scud missiles prevented U.S. forces in Operation Desert Storm from identifying launch sites. Scud crews ignored safety practices and launched via trucks, causing the launch sites to be highly unpredictable. Initially disregarded as a substantial threat, the Scud missiles proved to be a huge challenge to subdue despite massive air superiority by friendly forces (Snodgrass 1993). Reconnaissance and surveillance through E-8 Joint Surveillance Target Attack Radar System (JSTARS) aircraft in addition to ground invasions were all but futile attempts to prevent Scud launches (Snodgrass 1993).

Rising terrorist groups noticed that simple increases in targeting, Global Positioning System, and commercial satellite information enable a more robust mobile missile strategy than that which Saddam Hussein’s forces employed in Iraq. Moreover, impoverished countries realized that in order to face a global power such as the United States, a formal air force was superfluous. To compete for power on a global scale, underprivileged groups simply needed speed and the ability to penetrate air defense (Snodgrass 1993). Both of these objectives can be accomplished with a ballistic missile armament.

Projecting power via ballistic missiles can be seen currently in the Middle East. Israeli citizens constantly fear the possibility of missile attacks from state actors, such as Syria and Iran, and non-state actors, such as Hamas and Hezbollah. Fortunately, in the vanguard of ballistic missile defense, Israel has proved capable of withstanding these attacks. One example that demonstrates Israel’s BMD prowess is through the invention of the Iron Dome, which can distinguish, target, and neutralize hostile missiles all on its own (Missile Defense Advocacy Alliance [MDAA] 2018).

C. MISSILE DEFENSE TECHNOLOGY

Prior to incorporating advanced defense technologies such as the Iron Dome, other efforts have been made to neutralize the threat of TBM’s. Going back several decades, research on effective BMD gained momentum during the Cold War under the Reagan administration, in which the president advocated for the Strategic Defense Initiative (SDI) to protect against Soviet Union missiles. Also known as Star Wars, SDI included futuristic defense mechanisms such as x-ray lasers, computer-guided munitions, and a super-computer control center. Potential Soviet retaliation and technological constraints, however, reduced the project to manufacturing kinetic land-based weapons (Crowley 2019).

ICBM defense analysis, though, spawned the creation of military commands and governmental organizations whose missions were to research innovative solutions for TBM defense. SDI technology paved the way for the Ballistic Missile Defense Organization, which subsequently restructured into the recent Missile Defense Agency (MDA). Moreover, on the military side, the Tactical Air Command (TAC) originally formed to promote air defense after WWII. Later, the Strategic Air Command (SAC) was created and tasked with handling the potential nuclear conflict with the Soviet Union. Eventually, after the Gulf War, the SAC and TAC jointly reorganized into the current Air Combat Command (Snodgrass 1993). Over the course of this timeline, the Defense Advanced Research Technology Agency has been conducting research since its inception in 1958. BMD, historically, has been at the forefront of defense contracts and research, yet truly developed into its modern-day form following the end of the Gulf War in 1991.

After the coalition victory in the Persian Gulf, the Department of Defense (DoD) realized the ubiquity of the ballistic missile weapon system. The Scud missiles, initially considered by General Schwarzkopf as a terror weapon due to inaccurate guidance, proved to be a difficult problem to solve (Snodgrass 1993). Despite complete air-superiority and communications between reconnaissance aircraft, U.S. forces had trouble predicting launch locations. U.S. strategists ultimately countered by targeting the Iraqi command and logistic network since destroying launch sites of the highly mobile missiles was futile (Snodgrass 1993). The DoD believed new technological platforms were necessary to counter the rapidly deployable threats. Consequently, research was granted to develop new "smart" technology that could provide continuous surveillance and identify possible launch locations at a moment's notice. Several examples included the Multi-Sensor Target Recognition System technology, Warbreaker, and Assault Breaker. These projects were offensively driven as they focused on new methods of Intelligence, Surveillance, and Reconnaissance (ISR) such as continuous surveillance, area search reduction, target recognition and location projection, and even mission planning and preparation (Forecast International 1997).

One platform in particular that sought to perform these advanced ISR tasks was the JSTARS aircraft. Though a specialized aircraft, it is not the all-encompassing solution the DoD has been looking for as evidenced by its recent termination by Congress. Effective at gaining and relaying intelligence through extended periods of surveillance, JSTARS lacked any offensive or defensive measures to argue its renewal (Clark 2018). The ideal ISR capabilities determined after the Gulf War were aimed at identifying potential launch locations; however, countermeasures were deemed necessary. As a result, current BMD research and technology has naturally drifted towards effective post-launch defense, also known as active defense, mechanisms for interdiction.

Specifically, Terminal High Altitude Area Defense (THAAD) and PATRIOT Advanced Capability (PAC-3) missile defense systems have become the primary platforms for theater missile defense (TMD). While both systems rely on kinetic hit-to-kill techniques for interception, THAAD is able to intercept an incoming missile just outside the atmosphere, whereas PAC-3 can only intercept missiles in the terminal phase at lower altitudes (Missile Defense Agency [MDA] 2019c). Additionally, within the United States Navy, the MDA has implemented Aegis Ballistic Missile Defense as part of an overarching effort within the Ballistic Missile Defense System (BMDS). Already installed on over 30 ships, Aegis BMD detects and tracks ballistic missiles of all ranges. In addition to collecting data and alerting remote sensors about the hostile threat, the Aegis system uses the Standard Missile-3 (SM-3) to kinetically interdict the incoming missile (MDA 2019a). The Aegis BMD system also has an installation ashore in Romania, and one currently being built in Poland. These installations are part of the Phased European Adaptive Approach that was introduced in 2009 to address growing Iranian missile threats (Sankaran 2015). This technology is functional; reports of testing demonstrate the successful attempts of SM-3 interdiction (Larter 2018).

Elsewhere abroad, Israel has employed its Iron Dome missile defense system, composed of 10 stationary batteries, since it became operational in 2011. Responsible for intercepting approximately 90% of incoming short-range rockets, the Iron Dome helps thwart the aspirations of current and future terrorist organizations (MDAA 2018). Lastly, similar to the Aegis and Iron Dome systems, President Bush organized the deployment of the ground-based midcourse defense (GMD) system based in Alaska and California. This advanced BMD system employs exo-atmospheric kill vehicles to intercept mid-to-long range missiles outside of the Earth's atmosphere (MDA 2019b).

As one can see, there are numerous examples of expired, current, and future post-launch BMD platforms; yet, drawbacks to post-launch defenses such as BMD accuracy and Russian sensitivity limit the chances of successful interdiction.

Although the U.S. has many means of operationally effective BMD, each system does not come with a guarantee of success.

> Even under ideal circumstances and with the latest technologies, ballistic missile defense is exceedingly difficult. Destroying [a reentry vehicle] in flight requires an end-to-end sequence of successful tasks: detecting and classifying the threat missile, predicting the threat trajectory, cueing sensors down the line, tracking the target, discriminating the target from clutter and countermeasures, acquiring the target for intercept, intercept, kill assessment, and repeating the sequence as required. A failure anywhere in this chain precludes successful intercept. (Gompert and Isaacson 1999, p. 4)

In addition to the probability of failure, BMD countermeasures can reduce the probability of successful interdiction. Simple countermeasures, including radar decoys, chaff, trajectory manipulation, sub-munitions, etc., all can negatively affect the probability of interdiction (Gompert and Isaacson 1999).

Another constraint that reduces the full potential of high-performing TMD, is the politically unstable relationship that the United States maintains with Russia. Russian leaders expressed concern with both the Aegis Ashore station in Poland and the possible expansion of GMD stations throughout Europe. They have stated that these BMD systems threaten their strategic deterrent capabilities (Sankaran 2015). Therefore, the United States is limited as to the potential locations of BMD facilities, which subsequently limits the operational effectiveness of the overarching BMDS. Consequently, Russian sensitivity to U.S. post-launch BMD abroad introduces yet another method of effective TMD, deterrence.

Because the U.S. is denied access to potential areas of conflict, deterrent-based strategies can be difficult to implement. To address this concern, the Defense Science Board suggests the enactment of the Assault Breaker II program, a spinoff of the original Assault Breaker program studied after the Gulf War.

> If the U.S. wishes to be able to dissuade, deter, or if necessary, deny such actions using military force, it will need the ability to achieve decisive military from a range outside of the adversary [Anti Access/Area Denial] reach. Such effects can be achieved using long-range weapons, or by using shorter-range weapons that are pre-placed well before the outbreak of conflict. (Defense Science Board 2018, p. 10)

Though a form of deterrence, the Assault Breaker II program would still inherently rely on post-launch BMD should aggressors fail to acquiesce before a swift and decisive response. Even U.S. nuclear capabilities constantly fail to deter regional or dispersed enemies. Small aggressive nations or terrorist groups realize that U.S. decision makers would not respond to a theater ballistic missile launch with nuclear weapons. Such a response would be grossly disproportionate and lacking in any sense of morality. Yet adversaries unfortunately capitalize on this reluctance. Saddam Hussein continued to launch missiles in Iraq against the coalition and current non-state actors know the majority of ballistic missile responses are reactive and post-launch.

D. OFFENSIVE BALLISTIC MISSILE DEFENSE

Thus far we have discussed current BMD techniques on an individual basis. Active defense platforms such as THAAD, PAC-3, Aegis technology, and GMD significantly contribute to the protection of U.S. and allied territories and installations. However, the successful interdiction of an incoming missile is a formidable and uncertain task. Conversely, U.S. deterrent capabilities have been considered as a measure of BMD, yet adversaries recklessly exploit the U.S. reluctance to deploy an overwhelming response. A combination of these defensive tactics, though, lead to a more comprehensive BMD strategy. In fact, most strategic decision makers surmise that this multi-layer defense approach maximizes U.S. BMD capabilities.

> This 2019 [Missile Defense Review] also emphasizes that the missile threat environment now calls for a comprehensive approach to missile defense against rogue state and regional missile threats. This approach integrates offensive and defensive capabilities for deterrence, and includes active defense to intercept missiles in all phases of flight after launch, passive defense to mitigate the effects of missile attack, and attack operations during a conflict to neutralize offensive missile threats prior to launch. (Office of the Secretary of Defense 2019, p. 1)

While the DoD recognizes the essential elements to a comprehensive multi-layer approach, the DoD has not comprehensively analyzed each layer. Deterrence, passive defense and active defense measures have long been studied and operationally active; but, research regarding attack operations has not been prioritized despite the acknowledgement of its efficacy by analysts and government leaders alike.

> reliance on terminal defensive systems, point defense, or simply "catcher's mitt" systems is sheer folly—particularly when the [United States Air Force] and joint DoD air and space power can provide more options. Consequently, ranking prominently among those currently available and desirable antimissile options is attack operations. (Krause 1999, p. 3).

More specifically, attack operations (AO) will seek to "degrade, disrupt, or destroy an adversary's missiles before they are launched" (Office of the Secretary of Defense 2019, p. 14). To ensure the destruction of missiles pre-launch, AO would focus on "attacking strategic targets such as factories. Additionally, inter-diction targets, such as TBM and [weapons of mass destruction] storage sites, fixed and mobile C2 nodes, and supply lines, would be subject to attack" (Krause 1999, p. 32). Colloquially, the network of infrastructure and stations designed to facilitate the transportation and launch of mobile ballistic missiles is called the "left-of-launch" network (LLN). The offensively driven strategy of attacking an adversary's LLN has been contemplated in DoD circles because such an effort could reduce costs of post-launch missile defense systems and limit the proliferation of mal-intended ballistic missiles (Ellison 2015).

The ability to interdict an adversary's LLN also fosters the expansion of a modern and versatile theater ballistic missile defense scheme. Since over 20 countries sustain ballistic missile reserves, "threats and U.S. defensive goals will be diverse and dynamic" (Office of the Secretary of Defense 2019, p. 8). Pre-launch attack operations will ensure the multi-layer BMD strategy is sufficiently flexible and adaptable to account for the unpredictability of TBM launches (Office of the Secretary of Defense 2019). Ultimately cost-effective, this flexible advantage will require enhancements on current ISR, precision strike, and attack warning technologies; but, the DoD has stated in the 2019 Missile Defense Review that investments will be made to improve upon these functionalities.

While employing AO as a means of BMD has seldom been examined, the idea of attacking an adversary's logistic supply network is far from revolutionary. Besides the basic competency of U.S. strategists to identify and target choke points in an enemy's supply network, there exist historical examples of supply network interdiction. One famous example is the U.S. bombing of German ball-bearing factories in World War II. Ball-bearings were pinpointed as an essential cog in the functionality of German war machines, yet U.S. forces severely stunted their production with strategic attacks on their factories (Chen 2014). Another example appears in post-Gulf War analysis. "A given nation, such as Iraq, may have several hundred theater ballistic missiles but only a few dozen TELs. Consequently, the U.S. could gain significant leverage by hitting an adversary's TELs" (Snodgrass 1993, p. 24). As previously mentioned, Scud launches and locations were difficult to anticipate and active defense measures were not as reliable as they are today. Thus, the true vulnerability of Iraqi forces lay in the Transporter Erector Launchers, the mobile launch platforms tasked with transporting and launching the Scud missiles. Exploiting the enemy's weaknesses is the intent of warfare, and BMD AO effectively accomplishes this objective.

E. LITERATURE REVIEW AND RESEARCH SCOPE

With increased interest in AO as a viable layer of a BMDS, military analysts need to determine the best location of an LLN to strike. Assuming the intelligence has been gathered and the LLN network has been constructed, strategists have various options in terms of strike locations. However, the analysts lack the tools to assist in this critical decision-making process. The analysis of alternatives, therefore, is qualitative and projections on the effectiveness of AO can be highly speculative.

Quantitative analysis on post-launch BMD has been explored in terms of probability equations (Marshall 1994). Though Marshall's study (1994) pertains to post-launch missile defense, we acknowledge the analytical approach he introduces to quantify ballistic missile survival probabilities. These probabilities are dependent on the number of missiles surviving the ground movement phase and each of the three flight phases (i.e., boost phase, mid-course phase, and terminal phase). Marshall labels the number of surviving missiles as random variables and conditions them on the number of missiles that survived the prior phase. Ultimately, we are left with rigid mathematical models that measure the expected number of incoming warheads that are destroyed. Marshall's analysis is helpful to plug in parameters and quantify the defensive effect. He calculates the value of active defense in a BMDS; however, Marshall's equations are not sufficient to plan actual attack points within a particular LLN.

Furthermore, quantitative analysis on BMD has been performed by in the form of two-sided optimization models (Diehl 2004) and (Brown et al. 2005a). In these studies, the inner problem of the optimization model seeks to maximize the expected damage inflicted by the enemy, whereas the outer problem seeks to minimize the maximum expected damage by pre-positioning defensive forces. The min-max model created by Brown et al., called JOINT DEFENDER, can transform into a mixed-integer linear program and be solved on standard optimization software. While the studies conducted by Diehl and Brown et al. represent quantitative approaches to BMD, these min-max models still rely on post-launch ballistic missile interdiction. We aim to focus on more aggressive forms of BMD.

Accordingly, we research network interdiction with simulation. Our study is viewed from the attacker's perspective, by offensively interdicting an enemy's LLN for missile defense purposes; however, prior studies have largely analyzed network interdiction from the defender's perspective in order to optimally plan the positioning of defensive countermeasures. In addition to this subtle difference in defensive strategies (i.e., attack versus counter-attack), most of the historical literature on network interdiction applications quantify effects using optimization. Such studies include Brown et al. (2005b, 2006) and Alderson et al. (2011) that use optimization to solve attacker-defender models to identify vulnerabilities or weak points and maximize resilience of critical infrastructure. Lugo (2008) attempts to optimally place interdiction assets to maximize the expected interdiction value of vehicle borne improvised explosive devices. Optimal network interdiction strategies are also demonstrated by Brown et al. (2009) to maximize the delay of the completion of nuclear weapons projects.

Contrary to optimization, simulation techniques have seldom been applied to model network interdiction. One study in particular, though, uses simulated annealing to model drug interdiction in an unclassified smuggling network in the Caribbean region (Henry, IV 1992). In his research, the author demonstrates that simulation can be used to identify the best placement of counter-narcotic assets in order to raise the prices for imported drugs.

In our work, we take a similar approach to network interdiction modeling as Henry. We apply stochastic simulation techniques to address the uncertainty associated with the knowledge of enemy ballistic missile support networks. We seek to find the best strategy to negatively affect the output of an enemy's LLN. Future work may add stochastic optimization techniques to our approach.

Additional quantitative methods for examining the effects of interdicting a pre-launch missile supply and transportation network are needed. BMD analysts are beginning to focus heavily on offensive strike capabilities. They wish to interfere with an adversary's LLN and disrupt ballistic missile activity as much as possible. Military strategists lack analytical methods to select the best locations to strike.

In this thesis, we develop a methodology using simulation modeling to guide decision makers to determine the best strike operations to pursue to maximize BMD. Simulation modeling is preferred because it is flexible enough to model the stochastic behavior of complex systems such as an LLN. We begin by constructing an illustrative LLN and programming the appropriate logic to model pre-launch TBM flow and behavior. We implement binary control variables that allow the operator to select target locations to attack prior to running the simulation. Next, we perform experiments on the simulation model by striking various combinations of facilities and infrastructure. We replicate these simulations to develop statistics and confidence intervals for the appropriate metrics. The metrics we use to compare alternative strike combinations are average TBM time spent in the LLN and average time to complete all of the missile launches. Each scenario starts with a finite number of ballistic missiles in the system; thus, the goal is to maximize both of these time valued metrics to represent successfully delaying missile launches. Finally, we perform quantitative analysis and comparisons to determine the effects of striking various locations in the network and to identify the best strike operation with which to proceed.

More simply, we advance the notion that stochastic simulation modeling techniques can be implemented as a method of quantitative analysis of AO in a BMD scenario. The procedures and analysis presented in this paper are novel ideas and represent a proof of concept for successive research. Chapter II discusses the particular choice to use simulation modeling as the method of quantitative analysis. Chapter III provides detailed descriptions and assumptions of the LLN that was constructed for our simulation analysis. Chapter IV addresses the experimental setup, while Chapter V contains the results and analysis. Lastly, conclusions and areas for future research will be emphasized in Chapter VI.

II. SIMULATION MODELING

A. REASONING AND BENEFITS

This research's purpose is to build a stochastic simulation network model that may be used by planners to quantify the effects of different strike operations in an LLN. "The stochastic simulation method consists of generating realizations of the inputs, executing the system's logic to produce outputs and estimating system performance characteristics from the outputs" (Nelson 2013, p. 2). Simulation modeling is the preferred method of analysis due to its flexibility to take inputs, model system behavior over a period of time, and formulate output statistics for comparison.

An LLN is a composition of various inter-connected objects and functions. For example, the TBMs require a missile launcher platform to be available for transportation and launch. Another example is the transit time from storage unit to launch site depends on the route travelled. Because all of these relationships in the network are formed for the singular purpose of launching TBMs, we recognize the LLN as a system (Kelton et al. 2017).

Generally, models represent systems. Several types of models exist such as physical models, analytical models, and simulation models. Each type of model is designed to either generate observations of systems that do not exist in real life or to make changes to currently existing systems and observe the effects (Kelton et al. 2017). Physical models are limited, though, to performing real-world experiments and collecting data. Analytical models are limited to rigid equations that cannot accurately characterize system complexity. Therefore, simulation modeling is recommended to analyze a complicated system such as an LLN. Simulation has an unlimited structure that can model individual components and the system's response over time. Moreover, since the state of the system changes after specific events occur (i.e., TBMs are produced, a vehicle requires maintenance), we will analyze an LLN using discrete-event simulation.

Another benefit to using simulation modeling is the ability to represent stochastic systems. An LLN, in particular, contains many stochastic processes since many operations rely on human activity, external inputs, and unexpected events (Kelton et al. 2017). These processes include producing missiles, servicing missiles, transiting various routes, equipment malfunctions, etc. The time required to complete these processes is not deterministic but random. In our case, uncertainty in the adversary's system process performance is also a factor. As a result, analytical models and equations cannot effectively characterize system behavior. Conversely, simulation can be used to exhibit system responses and the resulting output metrics can quantify such behavior. Despite random system behavior, running replications of the model helps performance metrics converge to useful estimations.

B. APPLICATIONS

Simulation modeling techniques have been implemented in a wide range of applications. Supply chains, in particular, constantly benefit from the analysis derived from simulation tools, and these practices have led to reduced energy consumption (Andersson et al. 2013) and insightful analysis on the distribution of contraception methods in Egypt (Abdelsalam and Hassan 2014). Simulation has also been used to optimize personnel requirements including the appropriate number of maintenance crew members to service Malaysian helicopter fleets (Mohamad Rais 2016). More innovative applications include building tools to analyze effects of biochemical reactions on biochemical networks (Adalsteinsson et al. 2004).

C. BALLISTIC MISSILE DEFENSE SIMULATION

This research is intent on proving that simulation modeling can further be implemented within the DoD for BMD strike analysis. Using an originally designed LLN, not representing any particular adversary's system, we input the appropriate logic to route the flow of TBMs and the associated mobile missile launchers. We also set strike controls that allow the operator to hand-select unique locations in the LLN to strike. After running the network simulation, quantitative analysis can be performed to compare the effects of attacking the various locations. Output metrics denoting the TBM's time in the system and reduction of launches can assist in distinguishing and prioritizing the most effective points to interdict. This BMD application of stochastic simulation modeling is a proof of concept for current implementation with a foreign country of interest and future AO research.

A frequently asked question is, “Why not attack the missiles at the source? Strike the original missile factory from which all the missiles are created so there is zero flow across the LLN?” The reasons not to take this action are physically and politically grounded. First, adversaries likely comprehend the value of their ballistic missile armament. Consequently, the TBMs are protected in fortified facilities, rather than being stashed on more-vulnerable premises. This leads to either a lower probability of strike success or a more-costly BMD attempt, since in this study we only assume kinetic means of AO are employed. Additionally, the TBMs elsewhere in the LLN are still viable threats to launch. To answer this question with a question, why not strike a bridge at low cost if it results in the same effect on the LLN flow as striking a heavily armored TBM storage unit? Production and storage facilities can be located in civilian populated areas, which raises the risk of collateral damage. The U.S. will avoid striking places where there exists a high risk of civilian casualties. These are a few of the reasons that a more quantitative and analytical approach to BMD strike operations is crucial.

D. SIMIO DISCRETE-EVENT SIMULATION TOOL

We use Simio software to build the simulation model representing an LLN. Simio is a “multi-paradigm modeling tool” capable of incorporating several types of simulation into one model (Kelton et al. 2017, p. 5). Thus, Simio is sufficient for discrete event simulation purposes. More precisely, Simio is an object-oriented simulation software program that uses logic and animation features to facilitate user interaction. The software flexibility and graphical interface maximize transparency in a complex system. In turn, the user can vary the logical inputs of specific system components and visually analyze the effects prior to interpreting output statistics.

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III. MODEL DEVELOPMENT

This chapter describes the simulation model we developed to analyze a typical LLN. Characteristics and assumptions on specific network components are provided to generate understanding of the processes that TBMs experience prior to launch. Although we provide the specifications of an illustrative LLN, these input parameters may be altered to further refine the validity of the model and tailor it to represent a particular LLN.

A. LEFT-OF-LAUNCH NETWORK OVERVIEW

An LLN model is created using the aforementioned Simio software. This network can be seen in Figure 1. A broad overview of the model will be explained, with specific descriptions of each component to follow.

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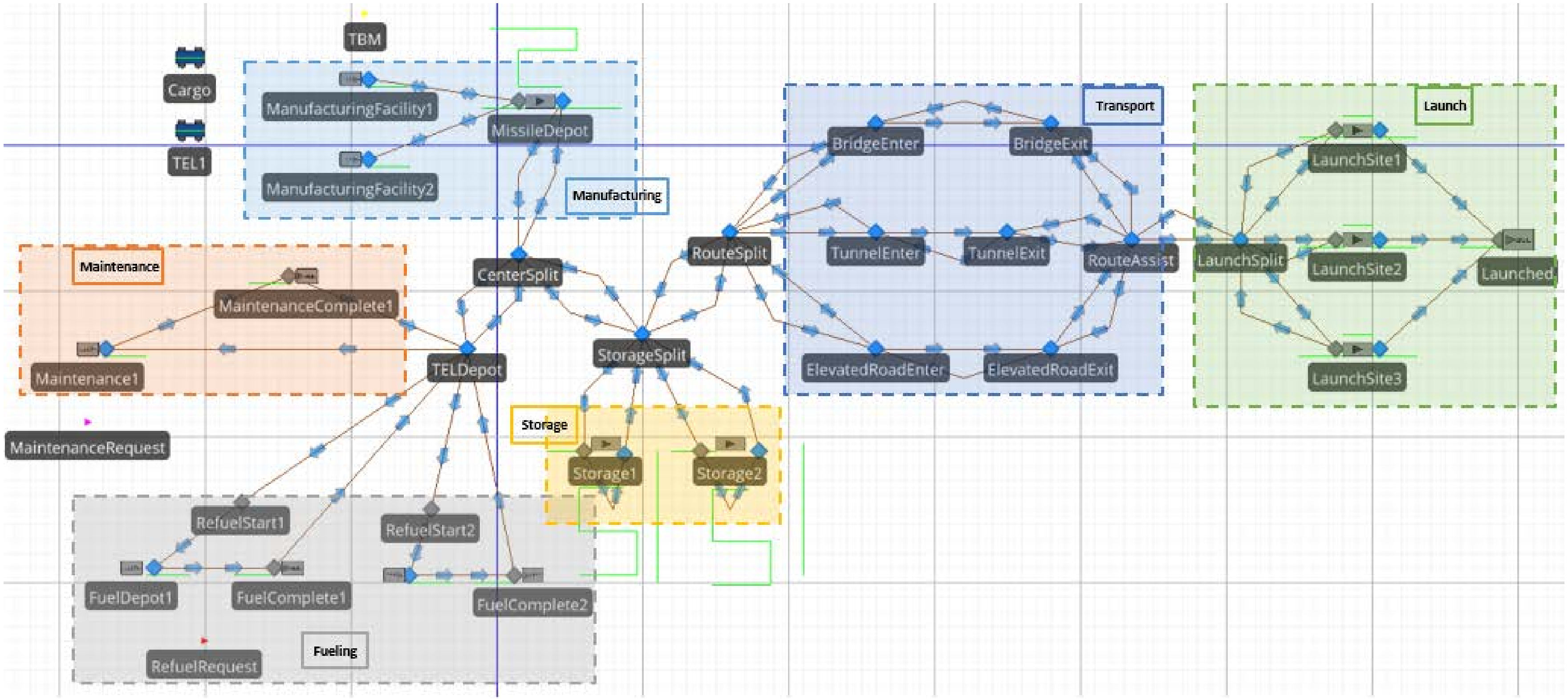


Figure 1. Illustrative Left-of-Launch Network

In general, the model depicts the flow of TBMs across a typical LLN. In order to travel to each location, the missiles must be carried by a vehicle. There are two types of vehicles in the model, cargo vehicles and TELs. The cargo vehicle carries the missiles from the originating factory to the initial missile depot, while the TELs are responsible for all other transportation services and launch.

In the network, we consider all of the relevant sites from the TBM manufacturing phase to the launch phase. Upon initialization of the system, TBMs are outputted from two different missile factories. From these production facilities, the missiles are brought by the cargo vehicle to the missile depot for long-term storage. From this initial storage center, the TELs route the TBMs to one of two short-term storage units. Once the missiles are stored at the short-term storage sites, the TELs go back to their home location where they wait for future transportation requests. Eventually, the storage facilities will release the missiles so they can be launched. Prior to exiting the short-term storage sites, the TBMs are assigned a random launch location of which there are three in the network. The TELs are responsible for hauling and launching the missiles at the appropriate launch sites. Additionally, there is more than one route to each of these launch locations. To prevent easy pattern detection, the TELs travel through these routes with equal probability. Each route contains a significant mode of infrastructure that is susceptible to attack. The notable bodies of infrastructure include a bridge, tunnel, and elevated roadway.

Lastly, the TELs are susceptible to the same limitations as any other vehicle. Namely, these mobile missile launchers must be refueled and maintained. Consequently, the network contains two fuel depots and two maintenance facilities to provide such services.

B. MODEL OBJECT DESCRIPTIONS

Various objects are implemented in the network model. We provide descriptions containing the purposes and characteristics of each object. Please note that all of the distributions and parameters used in this simulation model are notional and may be modified with specific information if available.

(1) Entities

Model entities are smart objects that behave based on user-specified characteristics or state assignments. Entities are generated by sources, routed along paths, serviced by servers, and destroyed by sinks throughout the network model.

- TBM—These model entities represent the TBM's generated by ManufacturingFacility1 and ManufacturingFacility2. These entities flow throughout the network and exit after they are launched.

- RefuelRequest—A symbolic model entity that simulates a TEL's need for fuel. This is a symbolic entity, generated at either fuel depot, that must be carried by a TEL to corresponding FuelComplete sink. This process symbolizes the refueling service. After every set of launches, a TEL has to be refueled.

- MaintenanceRequest—Another symbolic model entity that must be carried by a TEL to the MaintenanceComplete sink. This process simulates the request for maintenance to be performed on a TEL, and this entity's transit through the system represents the time the TEL undergoes maintenance. These entities are generated (i.e., a TEL breaks down and requires maintenance) at an exponential rate with mean five days.

(2) Vehicles

Vehicles are objects that are primarily used to transport entities between locations when the standard flow between nodes is not appropriate. They retain information and adhere to user-inputted process logic. Vehicles can also pickup and drop off one or more entities at specified destinations.

- Cargo—The high-capacity vehicle tasked with transferring the missiles from the manufacturing facilities to the missile depot. There is one Cargo vehicle in the network that can carry up to 10 TBMs per trip.

- TEL—The mobile missile launcher that transports TBMs from the missile depot to the short-term storage facilities and launch sites. The TEL launches the TBMs by dropping them off at the assigned launch locations. The network contains 6 TEL platforms capable of holding 6 TBMs each.

(3) Sources

Source objects create model entities and insert them into the network. A designated inter-arrival time distribution controls the rate at which the entities are produced.

- ManufacturingFacility1, ManufacturingFacility2—The factories where the TBMs are assembled and inputted into the network. 600 TBMs are inputted from these two sources.

- FuelDepot1, FuelDepot2—The refueling sites for the TELs. A RefuelRequest entity is generated at this source when a TEL needs to be refueled. A TEL requires fuel after every set of launches it executes.

- Maintenance1—The maintenance facility that services the TELs. The maintenance facility has two servers so two TELs may receive service at once. A MaintenanceRequest entity is generated at this source when a TEL needs maintenance.

(4) Servers

Entities enter a server to undergo a process with a designated service time distribution. Servers may have limited or infinite capacity to process entities simultaneously. After receiving service, entities wait in an output queue to be routed to the next destination.

- MissileDepot—This server represents the long-term storage warehouse of the TBMs. After creation, the TBMs are stored at this location prior to being routed to short-term storage sites. This server has an infinite capacity, meaning the missile depot can hold as many missiles as necessary. The TBMs are served/stored at this location according to a triangular distribution with parameters (5, 6, 7) days.

- Storage1, Storage2—This object represents a short-term storage site, in which the missiles are staged and prepared prior to launch. This storage location also has enough space required to store every missile that arrives. The TBM's are served/stored here according to a triangular distribution with parameters (1, 2, 3) days.

- LaunchSite1, LaunchSite2, LaunchSite3—These servers correspond to a TBM launch location. When a TEL drops off a TBM entity to this server, this delivery symbolizes a missile launch. TBMs are randomly routed to the launch sites and fire one at a time. The service time for launches corresponds to a triangular distribution with parameters (.33, .5, .75) hours.

(5) Sinks

Sinks destroy entities and record statistics about them as they exit the system. When an entity enters a sink object, it is exiting the network.

- FuelComplete1, FuelComplete2—The objects that represent completion of the refueling process for the refueling process. A TEL is successfully refueled after it drops off the RefuelRequest entity to the appropriate sink.

- MaintenanceComplete1, MaintenanceComplete2—The sinks that represent completion of the maintenance process. The service is complete once the TEL drops off the MaintenanceRequest entity to the appropriate sink.

- Launched—This sink corresponds to the output of TBMs from the system. When a TBM entity enters the Launched sink, it exits the LLN, symbolizing a successful launch.

(6) Transfer Nodes

Denoted by the blue diamonds, the transfer nodes do not represent any physical location in reality. They are implemented in the network for design simplification purposes. These nodes contain user-inputted processing capabilities to route the flow of TBMs and TELs across the network. Rather than linking every node together and filling the network with superfluous arcs, transfer nodes help reduce the complexity of the network.

- CenterSplit—A transfer node to simplify and separate the network into distinct segments. From this node, we can compartmentalize the network into a vehicle section, storage section, and launch section.

- TELDepot—The node that represents the home location for the TELs. When the TELs are not in demand for transportation or launch services, they return to the TELDepot node. This transfer node connects to the fuel depots and maintenance facilities for easy access to necessary service.

- StorageSplit—The node at which the TELs separate to deliver the TBMs to the short-term storage locations.

- RouteSplit—This transfer node contains the logic to route the TELs toward the launch sites via three different routes. The TELs have an equal probability of taking any of these routes.

- RouteAssist—This transfer node contains the logic to route the TELs to the fueling depots randomly across the three routes.

- LaunchSplit—The node at which the TELs separate to deliver the TBMs to the assigned launch locations.

- BridgeEnter/TunnelEnter/ElevatedRoadEnter—The nodes that indicate the entrances to the respective modes of infrastructure on each route.
- BridgeExit/TunnelExit/ElevatedRoadExit—The nodes that indicate the exits to the respective modes of infrastructure on each route.

(7) Time Paths

Time paths are links that connect the objects in the network model. Time paths are not distance based; instead, they require a user-specified amount of time to travel. The entire LLN relies on time paths to travel from one location to another, since vehicle speeds may vary greatly, and it is difficult to scale down such a complex network of paths to reflect actual distances in the model. Three time paths exist in the system to represent service times. These time paths connect the fuel depots and maintenance facility with their respective sinks. The time that a TEL takes to transport the MaintenanceRequest or RefuelRequest entities along their associated time paths, corresponds to the amount of time needed to service or refuel a TEL. The time paths associated with the maintenance process have triangular distributions with parameters (3, 10, 14) days, and the time paths associated with the refueling process have triangular distributions with parameters (10, 12, 13) hours. Therefore, a TEL will be incapacitated for three to 14 days to receive maintenance and 10 to 13 hours to refuel.

Other key time paths in this model LLN are connected to the launch sites. The travel times along these arcs also have triangular distributions, though they are conditional based on the route traveled. For example, the bridge is the furthest route from launch site three; thus, if a TEL tries to navigate from the bridge route to launch site three, then the corresponding time path will have a higher travel time distribution than it would if the TEL were routed through the closer elevated road route. The remaining time paths contain rough estimates for travel time distributions. Due to the fact that the network is generic, most travel times are inconsequential and can be tailored for more circumstantial analysis.

C. NETWORK FLOW LOGIC

With a fully constructed network model, add-on processing is applied to objects to establish the desired flow of TBMs across the network. Add-on processing is user-defined process flow logic that uses entity states and network characteristics to formulate logical statements that determine network operation. Process logic prescribed to the objects in the preceding section, for example, enable the routing of entities and vehicles to specified locations in the model. Now, we explain the relevant add-on processes that are implemented in the model to replicate an LLN.

After system initialization, the ManufacturingFacilities generate a collection of TBM model entities, specifically, 600 ballistic missiles. The cargo vehicle carries the TBMs to the MissileDepot where they are serviced by long term storage. The cargo vehicle proceeds to make deliveries until all 600 TBMs are shipped from the missile factories.

When the TBMs complete long-term storage at the MissileDepot and are ready to transfer to short-term storage sites, they initiate a ride request on the TEL vehicle. Initially, there are six TELs functioning in the network. The TELs have a carrying capacity of six TBMs and will dwell at each location until they are filled to capacity with outbound TBMs. If there are fewer than six TBMs available at the location, the TELs will depart early carrying as many missiles available. From the MissileDepot, the TBMs are moved to either the Storage1 or Storage2 servers, whichever server has the smallest sum of missiles currently being processed plus those currently en route to that server. The TELs are designed to take the shortest path to these storage units.

Once a TEL completes a drop off at the short-term storage servers, they either go back to the TELDepot node to wait for future transportation requests or they respond immediately to an unfulfilled transportation request. These transportation requests are satisfied by the nearest TEL at the time of demand. Besides transportation demands from the MissileDepot to the storage units, the TELs also respond to demands to be launched. Once more, the TELs will dwell at the storage sites until they are loaded with as many TBMs available to be launched (up to six).

After a TBM entity completes service at Storage1 or Storage2, they request to be delivered to the one of the launch servers. To simulate the unpredictability of ballistic missile launches, the TBMs are randomly routed to one of the three launch locations in the network. When the TEL encounters the RouteSplit node, however, the TEL will select among the bridge, tunnel, or elevated road routes. Each option has an equal likelihood of being chosen by the vehicle. After travelling the route, the TEL enters the LaunchSplit node.

At the LaunchSplit node, the TELs do not change course. They proceed to deliver the TBMs to their randomly assigned launch sites. The order in which the TELs pick up the TBMs is the order in which the TELs launch the TBMs. Therefore, after a TEL launches a TBM, it returns to the LaunchSplit node where it can travel to the other launch servers to initiate more launches. Recall the TBMs were randomly assigned to these launch locations. After a TEL fires the last TBM it is carrying and returns to the LaunchSplit node, the TEL recognizes that it is no longer carrying any missiles to launch. In this instance, the TEL has completed a set of launches and must be refueled. Thus, the TEL is routed from the RouteAssist node to the FuelDepot that has the smallest service queue.

When the TEL reaches the FuelDepot, a RefuelRequest entity is generated. The TEL is forced to carry this entity along the time path representing the refueling process. Once the RefuelRequest entity is dropped off at the appropriate sink, the TEL resumes function.

TELs are not only interrupted by refueling requirements, but also maintenance requirements. TELs, like any piece of military equipment, are inclined to fail after sufficient utilization. Therefore, a MaintenanceRequest entity is generated at the Maintenance source at an exponential distribution with mean five days to symbolize a TEL failure. A random TEL will be chosen for transporting this entity, meaning failures occur randomly among the fleet of TELs.

The network model, including all of the above logic and processes, runs continuously until the simulation is terminated. The system has a maximum simulation time of one year, but LLN activity concludes once all 600 TBMs are launched.

D. ASSUMPTIONS

Several assumptions are made to reduce the complex behavior of an LLN to a collection of logic-oriented objects. First, we assume all of the inter-arrival and storage (service) times of the TBMs mentioned thus far can be approximately estimated. Additionally, the transit times of the cargo and TEL vehicles to each location in the network are assumed to be known or estimable.

Besides time distributions, assumptions are made regarding the network flow. We assume the enemy uses two types of storage systems, long term and short term (in that order), prior to directing launch. Missile launches are not continuous at the same location; rather, the TBMs are fired intermittently and randomly at varying launch sites. This means, for example, that a TEL can fire one TBM at LaunchSite1, move to LaunchSite2 to fire a second TBM, then return to LaunchSite1 to fire the third TBM. This erratic procedure represents the irregular firing pattern of mobile missile launches. This also assumes, however, that each of the three routes leads to each of the three launch locations.

In addition to the randomly assigned launch locations, the routes are also assumed to be travelled with equal probability—which can be modified if additional information is known about preference for route selection. The random route selection prevents data collection and complicates LLN analysis for BMD strategists.

More assumptions are made regarding the refueling and maintenance processes. We assume that after every set of launches, regardless of the number of TBMs fired, the TEL must be refueled. Additionally, a random TEL will fail and require maintenance according to an exponential distribution with a mean of five days—which, again, can be easily modified if specific intelligence is available. We also assume the maintenance and refueling service times are known. Moreover, the resources required to tend to the TELs are assumed to be unlimited. This means there is no limit on fuel or maintenance hours provided to the TELs. Finally, the cargo vehicle will not require refueling or maintenance due to lighter travelling demands.

While these assumptions are essential to the operability of the LLN network model, as previously stated, they can be replaced and/or validated if real world data of an adversary’s LLN is collected.

IV. EXPERIMENTAL SETUP

A. MODEL ADAPTABILITY

With the network depicted in Figure 1, we run several experiments to observe the effects on TBM launches of striking various locations in a standard LLN. Recall that this research introduces innovative analytical BMD concepts; thus, the purpose of performing experiments is to demonstrate the methodology behind quantitative analysis of pre-launch BMD scenarios. Although we will proceed to analyze the results of experimentation on our modeled LLN, the goal is not to identify the best location to attack for every BMD scenario. Rather, the goal is to introduce a new analytical approach towards BMD AO to facilitate strategic, operational, and tactical targeting decision making processes. The subsequent experimentation may provide a means or a guide for military analysts to quantify and compare the effects of various strike operation scenarios on an adversary's LLN.

Every LLN is different, varying in geography, assets, travel times, etc. In turn, the LLN depicted in Figure 1 represents a generic network that can be altered to mimic the activity of an actual LLN in a country of interest. New parameters and time distributions can be implemented into the network model, yet the overall premise of outputting ballistic missiles remains the same. Accordingly, the type of pre-launch TBM network may change, but the process of simulating LLN movement, collecting metrics, and comparing interdiction alternatives will be similar for variations on the proposed model.

B. METRICS OF INTEREST

We design simulation experiments to observe TBM flow and output in an LLN under strike conditions. Each simulation run begins with the generation of 600 TBMs which are routed via TELs across the network. The various experiments contain different locations that are targeted for strikes. We attempt to analyze the effects of different strike operations by comparing system metrics including time to complete launches (TTC) and average TBM time in the system (TIS). These metrics demonstrate launch disruption by measuring the delay incurred by the enemy.

One important assumption to note is that upon initialization of the system, the strike on the LLN has already occurred. Strikes are not executed during the simulation run. Moreover, strikes are assumed to successfully hit and disable the designated location with 100% probability. Consequently, we experiment with a finite batch of TBMs and focus on TBM time delay rather than simulating LLN activity for a decided period of time and calculating quantity of output. We avoid simulating the LLN for a distinct period of time, such as six months or a year, because the strikes occur prior to initiating the system. This means that zero TBMs will be removed from the system due to a strike, and even though the run terminates, every repeatedly generated TBM will simply be re-routed and eventually be launched. Thus, analyzing the number of missiles created and launched of such a recurring system would be meaningless. Instead, we begin with a finite batch of ballistic missiles and examine the delay in missile launches as a proxy for measuring the effects of different strike packages. From a BMD perspective, the goal is to delay the launches of TBMs for as long as possible to grant more time for strategic decision making and prepositioning of retaliatory forces.

C. STRIKE IMPLEMENTATION

The experiments are executed in Simio by creating reference properties, which are special model parameters that can be directly manipulated from outside of the model layout. These referenced properties retain Boolean values and indicate whether a possible attack location is subject to a strike. When the referenced property retains the value of true, then a strike is initiated on that location. The reference properties incorporated into the program, denoted as strike_bridge, strike_storage1, etc., are assigned prior to the start of each simulation scenario. Only 9 locations in the relevant modeled LLN can be targeted for strike operations. These locations are the Bridge, Tunnel, ElevatedRoad, Storage1, FuelDepot1, Maintenance, LaunchSite1, LaunchSite2, and LaunchSite3. The reason that just one fuel depot and one short term storage site are selected as strike targets is that they are one of a pair of identical facilities with the same properties and service times. Additionally, while the maintenance facility initially has two servers, an attack prompted against the maintenance site results in a single functioning server. This means that only one TEL may be serviced at a time.

In addition to attacking the fuel, storage, and maintenance sites, all three modes of travel may also be subject to strike. When the bridge, tunnel, or elevated road is destroyed, then the associated route to the launch sites is no longer viable. Thus, the TELs are forced to transit across the remaining unaffected routes both to and from the launch sites. The three launch sites are also valid targets that may be rendered inoperable. In this case, the TBMs are launched from operational launch sites, still one vehicle at a time.

In order to represent the effect of LLN interdiction, we model congestion within the system. Congestion accounts for the increased flow through the uninhibited locations of the network. For example, when a storage facility is destroyed all of the TBMs must be routed and stored in the lone surviving short-term storage unit. Rather than increasing the queue at one server, we model congestion by increasing service times. This assumption can be validated by several reasons. The storage facility crew members may slow down due to an increase in workload, the extra TBMs could be physically stored in distant on-site locations, or possibly there are not enough resources to efficiently manage the extra load. Similar logic applies to the maintenance and refueling stations.

With respect to modeling route congestion, when a mode of infrastructure is destroyed, the transit time distributions increase on the uninhibited paths. The higher transit times can be attributed to re-routing, lack of route preparedness and driver hesitation, or further distance required to arrive to the destination. Nevertheless, route interdiction negatively affects the TBM launch sequence.

Thus far, we have discussed nine targets that exist in the applicable pre-launch ballistic missile network. Several sites, however, are not deemed valid strike locations. These locations include one of each of the fuel depots, storage sites, and maintenance facilities, in addition to the missile factories and long-term missile depot. Only one fuel depot, storage site, and maintenance facility is attacked because these installations are identical. Moreover, the missile factories and missile depots are not attacked because these represent unequivocal choke points. Striking these locations will prevent the simulation model from running since no entities would either be generated or flow through the system. Also, striking the missile depot or the missile factories may incur great cost, collateral damage, or may not even be feasible in the real world. Lastly, attacking such locations are idealistic and provide little room for quantitative analysis since zero TBMs would make it to the launch phase.

D. DESIGN OF EXPERIMENTS

Now that we have explained potential target locations and the resulting implications of AO within a standard LLN, we present the design of experiments in Table 1. This table outlines the various strike scenarios with which we experiment by simulating pre-launch ballistic missile interdiction.

Table 1. Left-of-Launch Network Simulation Design of Experiments

Scenario	Bridge	Tunnel	Elevated Road	Maintenance	Storage	Fuel Depot	Launch Site 1	Launch Site 2	Launch Site 3
1									
2	**X**								
3		**X**							
4			**X**						
5	**X**						**X**		
6		**X**						**X**	
7			**X**						**X**
8				**X**					
9					**X**				
10						**X**			
11				**X**				**X**	
12					**X**			**X**	
13						**X**		**X**	
14				**X**		**X**		**X**	
15				**X**			**X**	**X**	
16	**X**				**X**		**X**		
17	**X**	**X**						**X**	**X**
18				**X**	**X**	**X**			
19	**X**	**X**		**X**	**X**	**X**	**X**	**X**	
20		**X**	**X**	**X**	**X**	**X**	**X**	**X**	

For each scenario, strikes are executed on the locations marked with an X. Only a subset of combinations are considered to ease quantitative analysis for discrete changes in strike locations.

We do not use a full experimental design. There are combinations of strike locations that are not simulated. As previously stated, some combinations are not considered since they would result in zero flow of TBMs throughout the network. That is one reason, for instance, that the bridge, tunnel, and elevated road are not all subject to strike in the same scenario. Otherwise, the strike location combinations are selected to gain insight into the effects of destroying a distinct number of locations and identifying related targets. These scenarios will assist in distinguishing the best locations to strike when only location may be selected, or two locations, or three locations and so forth. Also, since our aim is to demonstrate the concept of using simulation to build LLNs for strike analysis, the specific strike scenario to implement in the generic modeled LLN is not as important as is the process of quantitative comparison of the scenarios.

Statistical comparison of scenarios and confidence interval half-width analysis reveals that 200 replications is enough to distinguish meaningful differences between the scenarios. Thus, each scenario is run with 200 replications, resulting in a cumulative 4,000 replications. The total run time in Simio lasted 55 minutes using a 64-bit Windows 10 laptop computer (Intel Core i7 4600M@2.9 GHz; 8.0 GB RAM).

V. RESULTS AND ANALYSIS

After all of the replications in the experiment are complete, we tabulate the results of the desired metrics. Because we analyze an LLN that is initialized with a finite reserve of TBMs, we collect metrics based on time. These metrics include mean TBM TIS and TTC.

A. AVERAGE TIME IN SYSTEM

We begin interpreting results by examining system metrics across all 20 scenarios. Table 2 organizes the mean TBM TIS values and their associated 95% confidence intervals. Mean minimum TBM TIS values for each scenario are also portrayed in Table 2. This number corresponds to the mean of the smallest TIS values across replications for each scenario.

Scenario 17 results in the greatest mean TBM TIS. Although we can observe this highest value in the simulation output, Simo has a ranking and selection function called the Subset Selection Analyzer that statistically chooses the possible best alternatives. This function highlights a subset of scenario sample means that are statistically higher than the other means (Kelton et al. 2017). In this case, the goal for BMD AO is to maximize the mean TIS experienced by a TBM. Given this objective, the subset selection analyzer is able identify the statistically best scenario from the others. The best one is scenario 17.

From a BMD perspective, scenario 17 is the desirable option. This option calls for striking the bridge, tunnel and launch sites 2 and 3. The mean TBM TIS of 69.78 days is 57% greater than the base case (scenario 1) in which there are no strikes executed on the pre-launch network. The next best alternative in terms of maximizing TIS, is scenario 20, which corresponds to striking everything except the bridge and launch site 3. The second-best option leads to a mean TIS that is just one day shorter than the best alternative.

Table 2. Average TBM Time in System

Scenario	Mean TIS (Days)	95% Confidence Interval		Mean Minimum TIS (Days)
		Lower Bound	Upper Bound	
1	44.43	44.12	44.73	8.58
2	53.94	53.64	54.24	9.18
3	55.82	55.54	56.10	9.16
4	52.76	52.48	53.04	9.11
5	50.17	49.89	50.45	9.12
6	57.39	57.10	57.68	9.16
7	49.01	48.73	49.30	9.05
8	46.53	45.90	47.16	8.58
9	44.93	44.58	45.28	11.05
10	44.07	43.77	44.38	8.58
11	48.25	47.62	48.87	8.59
12	46.59	46.26	46.93	11.10
13	45.90	45.60	46.21	8.61
14	47.67	47.11	48.24	8.59
15	47.99	47.40	48.58	8.60
16	50.36	50.04	50.67	11.58
17	69.78	69.50	70.05	9.51
18	46.71	46.09	47.33	10.99
19	49.00	48.35	49.66	11.46
20	68.82	68.22	69.43	11.78

The orange shading indicates the statistically best alternative for maximizing mean TIS. The best scenario is determined by the Subset Selection Analyzer function in Simio.

While the top two scenarios have similar mean TIS values, they incorporate a different number of targeted strikes. Scenario 20 contains seven strikes, while scenario 17 contains four strikes. This effect highlights the priority of strike combinations. Based on scenarios 8, 9, and 10, strikes against the maintenance site, storage unit, and fuel depot, result in marginal delays in mean TBM TIS. It matters more to strike the right locations, not the most locations. Instead of attacking seven locations in the LLN depicted in Figure 1, a better outcome can be achieved by striking just four locations.

To further advance the importance of strike combinations, view scenario 19. This scenario also calls for seven different attacks, yet the mean TIS is almost 30% less than the mean TIS after an equivalent number of attacks under scenario 20. Moreover, the seven strikes in scenario 19 delay the average TBM by only five days in the system compared to when there are no LLN interdictions. Even single strike operations, such as scenarios 2, 3, and 4, all have greater mean TIS values than scenario 19. This surprising result is likely due to the positions of the surviving locations in the LLN. When a bridge, tunnel, or elevated road is attacked, the TELs can still be randomly routed to any launch location, whether that destination is far or close. In scenario 19, however, the only remaining route (elevated road) and launch site (launch site 3) have the smallest distance between them. Thus, the TELs are forced to travel and launch ballistic missiles via this shortest path, causing a low average TBM TIS. More obviously, it is advantageous to maximize the distance between the locations that are not selected for strike.

Expounding on the notion of target selection, we are able to quantify the benefit of limiting the adversary to one route coupled with the furthest corresponding launch site. For example, in scenarios 17 and 20, the only routes remaining are the elevated road and the bridge, respectively. The only launch sites remaining in these scenarios are launch sites 1 and 3, respectively. These remaining launch sites are the furthest ones possible, as illustrated in Figure 1, in both scenarios. Consequently, scenarios 17 and 20 lead to the largest mean TIS values. On the other hand, in scenarios 15 and 19, the lone surviving launch site is accessible either by all routes or by the closest route. These two scenarios lead to small delays in mean TBM TIS. In sum, the strategy of sparing from strike one launch site and the longest associated route, as opposed to sparing one launch site and the nearest associated route, leads to an average increase of mean TIS of 43%.

Viewing Table 2, there is one output value that requires additional scrutiny that cannot be explained operationally. Scenario 10, which includes a fuel depot strike, results in a lower average TBM TIS than scenario 1. Generally, interdicting an adversary's missile supply network, especially such an essential installation, decreases efficiency in outputting TBMs. Two possible reasons that scenario 10 leads to a slight decrease in mean TIS are the assumed refueling service times and the stochastic nature of simulation modeling. When a fuel depot is neutralized by strike, the refueling time changes marginally from that of a random triangular distribution with parameters (10, 12, 13) hours to that of a random triangular distribution with parameters (15, 17, 18) hours. Moreover, the TELs travel times to reach the launch locations are stochastically generated, dependent on triangular distributions as well. As a result, the TELs may have traveled faster along these routes under scenario 10 than they did in scenario 1 leading to a smaller mean TIS. However, the mean minimum TIS for both scenarios are the same, indicating at least that the strike package represented by scenario 10 will have little effect on missile launches, given the parameters selected for our model.

We proceed to analyze the mean TBM TIS using specialized boxplots delivered by Simio for each of the 20 scenarios. Displayed in Figure 2, the boxplots are generated to illustrate the range of the mean TIS values across scenarios. Simio plotting functions overlay histograms on the boxplots to depict the output distributions of the mean TIS metric.

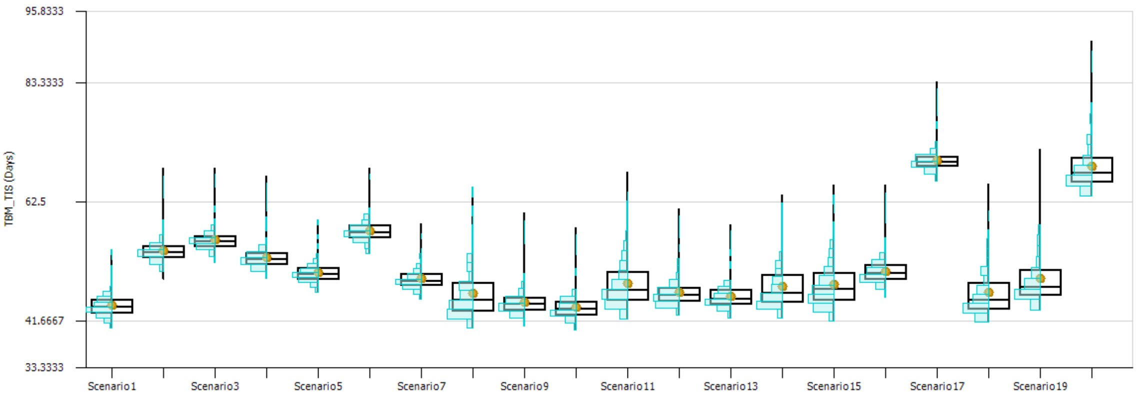


Figure 2. Boxplots of TBM TIS for Each Strike Operation Scenario

Scenarios 17 and 20 once again stand out from the group as having the greatest mean TIS. Among the other 18 alternatives in Figure 2, there is not a clear best attack strategy. However, scenario 6 appears to have the third greatest mean TIS, as evidenced in Figure 2 and Table 2. Scenario 6, which coincides with striking the tunnel and launch site 2, also has a relatively small range of possible mean TIS values. This effect is indicative of a reliable strategy. Furthermore, scenario 6 supports the aforementioned claim about maximizing the distance between spared locations. Demonstrated in Figure 1, both the tunnel and launch site 2 are located in the middle pre-launch network. Destroying these targets results in more distance to travel by the TELs. The longer TELs are required to travel, the longer the average TBM spends in the system.

Regarding the range of mean TIS, several scenarios appear to have larger interquartile ranges. These scenarios include scenarios 8, 11, 14, 15, 18, 19, and 20. These strike combinations share one location in common, the maintenance facility. The maintenance facility has the widest service distribution among all of the locations in the LLN. Destroying half of the enemy's maintenance capabilities induces greater variance in the resultant mean TIS values because more TELs may be immobilized at the same time.

Other than analyzing the mean TIS, we also observe the mean minimum TIS as shown in Table 2. Though this statistic is not the primary concern in this exploratory study, it can have greater importance in assessing the robustness of the different strike strategies. Rather than maximizing the average TIS, another critical goal could involve maximization of the mean minimum TBM TIS. Looking at the mean minimum TIS values across all of the scenarios, we notice that scenario 17 does not lead to the greatest mean minimum TIS. In other words, the strike combination that maximizes the average TBM TIS, is not necessarily the best solution for increasing mean minimum TIS. The greatest mean minimum TIS values come from scenarios 16, 19, and 20. Interestingly, each of these scenarios calls for a strike on the short-term storage facility. In fact, when the storage facility is not targeted in a strike combination, the mean minimum TIS barely surpasses the 9.5-day threshold.

Recall that the LLN operates on a first-in-first-out basis. Due to this method of operation, the minimum TIS values are linked to the TBMs generated soon after system initialization. Alternatively, missiles that are created earlier have lower average TIS values. This behavior occurs because the TELs waste less time refueling or undergoing maintenance. Nevertheless, because all TBMs are not equally likely to have the same TIS value, we consider another statistic in our analysis. In addition to TIS, we also investigate the overall time required to complete all 600 missile launches.

B. AVERAGE TIME TO COMPLETE LAUNCHES

The second metric we analyze is presented in Table 3. Table 3 displays the amounts of time required to launch the entire reserve of 600 TBMs for all 20 strike scenarios. Corresponding confidence intervals and standard deviations for mean TTC are recorded as well. The last column in Table 3 denotes the percentage increase in mean TTC from the base case scenario.

Table 3. Average Time to Complete All TBM Launches

Scenario	Mean TTC (Days)	95% Confidence Interval		Standard Deviation of TTC (Days)	% Increase from Base Case Scenario
		Lower Bound	Upper Bound		
1	75.40	75.05	75.75	2.49	-
2	93.05	92.71	93.39	2.44	23.4
3	96.90	96.57	97.23	2.35	28.5
4	90.96	90.64	91.27	2.27	20.6
5	85.56	85.26	85.86	2.15	13.5
6	100.23	99.90	100.57	2.37	32.9
7	83.45	83.13	83.77	2.29	10.7
8	78.01	77.28	78.74	5.20	3.5
9	75.08	74.69	75.47	2.78	-0.4
10	74.97	74.65	75.29	2.30	-0.6
11	81.32	80.61	82.03	5.05	7.9
12	78.31	77.92	78.71	2.80	3.9
13	78.49	78.14	78.83	2.48	4.1
14	80.52	79.89	81.15	4.49	6.8
15	81.51	80.82	82.19	4.91	8.1
16	84.60	84.26	84.93	2.40	12.2
17	124.44	124.13	124.75	2.21	65.0
18	77.27	76.54	77.99	5.21	2.5
19	80.07	79.32	80.83	5.38	6.2
20	119.36	118.73	120.00	4.52	58.3

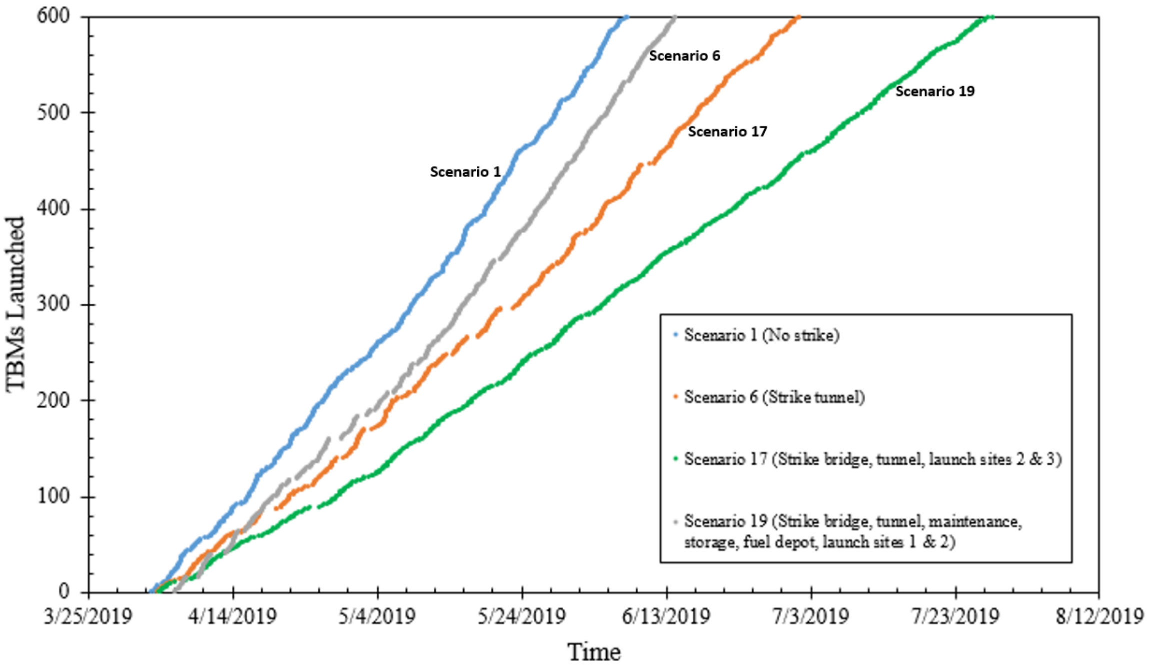
The orange shading indicates the statistically best alternative with the largest mean TTC value. The best scenario is determined by the subset selection analyzer function in Simio.

The results outlined in Table 3 reinforce the previous analysis regarding mean TIS. Scenario 17 is statistically the best, while scenario 20 is the next best alternative. On average, executing the strike combination under scenario 17 results in over 124 days to launch all 600 TBMs. Stated in Table 3, this effect presents a 65% delay in TTC than the base case. Scenario 20 also produces a significant delay in launch completion, increasing TTC by over 58% compared to the base case with no strikes.

Table 3 also supports strike scenario 6 as the third highest alternative. The associated mean TTC is roughly half of the delay of the best scenario, but still surpasses a 100-day threshold. Additionally, we quantify the futility of strike scenario 19. Considering this option calls for the maximum number of seven strikes, the corresponding five day increase in mean TTC feels marginal. Conversely, several single strike scenarios 2, 3, and 4 are more efficient in delaying TTC as portrayed in the last column in Table 3.

Because we are analyzing the same set of experiments, the inconsistency of scenario 10 still exists. Striking the fuel depot appears to slightly decrease TTC compared to the base case. Also, Table 3 indicates that scenario 9 results in a lower TTC than scenario 1. We attribute these irregularities to model error due to the assumptions made about service times.

Another way to visually analyze mean TTC is through a scatter plot of missile launches over time. Figure 3 shows four curves representing a subset of key strike scenarios 1, 6, 17, and 19. These scenarios are chosen to illustrate the effects of different strike combinations on the LLN.



The time series of ballistic missile launches of four of 20 possible scenarios are displayed. The purpose of the time series is to illustrate the delay of TBM launches resulting from the effects of BMD strike operations. Effects vary by quantity and location of strikes.

Figure 3. TBM Launches over Time

We intentionally label the horizontal axis with dates to highlight the magnitude of TTC increases. March 25, 2019 is the assumed initialization date of the LLN system for each simulation run. The date format provides a different perspective on the amount of delay incurred by the enemy.

As displayed in Figure 3, the curve representing scenario 17 strike conditions has the smallest slope. The shallower slope indicates a more gradual increase in TBM launches. In contrast, the curve corresponding to no strikes executed on the LLN retains a much steeper slope as time increases. Additionally, we gain a sense of the delay imposed on the enemy to launch TBMs by noticing the amount of separation between the curves. All of the TBMs are launched by June 7 for the base case as opposed to July 28 for the best case. Figure 3 was generated with one replication for each of the four alternatives, so future TTC values may vary.

Lastly, we analyze the variability of mean TTC values. We measure variability by calculating the standard deviations of mean TTC as listed in Table 3. Ranges can be visually analyzed as well using Figure 4.

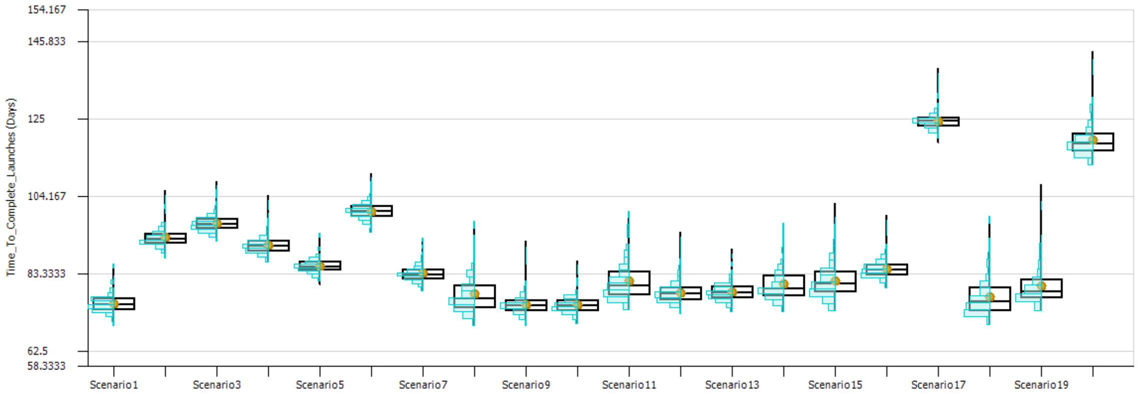


Figure 4. Boxplots of Average Time to Complete All TBM Launches

Once more, striking the maintenance facility appears to lead to a greater range of mean TTC values. All other strike combinations result in smaller interquartile ranges and standard deviations less than three days. Scenario 17 continues to dominate because it has the highest mean TTC and relatively low variance. Therefore, scenario 17 appears to be the best alternative to delay enemy ballistic missile launches.

VI. CONCLUSIONS

As technology improves and foreign adversaries grow competitive, TBMs will continue to threaten the United States and its allies. The ease of manufacturing and innate mobility make ballistic missiles an attractive weapon for hostile countries and terrorist organizations alike. Conventional methods of BMD, such as post-launch interception, deterrence, and passive defense, are insufficient and uncertain; however, combined with AO, this multi-layered approach can lead to improved regional security against TBMs. BMD AO is designed to prevent or delay ballistic missile launches by striking the enemy's LLN. While the strike capabilities exist, the decision-making tools do not. The DoD lacks a method to calculate and compare the effects of various strike alternatives. Consequently, military leaders may be risking lives and resources by failing to select the optimal locations in an LLN to attack.

In this thesis, we present research that enhances quantitative BMD strike operations analysis. We introduce a method to assist military strategists in making aggressive decisions to minimize foreign ballistic missile threats. This method employs simulation modeling techniques because of their inherent flexibility to model complex stochastic behavior. Not only can adaptive changes be applied to system input parameters, but also network effects and interactions can be investigated over time.

Over the course of this research, we outline the quantitative method we hope will guide future decision makers. Using discrete-event simulation software, we construct an enemy's standard LLN and implement the appropriate logic to approximately model the flow of TBMs. Then, we determine feasible targets and model the effects of striking these locations. The goal is to maximize the delay of a finite set of TBM launches. To measure this goal, we investigate time-based metrics including mean TIS and TTC. Finally, we replicate experiments and analyze the results. The design of experiments includes a variety of strike combinations, and the subsequent analysis includes comparing metrics and exposing trends.

The LLN used in this research is a placeholder for the LLNs of particular countries of interest. In turn, the conclusions we draw from our experimentation cannot be directly generalized. The main contribution is not that scenario 17 is the best alternative for strike operations; rather, that we can use modeling processes and experimentation to estimate the result of different actions. We do not seek to suggest specific strike locations, but to guide the thought process behind choosing such locations.

A. FUTURE WORK

Because this study establishes a proof of concept, there are numerous avenues for successive research. Primarily, future real-world applications would require refining model input parameters such as authentic service and transit time distributions. This refinement would also include modeling the limited capacity of the ballistic missile storage units. Future analysts can also incorporate strike probabilities since the strikes are not guaranteed to hit their intended targets. Similarly, the strikes may connect, but fail to completely incapacitate the facilities. Thus, analysts can implement a reduced flow into these handicapped installations. Moreover, researchers can investigate LLN reconstitution times. For example, if BMD AO involves striking a bridge, the enemy will likely rebuild the bridge for continued utilization. The stochastic effects of this reconstructive process can certainly be modeled in simulation software.

The BMD strike analysis performed in this thesis assumes that strikes occur prior to system initialization. Therefore, future work can focus on executing strikes during the simulation run. This adjustment would permit modeling the destruction of TBMs and their removal from the system. As a result, the number of missiles successfully launched would become a much more meaningful statistic in simulations over a fixed period of time. Future analysts would then be able to model an LLN with recurring TBM production at a specified inter-arrival rate instead of analyzing the delay of a finite set of launches.

Additionally, future analysts can proceed further left of a typical LLN. This means modeling the flow of materials and personnel required for manufacturing the TBMs into the pre-existing network simulation. In addition to preventing TBMs from launching, military strategists can aim to reduce the number of TBMs even created.

Lastly, applications of additional analytical tools may also be explored, such as optimization when the LLN characteristics are known well, or stochastic optimization as an adjunct to the simulation methods presented in the thesis.

B. IMPACT

As denoted in the 2019 Missile Defense Review, the DoD intends to focus on AO as a means of BMD. Currently, DoD analysts lack the requisite methodology for determining the optimal locations to strike. The research presented in this thesis attempts to fulfill this need.

In the modern world, information is power. Calculated tactics and rational responses distinguish the United States from hostile nations and organizations guided by temperamental leaders. Such analytical decision making is pivotal to saving lives and maintaining trust of U.S. service members and civilians alike. Every decision has consequences, but it is no longer enough to know what they are. We must quantify them.

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