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A SYSTEMS ANALYSIS ON THE EFFECTIVENESS OF HYPER-VELOCITY GUN SYSTEM (HVPGS) FOR GROUND-BASED AIR AND MISSILE DEFENSE

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THESIS

A SYSTEMS ANALYSIS ON THE EFFECTIVENESS OF HYPER VELOCITY GUN SYSTEM (HVPGS) FOR GROUND-BASED AIR AND MISSILE DEFENSE

by

Derek T. Tay

September 2020

Thesis Advisor: Eugene P. Paulo
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13. ABSTRACT (maximum 200 words)

This thesis investigates the employment of Hyper Velocity Projectiles (HVPs) as interceptors for the Army's Air and Missile Defense (AMD) enterprise in the 2030–2035 timeline. The research recommends a proposed systems architecture for the incorporation of an HVP Gun System (HVPGS) to an AMD enterprise operating in a contested environment, with emphasis on the operating characteristics of the HVPs and their integration onto the firing platform.

The study then develops a realistic operational scenario and models it using the ExtendSim modeling tool. Through the systems engineering process, the study traced the Army's AMD requirements and functions throughout the Requirement and Functional Analysis efforts up to the generation of an alternative concept of operation for the AMD enterprise. The analysis method enables the conduct of a quantitative comparison of HVP characteristics that influence the operational success of the AMD enterprise against an enemy in a missile defense engagement.

The objective of this thesis is to design an alternative system architecture and concept of operation for the Army's AMD enterprise to employ HVPGS to better defend key U.S. and allied bases in the Western Pacific. Such a system would capitalize on the versatile and cost-effective HVP interceptors to address a potential salvo attack's ability to overwhelm existing missile defenses as well as improve overall cost exchanges for enhanced operational sustainability in the longer term.

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A SYSTEMS ANALYSIS ON THE EFFECTIVENESS OF HYPER VELOCITY GUN SYSTEM (HVPGS) FOR GROUND-BASED AIR AND MISSILE DEFENSE

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	Anti-Access/Area-Denial
AMD	Air and Missile Defense
ARDEC	Army Armament Research Development and Engineering Center
ASCMs	Anti-Ship Cruise Missiles
BMD	Ballistic Missile Defense
C2	Command & Control
CEP	Circular Error Probability
CER	Cost Engagement Ratio
CMD	Cruise Missile Defense
CONOPS	Concept of Operations
C-RAM	Counter-rocket, artillery, and mortar
C-UAS	Counter- Unmanned Aerial System
DODAF	Department of Defense Architecture Framework
DOE	Design of Experiments
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership and education, Personnel, and Facilities
EKV	Exo-atmospheric Kill Vehicles
EMRG	Electro-Magnetic Rail Gun
EW	Electronic Warfare
FW	Fixed Wing
HHQ	Higher Head-Quarters
HVPGS	High Velocity Projectile Gun System
HVPs	High Velocity Projectiles
IAMD	Integrated Air and Missile Defense
IDEF	Icam Definition for Function Modelling
IFPC	Indirect Fire Protection Capabilities
IRBM	Intermediate Range Ballistic Missiles
JIAMDO	Joint Integrated Air and Missile Defense Organization
LACMs	Land-Attack Cruise Missiles
LML	Life cycle Modelling Language

LTAMDS	Lower-Tier Air and Missile Defence Sensor
MBSE	Model-Based Systems Engineering
MDA	Missile Defense Agency (MDA)
MDO	Multi-Domain Operations
MOE	Measures of Effectiveness
MOP	Measures of Performance
MRBM	Medium Range Ballistic Missiles
NOLH	Nearly Orthogonal Latin Hypercube
NSFS	Naval Surface Fires Support
OA	Operational Activities
OV-1	Operational View–1
PAC-3	Patriot Advanced Capability-3
PLA	People Liberation Army
RW	Rotary Wing
SATCOM	Satellite Communications
SCO	Strategic Capabilities Office
SM-3	Standard Missile-3
SOS	System of Systems
SRBM	Short Range Ballistic Missiles
TBM	Theatre Ballistic Missile
TELs	Transporter Erector Launchers
THAAD	Terminal High Altitude Area Defense
TTP	Tactics, Training and Procedures
UAS	Unmanned Aerial System
UAVs	Unmanned Aerial Vehicles
USASMC	U.S. Air and Space Missile Command

EXECUTIVE SUMMARY

The rise of near peer competitors and their expanding investments in missile technologies have yielded an increasingly volatile and complex security environment for U.S. forces operating globally (Joint Staff 2016). A notable concern lies with potential adversaries proactively embracing the proliferation of precision-strike systems, long-range sensors, command and control networks, and precision weapons to effectively hold key U.S. and allied infrastructure as well as personnel at risk particularly in the Western Pacific region (Thomas 2019). To compound the problem, conventional U.S. Anti-Missile Defense (AMD) systems have over time been optimized to address a more limited size of hostile munitions from smaller rogue nations and not the potentially larger salvos from other well-equipped and sophisticated near peer competitors. Inadvertently, the equipping strategy utilized by U.S. forces in the past have resulted in smaller interceptor procurement quantities that impede economies of scale and greatly increases overall cost of conventional AMD systems (Gunzinger and Clark 2016).

To address these concerns, this author explores the use of a Hypervelocity Gun System (HVPGS) to fire a new generation of projectiles known as Hyper Velocity Projectiles (HVPs) with the ability to reach speeds of Mach 5 and above in flight. It is expected that the capability offers great potential as a versatile weapon system in support of a wide range of mission profiles (O'Rourke 2016). The use of the HVPs also relieves the need for a propulsion system and together with its relatively small size, allows for the potential of a deeper magazine with a lower cost per shot (Sydney 2018). Therefore, this thesis discusses the prospective HVPGS system level design and proposes a revised operational concept for the HVPGS to be integrated with the existing Army's AMD Enterprise, bolstering its defensive capabilities against near peer ballistic salvo threats (U.S. Army Space and Missile Command [USASMC] 2019).

To validate these assertions, this author also proposes an enhanced Air and Missile Defense Enterprise Model (Using ExtendSim) that incorporates the use of the HVPGS to investigate a set of system level design characteristics that the HVPGS should achieve to

meet the defined threat scenario and survivability objectives. The proposed model considers six operational characteristics or factors which comprises of the HVPGS's Magazine Depth, Probability of Hit, Maximum Engagement Range, Munition Speed, Firing Interval (Rate of Fire) and Number of Launchers. To investigate these factors, a Design Of Experiments (DOE) methodology utilizing the Nearly Orthogonal Latin Hypercube (NOLH) technique was employed by the author to generate a multitude of design points for the various factors (Sanchez 2006). The designs points are simulated through the model to determine which design points meet the desired attrition and survivability objectives.

From the results, this author used linear regression analysis to develop a best-fit linear model to predict Blue Force Attrition whilst identifying the most significant factors. In summary, this author found that the Firing Interval (Rate of Fire), Probability of Hit and No. of Launchers had constituted the highest levels of influence on the overall system effectiveness in meeting the operational objectives. While the results may seem obvious, further analysis of the results delivered quantitative values for the various factors through partition analysis that would provide decision makers with critical reference figures when delving into the more technical design aspects of the system. In addition, the author also demonstrated that incorporating the proposed HVPGS into the Army's AMD enterprise would significantly reduce the Cost Engagement Ratio (CER) against adversarial missiles by reducing the use of the more costly PATRIOT interceptors in engagement. Finally, this author hopes that through this thesis, military planners will be provided with a much more sustainable and operationally effective missile defense alternative for U.S. forces in today's complex security environment.

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I. INTRODUCTION

Rapid advances in weapons technology and development are fielding potential challenges for the United States and its allies. Increasingly nations are capable of fielding an increasingly diverse and modern range of offensive air and missile systems that threatens U.S. forces, allies, and partners in varying regional theaters. These adversaries possess a growing arsenal of guided precision munitions that could be launched from the ground, air, and sea, with the intent of overwhelming existing air and missile defenses of U.S. forces and hold at risk U.S. forces (Department of Defense [DOD], 2019).

In this context, China, largely viewed as a revisionist power, is building up an array of Ballistic and Cruise Missiles that have increasingly demonstrated the capability to threaten U.S. forces, allies and partners. In particular, the possible use of large and complex Theatre Ballistic Missile (TBM) salvos attacks as part of China's Anti-Access/Area-Denial (A2/AD) strategy is deemed a core tenet that would effectively limit U.S. power projection and impose unfavorable cost exchanges in the event of engagement (McCarthy 2010).

As such, this thesis aims to provide U.S. defense planners with a technological alternative to offset the aforementioned asymmetries in AMD capabilities that may provide China with leverage to exercise coercive political and military advantages in the event of a regional crisis or conflict in the region. This research focuses on the systems level design and operational employment of a HVPGS in support of the Army's AMD Enterprise architecture against a potential ballistic missile barrage and to investigate its potential cost benefits and operational effectiveness in comparison to the Enterprise's existing Ballistic Missile Defense (BMD) systems currently in deployment.

A. BENEFITS OF STUDY

The missile threats faced by U.S. forces, allies and partners in the Western Pacific are becoming increasingly sophisticated with extended reach, mass and enhanced precision to effectively restrict U.S. freedom of movement and force projection capabilities. To combat such threats and level the unfavorable cost exchange ratio of missile defenses, new technological enablers must be readily explored and adapted to support the overall AMD capabilities of U.S forces. While still in the exploratory stages, research and development of High Velocity Projectiles (HVPs) have advanced significantly in recent years and are poised as a potential solution to the current operational challenge. As such, this research aims to design an alternative system architecture and concept of operation in the employment of a HVPGS to better defend key U.S and allied bases in the Western Pacific against a growing arsenal of potential ballistic missiles threats. Such a system would capitalize on the use of versatile and cost effective HVP interceptors to address a potential salvo attack's ability to overwhelm existing missile defenses as well as improve overall cost exchanges for enhanced operational sustainability in the longer term.

B. METHODOLOGY

Using a Systems Engineering approach, this study begins by looking into the capability needs for U.S. land-based assets/forces against ballistic and cruise missile threats. This is conducted through a thorough Stakeholder analysis to identify the needs and establish relevant and suitable Measure of Performance (MOP) and Measures of Effectiveness (MOE) to evaluate the suitability and performance of the HVPGS design.

The next step is to define and illustrate a feasible operational concept incorporating an HVPGS as part of the U.S. Army's AMD system architecture, using the DOD Architecture Framework (DODAF) operational view one (OV-1). Subsequently, through operational analysis, the study aims to discern the activities needed to achieve the intended mission objectives. The distillation of operational activities allows for the derivation of the envisaged system's required functions, followed by a mapping of the operational activities to the former to ensure all activities are addressed. The conduct of Functional Analysis results in a functional hierarchy that would further drive the subsequent conduct of sub-system analysis and function to sub-system mapping of the system.

The resultant system architecture ensures that traceability exists between the requirements, functions, and components of the HVPGS within the AMD system architecture and design. Next, through design of experiments and leveraging ExtendSim modelling Software, the study seeks to propose a system configuration in support of HVP interceptors to validate the Concept of Operations (CONOPS). The simulation allows for an investigation into the potential impacts of various HVP characteristics such as its rate of fire, probability of hit, projectile range and speed to determine the effectiveness and operational impacts to the system and how they enhance the overall survivability of protected ground forces or assets against ballistic missile threats.

Lastly, the study aims to conduct an analysis on the potential cost benefits from the employment of a HVPGS vs the use of conventional interceptors as part of the AMD mission. Overall, this methodology leverages the waterfall model process introduced by Royce in 1970. The process begins with the analysis of requirements by the stakeholders and finishes with the testing of the candidate designs through a series of simulation models for analysis. The key to this process is in the feedback loops, which can take place at any step of the process flow and allows for iterative improvement of the design at the individual stages. Figure 1 depicts the waterfall process.

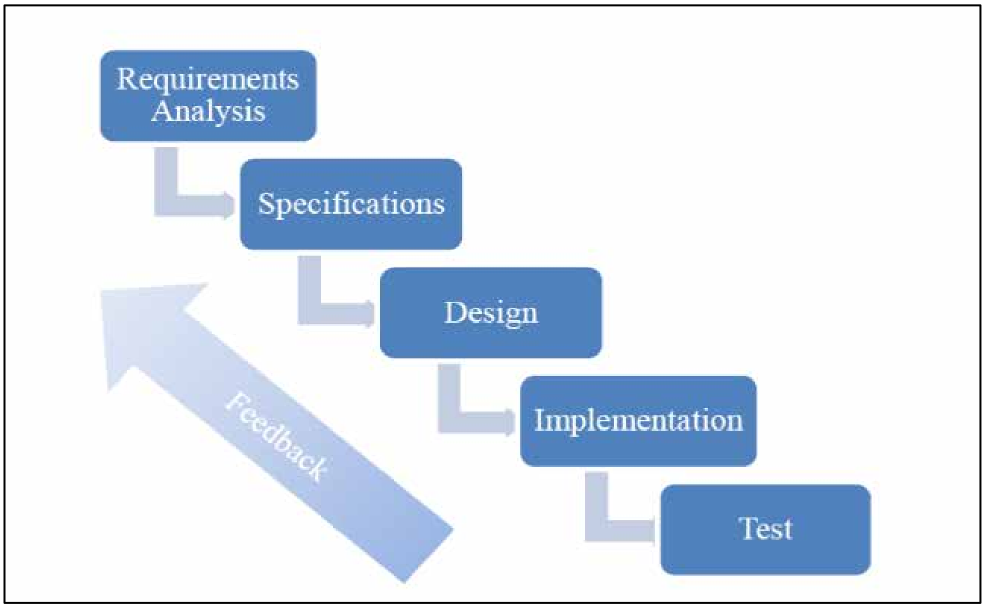

Figure 1. Waterfall Process Model. Adapted from Royce (1970).

C. RESEARCH QUESTIONS

(1) What benefits to overall operational effectiveness (to include lethality to the enemy and friendly force survivability) are provided by the employment of Hyper Velocity Projectiles (HVP) in support of the AMD Mission?

(2) What are the most significant factors in determining the contribution to operational effectiveness in the AMD mission of the HPVs compared to Conventional Interceptors especially against Salvo Threats?

(3) What potential cost benefits are there from the employment of a HVPGS over conventional missile interceptors as part of an AMD mission?

D. THESIS ORGANIZATION

Chapter II describes the fundamental geopolitical impetus with regard to the need for an improved U.S. missile defense capability and the gaps associated with existential systems as part of the current AMD architecture—their evolution and relevance against recent trends of a growing threat profile by Chinese missile capabilities. Subsequently, the concept of an AMD approach and an active and layered missile defense concept of operation is discussed to break down the System of Systems (SoS) architecture and provide a basis for consideration in the integration of an HVPGS into its construct and concept of operation. A brief categorization of current long to short range air and missile defense systems as well as HVP compatible gun platforms available in the U.S. defense industry is also discussed to inform the reader of the possible existing design alternatives for the proposed HVPGS.

Chapter III discusses the SE process used to direct the design of an HVPGS for the AMD architecture. Capability needs with respect to the current threat environment are first identified followed by the conduct of stakeholder needs analysis. This is succeeded by the development of the system's CONOPS and its prevailing operational activities to achieve its objectives. The determination of MOEs and MOPs are also discussed here to form the basis for the subsequent validation of the proposed concept of operations through simulation modelling.

Chapter IV outlines the scenario development for the simulation model and also describes the DOE conducted using the simulation results to explore several configurations and employment of the HVPGS comprised of various interceptor capabilities. The scenario details an engagement between a deployed U.S. AMD capability (Blue force) against a barrage of ballistic missile threats (Red force) in the 2030–2035 timeframe. Using the model and DOE conducted, the study investigates the operational effectiveness of integrating an HVPGS within an AMD System against current capabilities and also evaluates the impact of HVPs through a variation of its operational characteristics in engagement. The engagement is modeled using the ExtendSim modelling tool and the results will be discussed with reference to the previously defined MOEs for the model.

Chapter V incorporates the findings from the DOE and simulation results to provide recommendations and insights for the ideal force composition of an HVPGS operating within the AMD architecture to enhance U.S. AMD capability. In addition, a cost analysis comparison is also conducted to provide credible recommendations on the use of HVPGS in AMD operations. Finally, a conclusion and proposal of potential areas of future research is suggested.

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II. LITERATURE REVIEW

This chapter discusses contextual information that is fundamental to the thesis research. The span of coverage includes the impetus underlining the strategic competition between the U.S. and China to the concept of the existing U.S. Army Air and Missile Defense strategy. In addition, this chapter also provides an overview of existing missile defense systems, new and emerging HVP technology and finally a discussion on the Model Based System Engineering approach to system design and analysis.

A. A NEW CONTESTED ENVIRONMENT

In recent years, China has emerged as a regional powerhouse both economically and militarily. As such, it has increasingly challenged the global geopolitical landscape and world order led by the United States since the end of the Cold War. This emergence has inevitably led to rising tensions and rivalry with the United States, raising the possibility that China will become a military powerhouse that the U.S. may have to contend with in a future conflict scenario (Gvosdev 2019).

In recent years, China's geopolitical orientation and aspirations have refocused the People Liberation Army's (PLA) traditional continental emphasis to an increasingly maritime orientation that challenges the traditional American strength of power projection (Thomas 2019). Critically, China have exploited the technological as well geographical asymmetry against the U.S., embracing the proliferation of C2 networks, precision-strike systems and space or over-the-horizon (OTH) sensors to efficiently hold U.S. and allied infrastructure as well as personnel at risk key in the Western Pacific region (Thomas 2019).

The proliferation of growingly affordable advanced technology will also enable adversaries to increasingly contest the U.S. military's capabilities to project power and maintain dominance across domains in a new contested environment. The 2016 U.S. Joint Staff J-7 publication titled Joint Operating Environment in 2035 describes this new contested environment as such.

> The emerging security environment can be described by two distinct but related sets of challenges. The first is contested norms, in which

> increasingly powerful revisionist states and select non-state actors will use any and all elements of power to establish their own sets of rules in ways unfavorable to the United States and its interests. The second is persistent disorder, characterized by an array of weak states that become increasingly incapable of maintaining domestic order or good governance. These twin challenges are likely to disrupt or otherwise undermine a security environment that will remain largely favorable to the United States, but less overtly congruent with U.S. interests (Joint Staff 2016, 4).

From the above excerpt, we understand that competition will continue to manifest largely within a military dimension with its character punctuated by the use of proxy non-state actors, leveraging of asymmetric capability advantages and antagonistic posturing in multiple operational domains to challenge the status quo and U.S military primacy. Yet, as an expeditionary force, the U.S. military has largely become reliant on the safe and uninhibited deployment into theaters since the Vietnam War (McCarthy 2010). Therefore, this new challenge to the America's long held superiority is a new paradigm of the contested environment that will see an expanded battlefield across new domains.

B. MULTI-DOMAIN OPERATIONS

From the U.S. Joint Staff J-7 publication titled *Joint Operating Environment in 2035*, one can see that potential adversaries such as China and Russia have expanded the battlefield in many ways. To address these challenges, the U.S. Army articulated a new Multi-Domain Operations (MDO) approach in the TRADOC Pamphlet 525-3-1 titled *The U.S. Army in Multi-Domain Operations 2028* explaining the need to be able to compete and fight over a Multi-Domain spectrum to counter these near-peer adversarial threats and capabilities. They further defined MDO as a military concept approach to achieve U.S. strategic objectives articulated in the *National Defense Strategy*.

The U.S. Army describes Space, Cyberspace, Electronic Warfare (EW), and Information as key facets of adversarial operations. Traditional battlefield limitations are now being overturned due to the effects of multi-domain capabilities, resulting in potential adversaries being less bound by traditionally known geographic and time constraints (TRADOC 2018). Figure 2 depicts an overview of the MDO framework with the various threats and challenges superimposed on the contested areas.

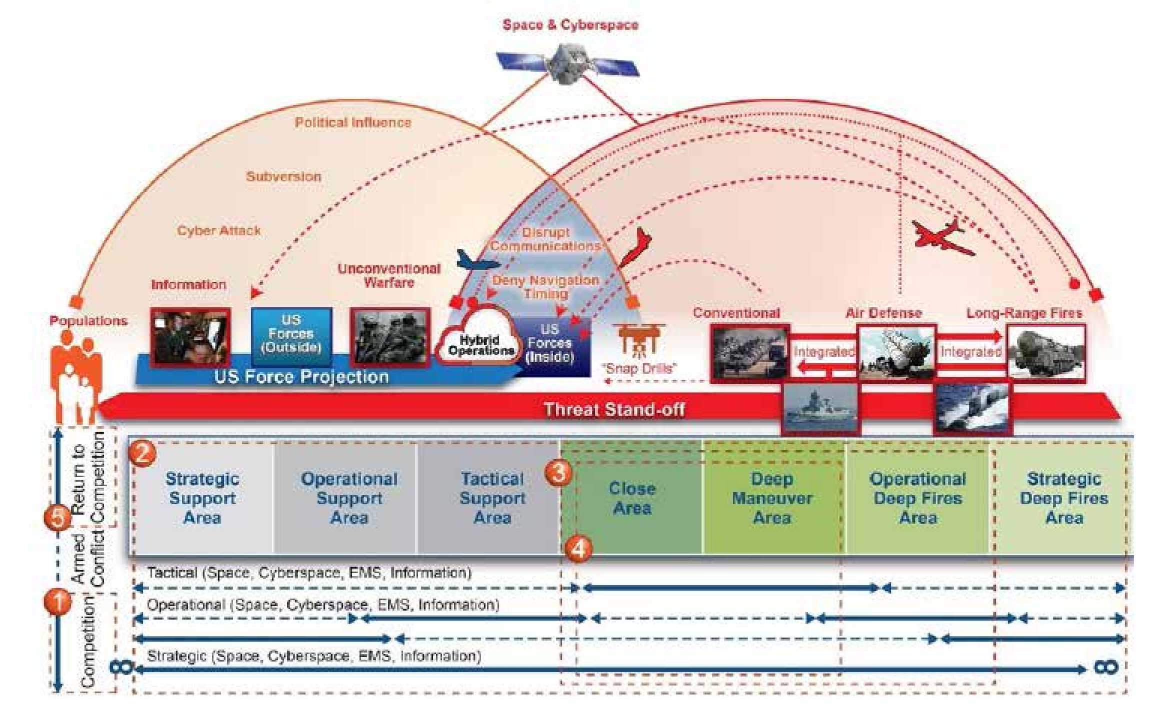

Figure 2. MDO Framework with the Threat Challenges. Source: TRADOC (2018).

From Figure 2, one can see that the threat of long-range precision fires, leveraging space and cyber domain as enablers for pre-emptive and precision targeting, is increasingly being employed to increase the threat standoff advantage and limiting the freedom of maneuver for U.S. force across the operational spectrum. These long-range precision fire capabilities are expected to be employed with enemy air defenses, conventional fires and even in concert with special or unconventional operations to deny or limit U.S. forces in MDO. Therefore, this thesis aims to look at an alternative solution to the current AMD force structure to better support MDO in line with its core tenets.

The publication explains MDO as comprised of three main tenets: (1) Calibrated force posture, (2) Multi-domain Formations, and (3) Convergence. These are mutually reinforcing and common to all, yet their operational realization varies and is dependent on the context in application. However, most importantly for AMD force is the adoption of a calibrated force posture. This is defined as "the combination of capacity, capability, position, and having the ability to maneuver across strategic distances" to support the Joint

Force objectives (TRADOC 2018). Here, the envisaged HVPGS would be employed to provide an improved all rounded defense against a larger spectrum of long-range munitions that could endanger U.S. forces in theater and better support the required mobility across strategic distance unimpeded by enemy fires.

Next, the construct of having multi-domain formations as discussed by the text is to "possess the combination of capacity, capability, and endurance to generate the resiliency necessary for operations across multiple domains" which would be key for self-sufficiency in operations (TRADOC 2018). Here, the HVPGS with its envisaged mobility should be capable of providing a more localized AMD capability against enemy threats that is inbuilt within formations, allowing greater self-sufficiency for independent operations. Finally, the last tenet of convergence refers to "the rapid and continuous integration of capabilities in all domains, the EMS, and the information environment that optimizes effects to overmatch the enemy through cross-domain synergy and multiple forms of attack all enabled by mission command and disciplined initiative" (TRADOC 2018).

C. CHINESE THREATS TO U.S. FORCES, ALLIES AND PARTNERS

Given the vast distances between the areas of primary territorial concerns for China to the United States, the former readily exploits their geographical asymmetry with standoff, long range precision strike weapon systems enabled by a vast network of aviation, submarines, naval systems / platforms to hold U.S. and allied bases in the contested regions at risk (Easton 2014).

For clarity, the Chinese ballistic missile inventory can be classified into Short Range Ballistic Missiles (SRBMs) also known as TBMs, Medium Range Ballistic Missiles (MRBM) and Intermediate Range Ballistic Missiles (IRBM) for distinction. For the purpose of this study, the author aims to examine the key threats posed by the Chinese's ballistic missile inventory to key point targets, such as air bases and naval facilities in the region. Therefore, the focus would be on TBM threats which can be countered or mitigated by the thesis's proposed HVPGS firing HVPs with minimal guidance electronics (Low Probability of Hit) and lower production costs. Figure 3 presents a summary of the known

Chinese ballistic missile inventory while the follow-on section describes the various missile categories for discussion.

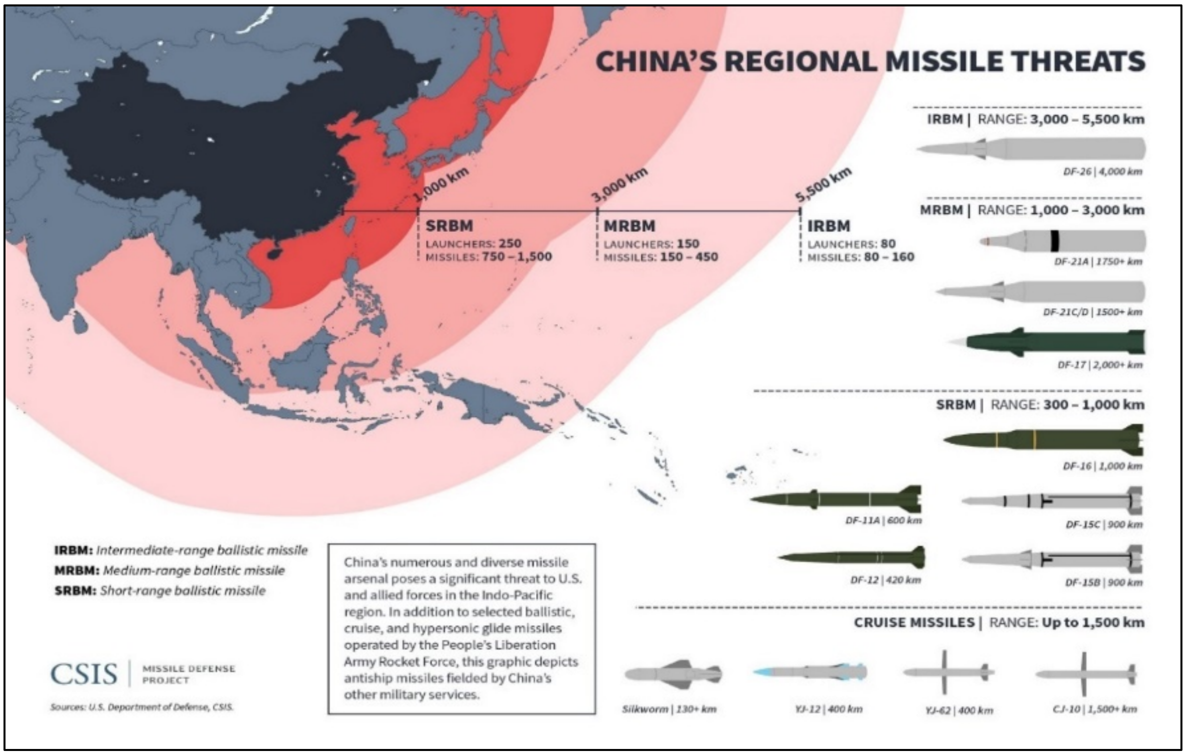

Figure 3. China's Regional Missile Threat. Source: Missile Defense Project (2019).

1. Ballistic Missiles Threats

China's ballistic weapons arsenal comprises largely of mobile regional ballistic missiles that are capable targeting U.S. forces and allies up to the first and second island chain in the Western Pacific (See Figure 3). Critically, China's array of SRBM, MRBM and IRBM are capable of targeting immediate U.S. bases in Okinawa and up to Guam with ranges extending up to 5000 km that supports their increasingly aggressive maritime posture and aspirations (DOD 2016).

Of significance is the large inventory of SRBMs held by China. Notable SRMBs would be the Dong Feng-15A (DF-15A) and its intended replacement, the MRBM Dong Feng-16 (DF-16). These missiles were designed for a "counter-intervention" capability to target U.S. air and naval bases in Japan in the event of a confrontation over Taiwan (Easton 2014). The missiles are mounted on mobile launchers for increased survivability and have ranges up to 1000 km. The DF-15A is largely employed as a tactical missile due to its range and is designed to strike ground based High Value Targets (HVTs) and critical infrastructure. It is estimated that there are around 300–450 DF-15A that are operational since 2015 and it is believed that at least 30 DF-15As have been produced annually till date (Missile Defense Project 2019).

Another notable example to highlight would be the Dong Feng-21C (DF-21c) MRBM. The DF-21C is a land attack, medium-range ballistic missile system that can deliver a payload up to 600 kg, with a maximum range of 2,150 km. It is estimated that there are about 200 DF-21C ballistic missiles held in the Chinese inventory, not accounting for the other DF-21 variants (Missile Defense Project 2019). Altogether, the large inventory of SRBMs and MRBMs means China can likely employ these shorter and cheaper ballistic missiles in ballistic salvos strikes which would be difficult to defeat with current AMD capabilities.

2. Cruise Missile Threats

A secondary and emerging threat aside from ballistic missiles pertains to the recent developments of Chinese capabilities fielding an assortment of ground and air launched Land-Attack Cruise Missiles (LACM) to augment their ballistic missile capabilities (DOD 2016). Notable cruise missiles systems include the ground-launched Changjian-10 (CJ-10) LACM, ground and ship-launched Yingji-62 Anti-Ship Cruise missiles (ASCM) and the Yingji-63 and CJ-20 LACMs that has an operational range of up to 1500 km.

Even though these cruise missiles are much harder to detect than their ballistic counterparts, their flight speed makes them easier to intercept than Ballistic Missiles given that they fly a major portion of its flight path at an approximately constant speed (Reif 2019). However, due to their unpredictable flight path and trajectory, the use of the HVPGS with HVPs that rely on kinetic energy without rocket propulsion capability greatly limits the projectile’s flight maneuverability. This shortcoming indirectly limits its present ability to neutralize Cruise Missiles threats on the battlefield over longer distances. Hence, this author focuses the employment of the HVPGS to augment the AMD defense capability primarily against ballistic missile threats given the current known HVP capability.

Nonetheless, given that Cruise Missiles are considerably inexpensive in contrast to Ballistic Missiles offering the enemy a significant cost exchange advantage against traditional Air and Missile Defense (AMD) systems, it is clear that the asymmetric advantages in further development of these cruise missiles would have serious tactical and strategic implications for regional security moving forward that is deserving of further research in the future (Gormley 2014).

D. U.S. ARMY AIR AND MISSILE DEFENSE

A 2019 publication titled *Army Air and Missile Defense 2028* published by the U.S. Air and Space Missile Command (USASMC) states that to support MDO, there are three essential tasks that AMD forces must execute. These three tasks are defined as "First, AMD must protect maneuvering forces, and their fixed and semi-fixed assets.," "Second, AMD must defend critical assets in the theater and operational support areas against complex, integrated attacks." and "Finally, AMD capabilities must converge to help the joint force air component commander or area air defense commander create windows of superiority in the air domain that the joint force can exploit." (4) according to USASMC (2019). The publication further lists "ballistic missile defense (BMD), cruise missile defense (CMD), defense against manned FW/RW aircraft, counter-UAS (C-UAS), and counter-rocket, artillery, and mortar (C-RAM)" (8) as the primary mission sets for the Army's AMD forces (USASMC 2019).

To achieve these tasks, the publication highlights the use of satellites to augment ground-based sensors for enhanced surveillance capabilities and to enable communications over greater distance. As whole, this network of sensors should provide greater situational awareness to the Army AMD force and facilitate early warning against impending threats (USASMC 2019). In addition, the Army's existing AMD force has built up a portfolio of systems to defend and defeat air and missile threats across the strategic, operational, and tactical operating areas, however, the author believes that the concept and systems employed still have certain gaps that needs to be covered.

The U.S. Army's conduct of BMD includes the use of the Terminal High Altitude Area Defense (THAAD), the PATRIOT System and the Ground Based Missile Defense System to protect assets located in the "Strategic through Tactical Support Areas" (USASMC 2019). BMD systems are designed to counter ballistic missiles, providing multiple engagement opportunities to destroy them before impact (Missile Defense Agency [MDA] n.d.). Neutralizing ballistic missiles in mid-course of the attacking ballistic trajectory entails the use of ground-based interceptors equipped with Exo-atmospheric Kill Vehicles (EKV) to collide with the incoming ballistic missile while coasting in apogee. In the terminal defense phase, BMD systems such as the THAAD and the Patriot Advanced Capability-3 (PAC-3) are employed as the last mile defense against the incoming threat (Hill 2017).

Against cruise Missiles and Fixed /Rotary Winged aircrafts, the U.S. Army utilizes the AMD force to protect assets located in the "Operational and Tactical Support Areas and the Close Areas" (USASMC 2019). Current cruise missile defense capabilities span land, air, and maritime domains. However, in comparison to the BMD system, traditional Cruise Missile defense operate in disparate efforts as there is no overarching system architecture that links the various sensors and shooters in a common operating picture for interoperability (DOD 2019). On land U.S. Army AMD primarily employs the Patriot System which is designed to counter air breathing targets but has since been largely optimized for defense against short ranged ballistic since the Gulf War in 1991, even though the system still retains its capability to counter air breathing threats (Korda and Kristensen 2019) .

The Counter-Unmanned Aircraft System (C-UAS) and Counter-Rockets, Artillery, Mortars (C-RAM) capabilities are primarily employed to provide AMD in the "Close Areas" for localized protection (USASMC 2019). This is a persistent threat that AMD forces will continue to face moving forward, because the sheer volume of these threats in the battlefield can be overwhelming and this threat profile is expected to expand further in the future. Unmanned Aerial Systems (UAS) have also proliferated exponentially and have developed the capability to conduct both reconnaissance and attack operations, representing a significant threat from both state and non-state actors. Swarm technology using drones also adds another dangerous facet to the enemy's potential capability within the threat set. In this area, the publication highlights that the AMD force employs an Indirect Fire Protection Capability (IFPC) which involves using a "kinetic interceptor," a "Lower-Tier Air and Missile Defence Sensor (LTAMDS)," and a "common networked C2 capability," (11) to provide AMD against these threats according to USASMC (2019). Figure 4 depicts the various AMD components in their battlespace.

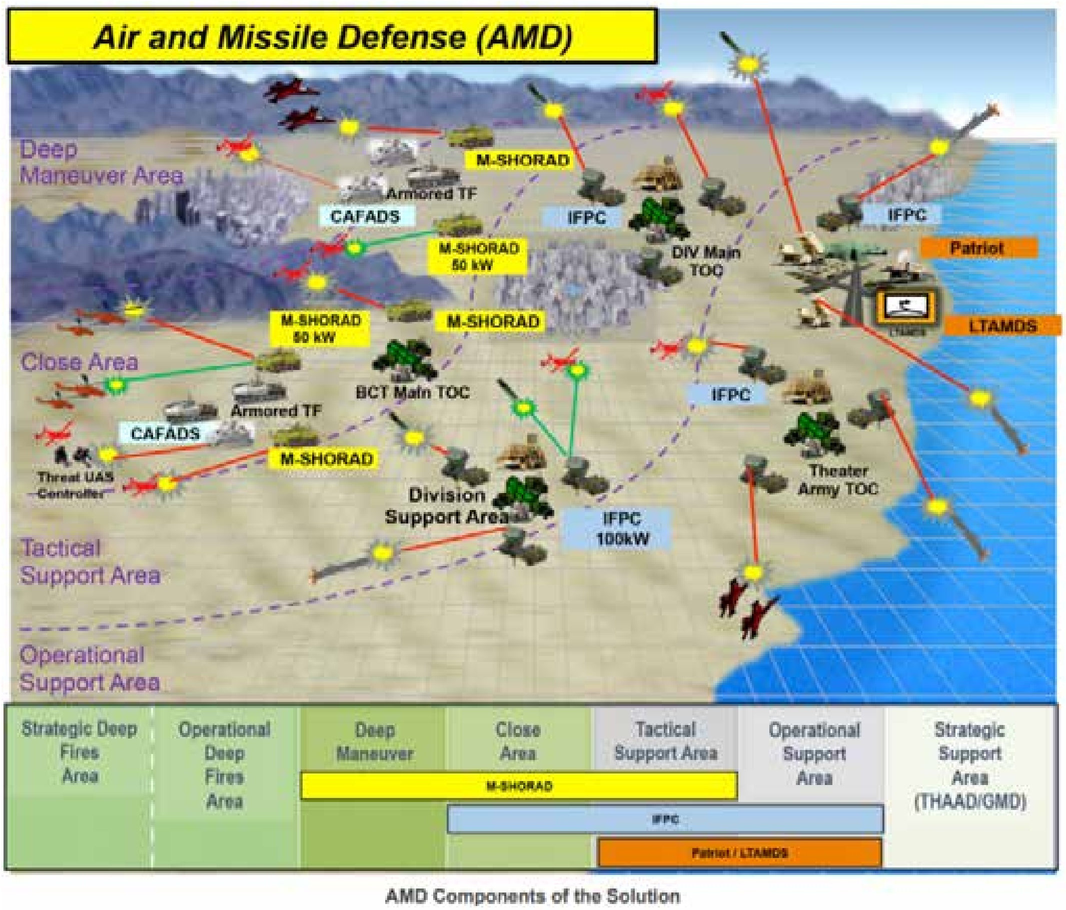

Figure 4. AMD Enterprise. Source: USASMC (2019).

E. SHORTCOMINGS OF CURRENT CAPABILITIES AGAINST BALLISTIC MISSILE SALVO ATTACKS

Current AMD capabilities have exhibited several acute weaknesses in addressing the increasingly complex missile threat landscape. Key factors contributing to this apparent weakness includes a capacity imbalance in missile inventories and an unfavorable engagement cost exchange ratio (Karako 2017). Inadvertently, the vulnerabilities exposed by these shortcomings could expose U.S. targets in forward deployed locations and bases to a devastating first strike. To mitigate these threats, U.S. military may be compelled to relocate its forces outside of the threat envelope, however, the move would also inevitably undermine the credibility of U.S. security guarantees to the global commons (Cohn et al. 2019). Hence, in order for the U.S. to prevail in a conflict against future potential adversaries such as China, it will need to win the race to improve its Missile defense capabilities in competition to its near-peer adversaries. The next section will discuss the challenges and shortcomings highlighted above.

1. Capacity Imbalance

For over three decades, China has invested considerably to strengthen their missile capabilities, taking the lead in fielding ground-launched nuclear-armed and conventionally armed missiles, giving them a significant advantage in terms of missile lethality and inventory relative to the U.S. (Cohn et al. 2019). To compound the problem, U.S. commitments to the INF treaty in the past and a narrowing fiscal environment going forward for the U.S. is also limiting her ability to keep pace with Chinese developments (Weiss 2014). The result is a capacity imbalance especially in terms of ground launched theater missiles which are capable of threatening regional airbases and ports and keep U.S. forces, allies and partners at risk. This capacity imbalance is depicted in Figure 5.

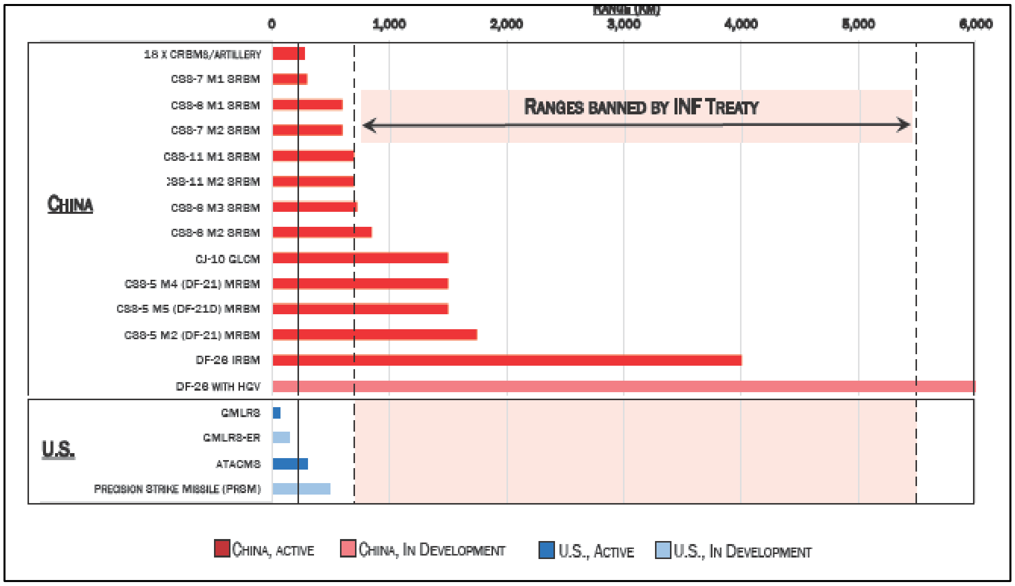

Figure 5. Missile Capability Comparison. Adapted from Cohn (2019).

Consequently, U.S. AMD capabilities are now experiencing a capacity gap in addressing the possibility of these large salvo strikes of guided weapons. Given that the current doctrine employs a layered air and missile defense concept, active defense systems are inherently designed to first intercept enemy missiles at long ranges followed by medium ranges and lastly at short range in a largely sequential order (Joint Staff 2018). The implicit challenge imposed by this operational concept is that larger interceptors with longer ranges are needed to engage the threat from further stand-off distances, hence reducing the total number of interceptors that can be carried by combatants (Gunzinger and Clark 2016). Additionally, these long-range interceptors are costly endeavours which imposes greater fiscal constraints on the number of interceptors that DOD can afford to procure and field for AMD capabilities.

2. Cost and Sustainability

The challenge is that the current generation of missile defense systems have over time been optimized to defeat a limited number of incoming munitions from smaller rogue nations and not the larger salvos within China's inventory (Gunzinger and Clark 2016). Indirectly, the smaller intermittent procurement strategy by the U.S. in the past to address such threats also impede economies of scale which does not improve the overall cost of traditional AMD systems.

An over-emphasis on the development of anti-ballistic missile systems as discussed in the earlier section have also yielded a capability gap in addressing the smaller class of Cruise Missiles threats. This limitation could result in a scenario where a PAC-3 interceptor that is optimized against ballistic threats inadvertently becomes an unnecessarily expensive counter-measure against an incoming cruise missile threat, resulting in an unfavourable cost exchange factor for such interceptions (Karako 2016).

The current unit cost for a ground-based PAC-3 interceptor is about $5.38 million (Gunzinger and Clark 2016). The THAAD interceptor is about $9.4 million each, whilst the SM-3 interceptor for the Aegis BMD is even more expensive at $12.8 million each (Cohn et al. 2019). Comparatively, it is believed that given China's ability to ramp up production of its arsenal of TBMs, each missile would only cost China about $0.5 million each to be produced and developed (Scobell 2001). As such, assuming a counter munition doctrine in which each incoming missile is targeted by a salvo of two interceptors for a higher probability of kill, this engagement strategy would yield a huge asymmetry in the cost exchange factor and will not be sustainable against salvo attacks in the long run (DOD 2002).

F. HYPER VELOCITY PROJECTILE GUN SYSTEM

HVPs are a new generation of projectiles that has the ability to reach speeds of Mach 5 and above in flight and offers great potential as a versatile weapon system to support Naval Surface Fires Support (NSFS), AMD as well as Anti-Surface and Anti-Air capabilities (O'Rourke 2016). Figure 6 depicts the potential capabilities for the employment of HVPs in conjunction with an Electro-Magnetic Rail Gun (EMRG) or Conventional Powder Gun System.

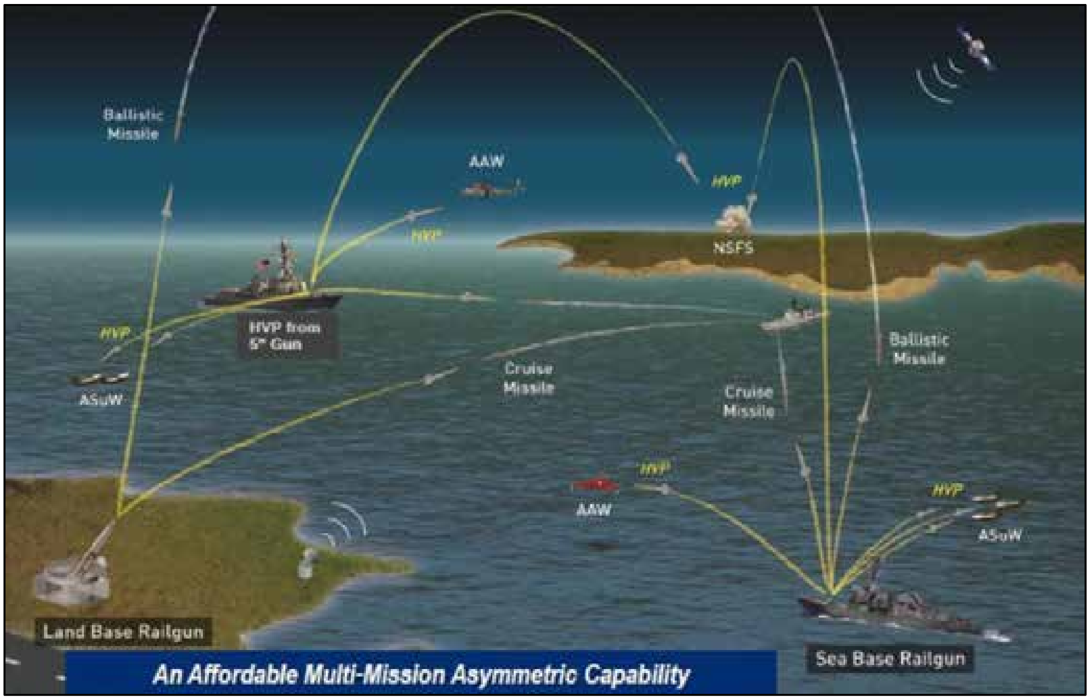

Figure 6. HVPGS CONOPs Application. Adapted from O'Rourke (2019).

The HVP adopts a high velocity compact design that relieves the need for a rocket propulsion motor and creates room for potentially deeper magazines at a lower cost per shot. Current projections of the projectile sit at approximately $86,000 per round. These are equipped with sensors and basic manoeuvrability characteristics for counter missile performance. In addition, the HVP's modular design enables it to be configured for a variety of gun systems/platform to meet different mission requirements. Most importantly, because the HVPs have a lower cost per shot, an operator can choose to fire multiple shots to improve the overall probability of kill (Sydney 2018).

Lastly, given that the HVP modularity in terms of design allows it to be fired from multiple gun systems including powder guns (O'Rourke 2016), this flexibility in employment would greatly reduce development and production costs due to quicker technology adoption and ease of integration with existing gun platforms. An example would be the introduction of the HVPs to the Army to be fired by their Howitzers. This would vastly improve their AMD mission given the abundance of howitzer platforms that are currently in operational service (Sydney 2018). Figure 7 depicts the different projectile construct for varying gun systems and its technological potential.

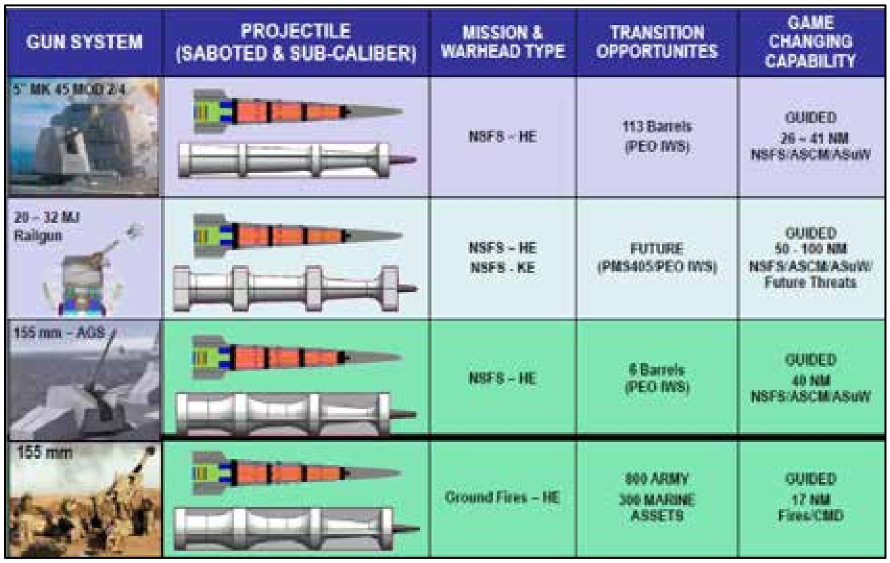

Figure 7. HVP Variants. Adapted from O’Rourke (2019).

Given that extensive Research and Development efforts are still being committed to this area of technology, newer prototypes in development would possibly bring about better performance of the system over time. For instance, General Atomics in 2018 announced the feasibility of a 10MJ multi-mission medium-range railgun weapon prototype capable of firing HVPs with a range of more than 60 miles and is able to fire about 20 rounds per minute (Harper 2018). Ultimately, the EMRG variant of the HVPGS with ideally the longest range and projectile speed is a very promising system that could change the missile cost exchange equation in the future.

G. MODEL DEVELOPMENT

Through the employment of DODAF, this thesis aims to define the boundaries, requirements and functional architectural views using Innoslate as the medium to visualise the design architecture. The completed design would then be used to inform the construct of an engagement simulation scenario using ExtendSim to facilitate the analysis of the proposed HVPGS behaviour and its interactions.

1. DOD Architecture Development Framework

A six-step process in the high-level development of architecture products from DODAF 2.02, as shown in Figure 8 (DODCIO 2017) is used for this thesis's architectural presentation.

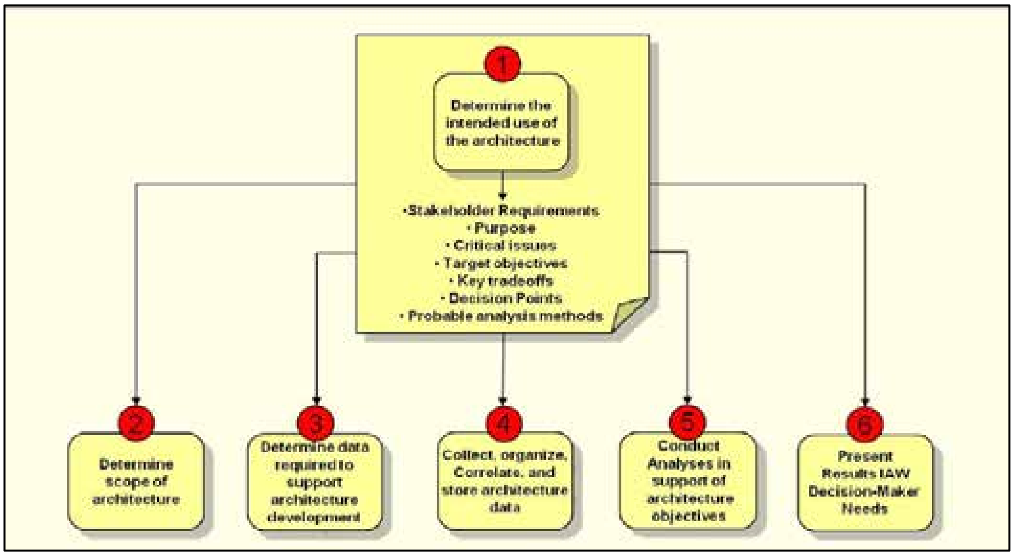

Figure 8. Architecture Development Six-Step Process. Source: (Department of Defense Chief Information Officer 2017).

Step one of this process lies in the determination of the intended use of the architecture. This is accomplished through the definition of the purpose and requirements of the architecture. The second step is the determination of the scope of the architecture by defining the boundaries and establishing the depth and breadth of the architecture. In this aspect, the author has chosen to scope this thesis in an AMD scenario against a near peer adversary in a contested environment. Third is to determine the data required to support the architecture development as it supports the subsequent lead on to step four which involves the collection, organization, correlation and storage of the necessary data to represent the different perspectives in which the system can be examined. This report aims to examine the capability view point, operational view point as well as the system viewpoints using Innoslate throughout the MBSE approach. Next, step five involves the analysis of the architecture data in support of the intended objectives to determine the level of success in which the system architecture design meets the given requirements. Finally, step six is the presentation of architectural data to a decision maker or stakeholder to elicit the relevant information of interest and support the overall evaluation of the architectural data or decision making.

2. Models Based System Engineering Approach using Innoslate

This thesis adapts the MBSE based analysis methodology proposed by Beery, Paulo (2019). The research describes a methodology to employ architecture design for system analysis through modelling and simulation and is comprised of the steps displayed in Figure 9.

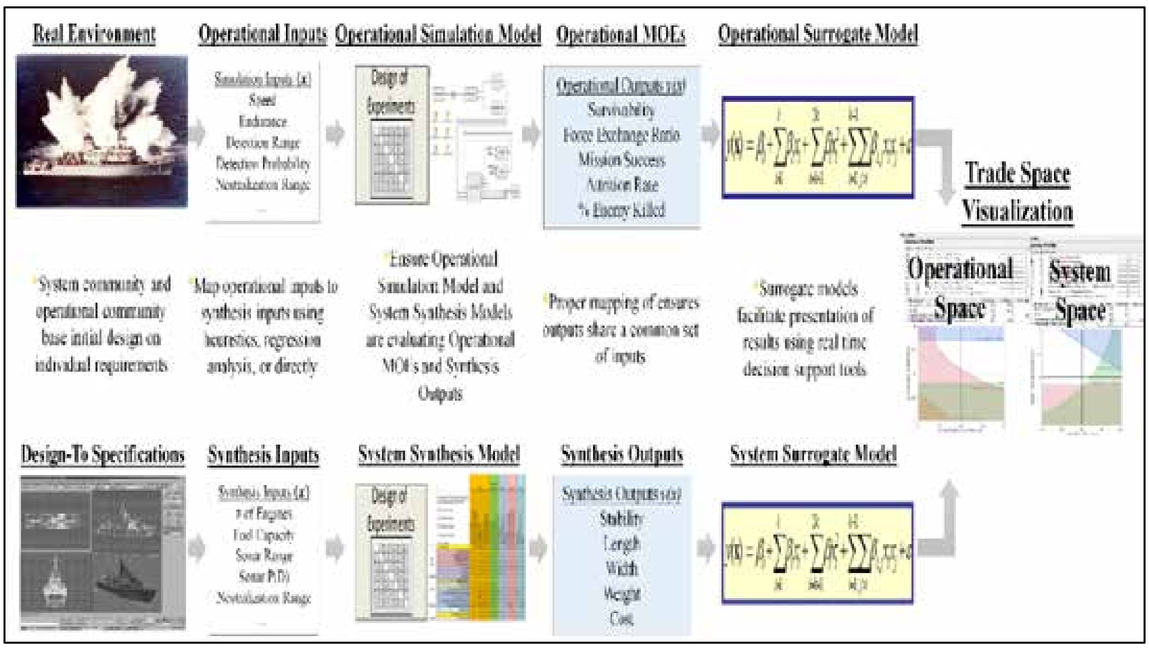

Figure 9. MBSE Analysis Methodology. Source: Beery (2019).

To support the steps revolving around the above approach, Innoslate is used to develop the DODAF 2.02 architectural viewpoints (See Figure 10) for this thesis. Innoslate provides for an open ontology, using the Life cycle Modelling Language (LML) to simplify the ontology from both SysMl and UML (SPEC 2017). Therefore, using Innoslate for the design architecture developed in this thesis will help the author comply with the described DODAF framework when possible.

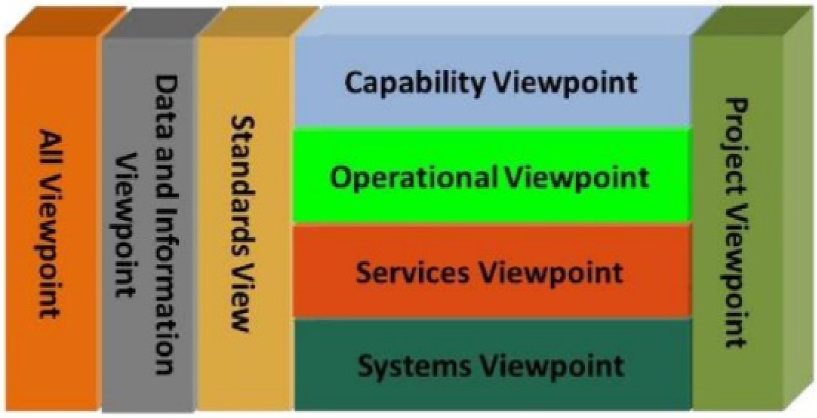

Figure 10. DODAF Viewpoint. Source: Department of Defense Chief Information Officer (2017).

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III. THE SYSTEM ENGINEERING APPROACH

The systems engineering approach provides a systematic and tailored process to develop the architectural design for a HVPGS to support the AMD mission. The approach is based on the waterfall model as depicted in Figure 11 and has been modified accordingly for this study. In this chapter, the author begins with the definition of the problem within the implied system boundaries followed by thorough stakeholder analysis and their operational requirements. As part of the system's operational analysis, the concept of operation for the HVPGS is also described to delineate the necessary operational activities that are mapped to the system level functions as part of the functional analysis process. From the functional decomposition output, an experimental model is designed to emulate the system functionalities for simulation study and analysis. Finally, the chapter describes the MOEs that are important to the HVPGS mission objectives.

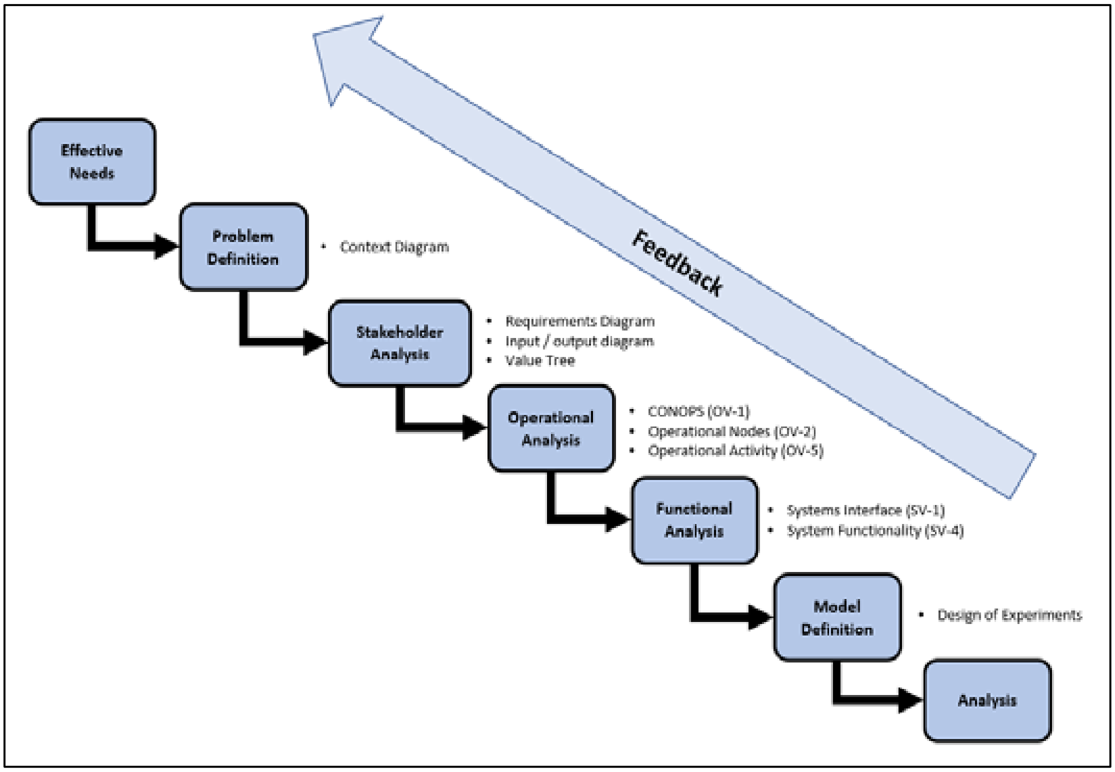


Figure 11. Modified System Engineering Waterfall Model.

A. PROBLEM DEFINITION

Contemporary AMD Systems are ill-equipped to handle complex salvo attacks from both ballistic and non-ballistic threats. As demonstrated in China’s pursuit of advanced stand-off weaponry and accumulation of a large inventory, the employment of Ballistic Missile salvo attacks with the ability to overwhelm traditional U.S. missile defenses are becoming an increasingly real threat. This means that it is no longer viable for AMD to rely on conventional missile defense systems and interceptors which are primed optimally against a smaller and much more limited ballistic inventory for protection of critical air bases and ports of U.S. forces and allies. Therefore, it is vital that military planners explore alternative means to augment existing capabilities to defend against such salvo attacks in the future in a sustainable manner.

B. STAKEHOLDER ANALYSIS

To better understand the problem space, we need to recognise the key stakeholders that would ultimately shape the HVPGS within the AMD construct. An analysis of the various stakeholders involved in defining and developing the AMD force across DOD is a complex undertaking given than the AMD force structure and capability ultimately contributes to the joint force IAMD architecture. In addition, there is no single entity with the authority and allocated resources to develop, field, and operate joint IAMD capabilities within the DOD.

To identify the stakeholders, the author began by researching publicly available resources and documentation to understand the varying needs and issues related to problem. In addition, due to the multitude of stakeholders responsible for IAMD at the joint mission level, the author has decided to focus the analysis to be from the Army’s system level perspective given that the specific area of interest for this thesis lies with its AMD capabilities. The needs, goals and concerns of the respective stakeholders are summarized in Table 1 and further manifested in Figure 12 as an Objective Tree Diagram.

Table 1. Stakeholder Analysis Table

Stakeholders	Type	Need	Goal	Concerns
DOD Strategic Capabilities Office (SCO)	Orchestrator / Idea Originator	A cost-effective multi-mission projectile capability against a wide range of missile and munition threats (Sydney 2018)	Program Success / HVP and HVPGS Technology maturity	High cost exchange ratio in the use of traditional interceptors against Chinese Missiles
U.S. Combatant Commanders	Combatant (User) / Requirements Generator	An effective force protection capability against overwhelming Chinese Salvo Missile Threats (Tucker and Lyons 2014)	Ensure all U.S. operating bases, ports and asset survivability	HVPGS Technology Readiness Level Combat Effectiveness & Reliability
U.S. Army Space and Missile Defense Command (USASMDC)	Operational Systems Integrator	A land-based missile defense capability that is effective against the full spectrum of Ballistic, Cruise and RAMs threats (USASMC 2019).	To advance the Army's missile defense capabilities and drive new CONOPS development	The lack of an operationally effective AMD Force that is capable of meeting its near peer adversary missile threats
Joint Integrated Air and Missile Defense Organization (JIAMDO)	Joint Requirements Generator	A multi-mission capability to support the joint IAMD operational architecture (Almodovar et al. 2018)	To support the development of a global missile defense capability	Inter-operability of IAMD capabilities Integration of requirements and expectations across the DOD
Missile Defense Agency (MDA)	DOD Research, Development & Acquisition Agency	A supporting capability that can be integrated to existing ballistic missile defense systems (Karako 2016)	A cost effective alternative terminal missile defense solution against tactical ballistic missiles threats	Integration challenges to existing Ballistic Missile Defenses
Army Armament Research Development and Engineering Center (ARDEC)	Army Research & Development Agency	To validate the possibility of a HVPGS capability and meet operational requirements (Rogoway n.d.)	To support the Army's research and development of new and innovative missile defense technology	Technology Feasibility and Technical Characteristics
Defense Contractors	Commercial Supplier	To achieve sales and profit	Meeting DOD's requirements within budget and schedule	Market Competition Financial losses

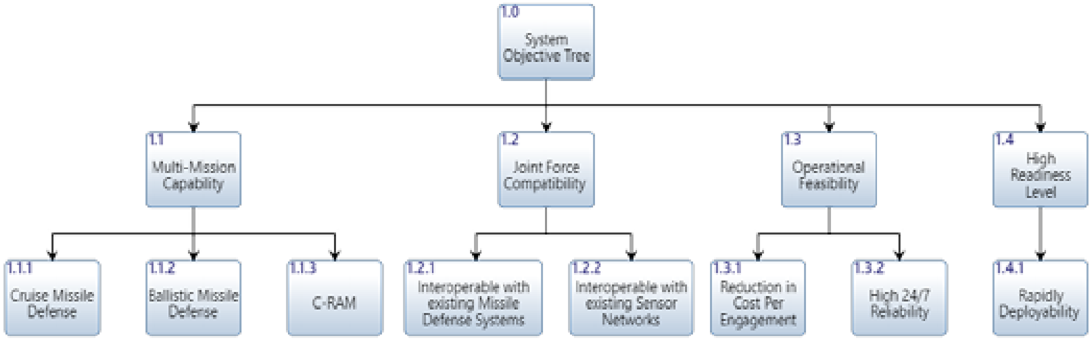


Figure 12. Stakeholders Objective Tree

1. Stakeholder Matrix Diagram

From the findings in Table 1, the author further categorizes the respective stakeholders using an influence-interest matrix diagram (Mendelow 1981) as depicted in Figure 13. The matrix aims to prioritize the respective stakeholders influence relative to their interest in terms of development and success. The larger the bubble, the more representative it is of the stakeholder’s influence. The following section also proposes the actions to manage the respective stakeholder groups.

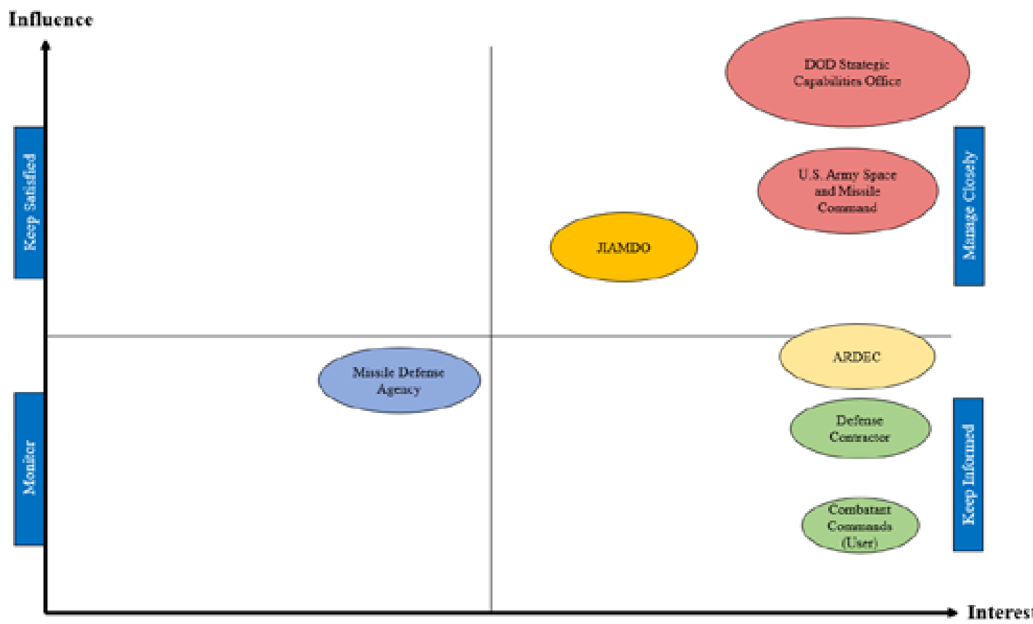


Figure 13. Stakeholder Matrix

a. High Influence, High Interest

DOD Strategic Capabilities Office (SCO) and U.S. Army Space and Missile Command (USASMC) are identified as the most significant stakeholders with regard to the system / capability. Given that DOD SCO has the ability to influence service level technological developments, they are able to direct the necessary support for the HVP program in its early developmental phase before passing onto the service to complete the system development process. Similarly, USASMC is the main operational integrator of the system and is responsible for building and maturing missile defense capabilities for future threats. Therefore, the inputs and direction given by DOD SCO or USASMC have the highest impact on the program's developmental progress and it will be of utmost importance to manage them closely. Additionally, within this quadrant is the JIAMDO which holds a high interest in the system but is less influential over its development compared to DOD, SCO and USASMC. JIAMDO seeks to ensure that the any integrated missile defense related capability incorporates the joint war fighter's requirement and is congruent to the broader joint IAMD capability architecture framework. This particular group should be kept abreast and of the latest system level developments and continuously engaged on their inputs to the overall requirements generation whilst bearing a less significant role compared to the former two stakeholders mentioned.

b. Low Influence, High Interest

Within this quadrant, the primary operators (U.S. Combatant Commands), Defense Contractors and ARDEC are deemed to have a high level of interest in the HVPGS project as they are the operational users and last mile developers of the system itself. For the operators, it is important them abreast of the latest developmental status to provide sufficient lead time for the commands to review the relevant doctrine and fighting tactics in anticipation of the introduction of this system into their fighting arsenal. Secondly, the Defense Contractors and ARDEC here have a higher level of influence on the system's developmental and design process as they collaborate on the technology, working to mature it to a higher readiness level for operational deployment. However, it can be seen that ARDEC being part of the Army's research arm would hold a greater level of influence in the direction of the HVPGS project compared to the defense contractor who would be primarily more concerned with profit and sales of their end product. Therefore, for this group of stakeholders it would be important to keep them well informed of the requirements development and monitor their research and developmental efforts that could contribute to the technology's readiness level.

c. Low Influence, Low Interest

The Missile Defense Agency (MDA) is the least interested stakeholder with no direct influence on the HVPGS program. The MDA is primarily concerned with the development and fielding of Ballistic Missile Defense Systems and is largely concerned only with the interoperability of newer IAMD systems with existing Ballistic Missile Defense Systems. They play a technical consultant role in this endeavour and hence do not have significant influence in the conceptualization of the HVPGS program. Nonetheless, it is still relevant for the project team to be keenly aware of any new and emerging capabilities for Ballistic Missile Defense as these have the ability to affect critical system interoperability requirements for a combined BMD capability that incorporates the HVPGS.

C. PROBLEM BOUNDARY AND INTERACTIONS

Having articulated the needs from the stakeholder analysis, the next step would be to establish the envisioned system boundaries and its key interactions with external entities / systems within the desired operational environment. This thesis utilizes a system context diagram as seen in Figure 14 to visualize the key proponents within the battlespace and its interactions with the proposed HVPGS. The following is an elaboration of the various entities and its interactions which impacts the HVPGS ability to operate effectively.

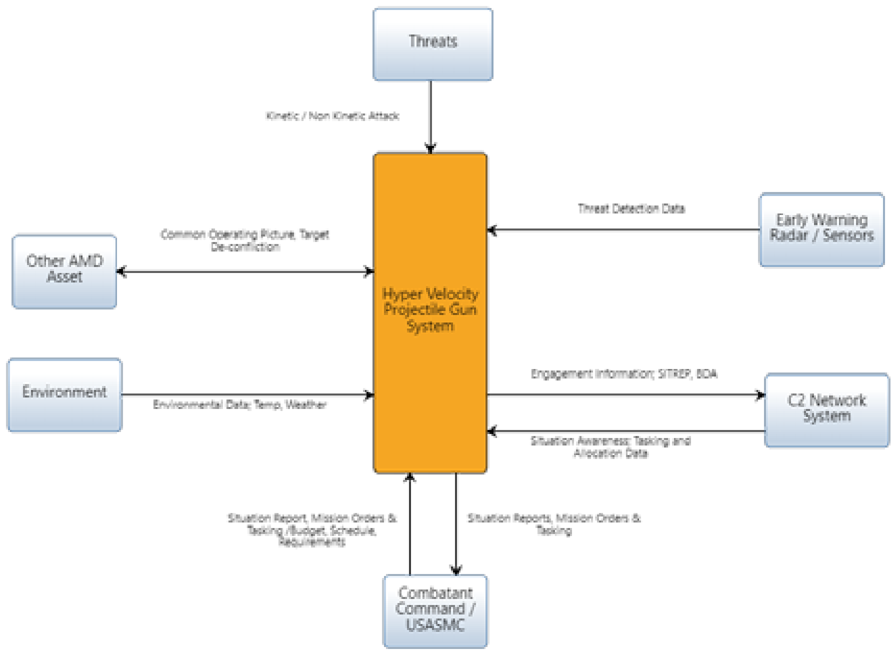


Figure 14. System Context Diagram

a. Environment

Environmental interactions here include both weather and terrain. This is seen as a unidirectional input into the HVPGS which affects how the system operates. In particular, the weather could greatly impact the projectiles from the HVPGS as they are not equipped with manoeuvrable thruster and fins to redirect their trajectory and may also suffer kinetic energy loses due to wind resistance. Secondly, the environment / terrain could also impact the observability and susceptibility or the system in deployment, increasing its vulnerability as a target. If the HVPGS is not designed correctly for its intended operational environment, it will inevitably compromise the system's effectiveness and survivability.

b. Threats

The threat interaction includes a wide range of ballistic missiles, cruise missiles as well as UAS and RAM attacks, which are inputs into the HVPGS. However, when a threat is detected and the HVPGS identified as the appropriate counter-fire responder, the HVPGS will proceed to engage and destroy the threats and hence, directly affecting the survivability of the protected force within its engagement radius. In addition, the retaliation / engagement of the incoming threat would also give away the HVPGS position and increase its vulnerability.

c. Combatant Commands / USASMC (HHQ)

The next external interaction stems from the system's higher operational command. The higher command decides the operational objective and influences the operational deployment of the HVPGS in the battlefield. Mission commands and tasking orders translate to the system's operational tactics, techniques and procedure on the ground. Fire requests from ground troops and situational reports are also constantly exchanged between the system and HHQ Commands. At the technical level, USASMC also plays a part that influences the HVPGS future upgrades and system design, impacting delivery schedules, budget and requirements.

d. Other AMD Assets

The HVPGS is expected to interact and work cooperatively with other existing AMD assets in the enterprise architecture. These could include the THAAD, PAC-3 as well as other non-kinetic shooter systems to provide a ubiquitous protection umbrella for the Army and Joint Force in combat. These systems interact exchanging weapon readiness data, target deconfliction as well as Battle Damage Assessment (BDA) reports on their targets.

e. Early Warning Sensors and Radars

Sensors and Radar provide the HVPGS with the intelligence preparations as well as targeting data needed to direct the system fires onto an inbound threat. One can link the sensor and radar data to threat warning and situational awareness needed to maximize the potential capabilities of the HVPGS beyond simple line of sight targeting. Only when the HVPGS is informed of the inbound threat, then the HVPGS can be better employed for the appropriate actions to engage the enemy. Interactions here include inbound threat coordinates, type and classification as well as metrological data that would support the targeting of the system.

f. C2 Network System

The C2 Network System is expected to fuse intelligence data from various sensors and shooter platforms into an integrated and coordinated fire control network. This network should provide ground commanders with the agility necessary to support flexible command relationships across different operating units allowing them to operate seamlessly with collaborative engagement capabilities for different missions (USASMC 2019). This interaction provides the HVPGS with key network information that would allow it to better support the battle commander's objective in an integrated and joint manner, synergizing assets across the AMD portfolio.

D. OPERATIONAL ANALYSIS

In this thesis, the author proposes for the HVPGS to be integrated as part of the Army's AMD Enterprise. The system is envisaged to augment the existing enterprise by providing the AMD force with an added cost-effective interceptor capability against ballistic threats targeting U.S. forces (USASMC 2019). Building on the layered defense concept for AMD with the Patriot System and THAAD System as the primary and secondary AMD Systems as described in the 2002 Field Manual titled *Patriot Battalion and Battery Operations* by the Army, the HVPGS would augment the Lower-Tier Defence layer in conjunction with the Patriot System in an effort to thin out incoming ballistic salvo attacks that leak through the THAAD defences. Given the need for the AMD force to keep up with Army operations, the HVPGS is expected to be highly mobile to allow for greater deploy-ability, enabling a strong forward presence together with the other assets within the AMD enterprise. In addition, the HVPGS is also capable of conducting surface warfare by engaging designated surface targets using the HVPs for force protection of itself and the larger AMD force as well as for offensive actions against identified surface threats.

The proposed CONOPS for the HVPGS is to have the system nested within the larger CONOPS of the AMD enterprise. The first intercept layer of defense would be conducted by the THAAD system against longer range ballistic threats such as IRBMs and MRBMs. The system seeks to engage the identified incoming ballistic threat at the Exo-atmospheric level while the missile is still in apogee and approaching terminal entry. Space and aerial sensors that can detect heat signatures are employed to detect and track inbound threats early in the launch phase, relay the target's information and trajectory to ground based C2 systems to direct and ready the THAAD system for counter fire upon reaching the terminal phase. Alternatively, the THAAD's organic AN/TPY-2 radar can also be used to detect and cue its interceptors (Korda and Kristensen 2019). Leaker missiles from the salvo attack which manages to penetrate the first layer of defense would next be engaged by the HVPGS as part of the Lower-Tier Defense.

In this layer, the HVPGS would employ HVPs to target and neutralize the incoming leaker ballistic missile salvos. Given the lower cost of the HVPs used by the HVPGS, it affords the AMD force with a lower cost exchange ratio and deeper magazines to counter salvo attacks with parity in mass (O'Rourke 2016). The proposed idea here is to thin out the leaker BM salvo before the second wave of leakers are handed over to the Patriot System as a last line of defense. Here, multiple HVPGS can be dispersed within the WEZ of a Patriot Battery to augment the Lower-Tier Defense with better coverage of the protected region, increasing survivability of the assets by widening the field of engagement and compounding the total rate of fire against incoming threats. The HVPGS would fire multiple successive HVPs against an inbound target, leveraging its high rate of fire to increase the probability of kill against each threat (Sydney 2018). The HVPGS can be equipped with its own fire control system or be supported by the AMD's LTAMDS for search, detection and target tracking of inbound threats.

Finally, the Patriot System employing PAC-3 Missile Segment Enhancement (MSE) interceptors holds the line as the final layer of defense against BM leaker threats that are not neutralized by the THAAD and HVPGS system. These interceptors utilize a similar hit to kill technology like that THAAD system but operate at a much lower altitude. The Patriot System is supported by the sensing capabilities of the LTAMDS to conduct search, detection, target tracking and missile guidance of the Patriot System. Depending on the missile configuration adopted by the AMD force, the Patriot System can also employ its Guidance Enhanced Missile (GEM) interceptors against adversary air platforms such as Fixed Wing (FW) and Rotary Wing (RW) aircrafts that constitutes the "Shooter" component of the enemy force that come within its WEZ (Korda and Kristensen 2019).

Figure 15 illustrates the high-level concept of operations (CONOPS) or OV-1 for the HVPGS.

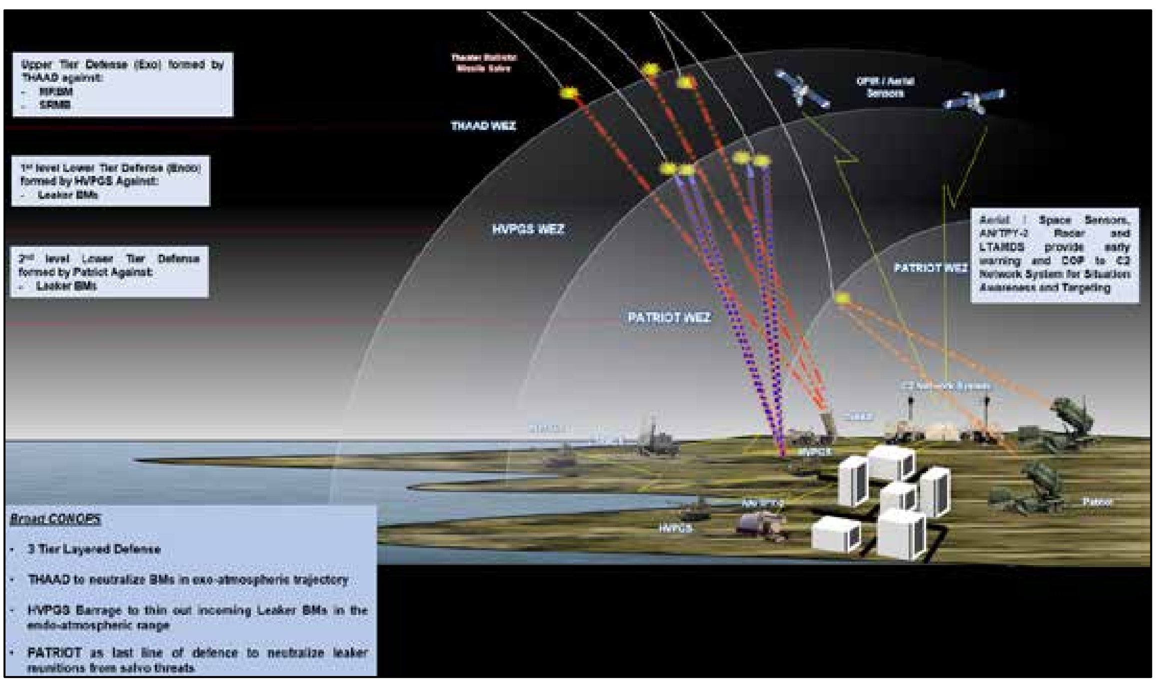


Figure 15. Operational View-1 (OV-1) Diagram

1. Mission Capabilities

Having specific the high level CONOPS of the HVPGS within the broader AMD force, the next step would be to distill the specific mission sets and the associated capabilities that the HVPGS is able to deliver. Capability here is defined by DOD as "the ability to achieve a desired effect under specified standards and conditions through a combination of means and ways across doctrine, organization, training, materiel, leadership and education, personnel, and facilities (DOTMLPF) to perform a set of tasks to execute a specified course of action" (DOD 2017, 10). Table 2 spells out a tailored list of the capabilities and sub-capabilities identified for the HVPGS mission as part of the AMD force (O'Rourke 2016). It is also specified here that theatre AMD would remain a primary mission of the HVPGS as part of the AMD force.

Table 2. Mission Set and Capabilities List

Mission Set	Mission Capabilities
Force Projection	All Terrain Mobility
	Strategic-lift Compatibility
	Force Sustenance
Surface Warfare	Defensive Actions against Surface Threats
	Offensive Actions against Surface Threats
Theater Air and Missile Defense	Ballistic Missile Defense (Primary Mission Capability)
	Cruise Missile Defense
	Air Defense
	Counter-UAS Defense
Indirect Fire Protection	Counter-Rockets
	Counter-Artillery
	Counter-Mortar
Command and Control	Communications
	Collaborative Engagement
	Common Operating Picture

2. Operational Activities

From the high-level CONOPS, one can further derive the Operational Activities (OA) that the HVPGS needs to conduct or execute to achieve its mission objectives. DOD defines Operational Activities in terms of what work is required, and is specified independently of how it is to be carried out (DODCIO 2017). The top-level operational activity model is presented using an IDEF0 activity model to describe the operational activities of the HVPGS in the conduct of its mission as part of an OV-5b diagram. The author defined seven parent nodes in the main OV-5b model which can be further decomposed into the second order detailed operational activities that support the parent node's function / goal. The detailed decomposition of the various nodes is elaborated in greater detail in appendix A. In summary, the capabilities required and the activities that enable those capabilities are mapped together as part of a CV-6 mapping illustrated in Table 3.

Table 3. Capability Viewpoint-6 (CV-6) for HVPGS

CV-6 Mission Capabilities to Operational Activities Matrix		*Capabilities*																			
		1.0 Force Projection	1.1 All Terrain Mobility	1.2 Strategic Lift Compatibility	1.3 Force Sustenance	2.0 Surface Warfare	2.1 Defensive Actions against Surface	2.2 Offensive Actions against Surface	3.0 Theatre Air and Missile Defense	3.1 Ballistic Missile Defense	3.2 Cruise Missile Defense	3.3 Air Defense	3.4 Counter-UAS Defense	4.0 Indirect Fire Protection	4.1 Counter Rockets	4.2 Counter Artillery	4.3 Counter Mortar	5.0 Command & Control	5.1 Communications	5.2 Collaborative Engagement	5.3 Common Operating Picture
Operational Activities	1.0 Conduct Movement	X	X	X		X	X	X													
	2.0 Conduct Deployment	X			X				X	X	X	X	X	X	X	X	X				
	3.0 Process Intelligence Updates					X	X	X	X	X	X	X	X	X	X	X	X		X	X	X
	4.0 Exercise Command & Control																	X	X	X	
	5.0 Engage Targets					X	X	X	X	X	X	X	X	X	X	X	X				
	6.0 Conduct BDA					X	X	X	X	X	X	X	X	X	X	X	X	X			X
	7.0 Conduct Maintenance & CSS	X			X																

E. FUNCTIONAL ANALYSIS

Following the definition of operational activities for the HVPGS, next would be to identify the functional composition of the envisaged system. Using the DODAF SV-4, the author developed a graphical depiction of the system's functional decomposition tree to facilitate functional analysis. Figure 16 depicts the high-level functional hierarchy decomposition of the HVPGS as described in its AMD CONOPS.

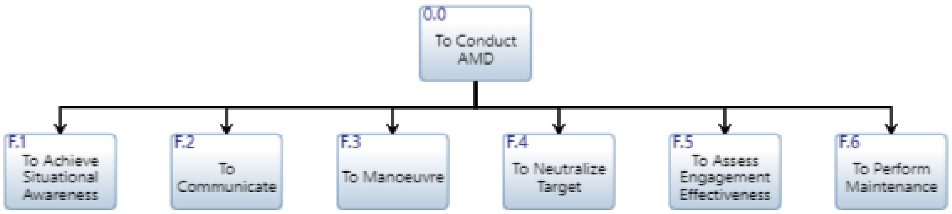


Figure 16. System Viewpoint-4 (SV-4) for HVPGS

The six main high-level functions identified are as such; (1) To Achieve Situational Awareness, (2) To Communicate, (3) To Maneuver, (4) To Engage, (5) To Assess Engagement Effectiveness and (6) To Perform Maintenance. These functions are aimed at supporting the HVPGS in delivering its mission required capabilities. The secondary functions supporting the primary functions are further elaborated in the subsequent sections through Figures 17 - 22. The SV-4 as depicted in Table 4 also facilitates the visualization of the SV-5 which maps the HVPGS's operational activities to its system functions.

Table 4. System Viewpoint-5 (SV-5) for HVPGS

SV-5 Operational Activities to System Functions Matrix		*Operational Activity*						
		1.0 Conduct Movement	2.0 Conduct Deployment	3.0 Process Intelligence Updates	4.0 Exercise Command & Control	5.0 Employ Firepower	6.0 Conduct BDA	7.0 Conduct Maintenance & CSS
System Functions	F.1 To Achieve Situational Awareness			X	X			
	F.1.1 To Detect Threat Signature			X	X			
	F.1.2 To Classify Threat Type			X	X			
	F.1.3 To Track Target Trajectory			X	X	X		
	F.1.4 To Track Own Force Position				X	X	X	
	F.2 To Communicate	X	X	X	X	X	X	X
	F.2.1 To Transit / Receive SATCOM			X			X	
	F.2.2 To Transmit / Receive UHF/VHF	X	X		X	X		X
	F.2.3 To Process Data			X	X	X	X	
	F.3 To Manoeuvre	X	X			X		
	F.3.1 To Perform Navigation	X	X					
	F.3.2 To Perform Movement	X	X			X		X
	F.4 To Neutralize Target					X		
	F.4.1 To Evaluate Environmental Data			X		X		
	F4.1.1 To Monitor Air Pressure			X		X		
	F4.1.2 To Monitor Temperature			X		X		
	F4.1.3 To Monitor Wind Speed			X		X		
	F.4.2 To Calculate Firing Solution				X	X		
	F.4.2.1 To Determine Engagement Range				X	X		
	F.4.2.2 To Determine Firing Coordinates				X	X		
	F.4.2.3 To Determine Target Priority				X	X		
	F.4.3 To Engage				X	X		
	F.4.3.1 To Load Projectiles					X		
	F.4.3.2 To Fire Projectiles				X	X		
	F.5 To Assess Engagement Effectiveness			X			X	
	F.5.1 To Evaluate Own Force Damage			X			X	
	F.5.2 To Evaluate Target Damage			X			X	
	F.6 To Perform Maintenance							X
	F.6.1 To Perform Repairs					X		X
	F.6.2 To Perform Resupply of Fuel / Ammo	X	X					X

1. To Achieve Situational Awareness

The HVPGS operates on a high level of situational awareness to successfully defend its protected asset or locality against incoming munition threats. To achieve this functionality, the HVPGS needs to be able to detect incoming threat signatures, classify the threat and thereafter establish a track on its trajectory to evaluate its impact point and prompt the necessary engagement actions that follow. Similarly, it will also need to monitor and track own-force locations to bring fidelity to its air operational picture and provide support when necessary. The functional hierarchy of this sub-branch is illustrated in Figure 17.

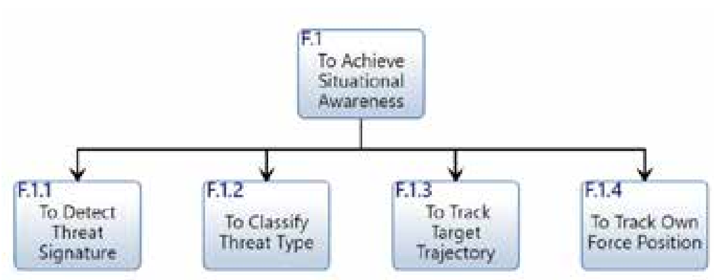


Figure 17. To Achieve Situational Awareness Functional Hierarchy

2. To Communicate

The ability for the HVPGS to communicate effectively with both internal systems and external systems is a key enabler for the command and control of the weapon system. To be able to expeditiously transmit and receive data across the battlefield on incoming threats identified and subsequently process that data to drive the engagement process is vital for collaborative engagement capability and facilitate tactical adjustments in deployment. For the HVPGS commander, the ability to communicate via SATCOM would allow him or her to receive orders and relay situation reports which have lower data rates and is transmitted over long distances while the UHF/VHF functions allows for communication with peer commanders for coordination of action and mutual support in combat. In addition, the processed data would yield information that can be shared to build the common operating picture needed to support the wider AMD effort. The functional hierarchy of this sub-branch is illustrated in Figure 18.

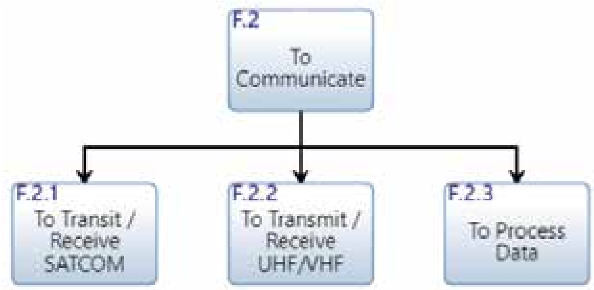


Figure 18. To Communicate Functional Hierarchy

3. To Maneuver

Maneuverability of the HVPGS will increase the deploy-ability of the system and allow rapid transition between deployment sites to close AMD gaps around the battlefield when necessary as the centre of gravity for the land force shifts and evolves. HVPGS units require good mobility to move swiftly within the operational theatre to execute deployment strategies to support other AMD assets and the functions of performing navigation and movement enables it to take up designated positions in fixed deployment or to engagement surface targets on the move. The functional hierarchy of this sub-branch is illustrated in Figure 19.

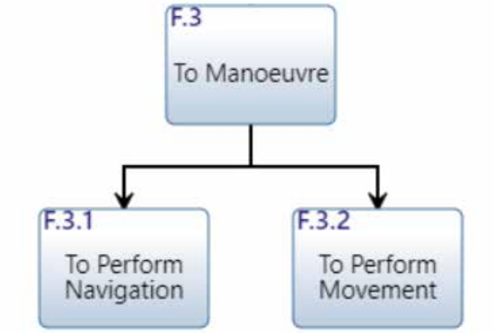


Figure 19. To Maneuver Functional Hierarchy

4. To Neutralize Target

The most important function of the HVPGS is to be able to engage and neutralize the enemy threat. To do so with the ballistic trajectory of non-guided Hyper Velocity Projectiles, the system will need to be able take into account and evaluate the environmental data that would affect the speed and range of the rounds fired downrange. Secondly, the determination of the range and impact coordinates viability for engagement would also impact the target's priority list for engagement when the target approaches the HVPGS's WEZ. Finally, the physical engagement of the targets will require the function of loading projectiles and readying them for firing. The functional hierarchy of this sub-branch is illustrated in Figure 20.

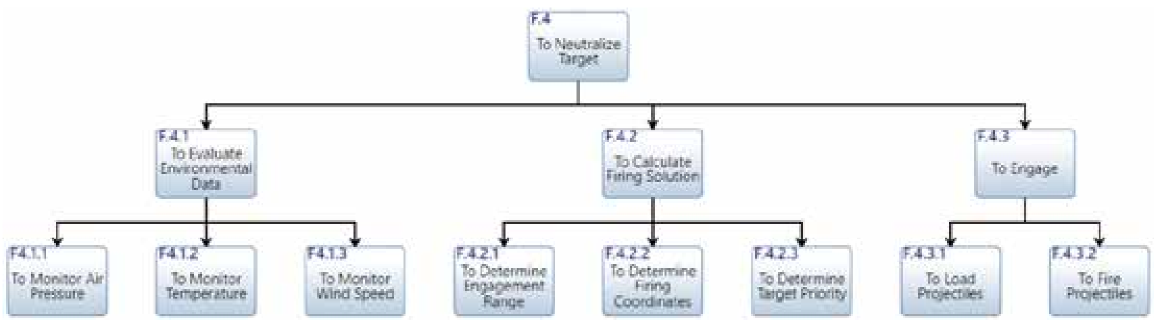


Figure 20. To Neutralize Targets Functional Hierarchy

5. To Assess Engagement Effectiveness

The ability to assess the HVPGS's engagement effectiveness is an important pillar in the post battle damage assessment activity as well as to provide timely feedback to HQ or mutually supporting assets for a follow up engagement onto the target, should the initial engagement fail to neutralize the target. To adequately assess the engagement effectiveness, the system would need to be able to evaluate the damage done to the target to inform the need for crew and assets on the ground to brace for impact as the target was not fully neutralized or cue another asset for a secondary engagement attempt. Secondly, the ability to evaluate damage incurred on the platform during the engagement would inform the commander and HQ of the operational status of the system to carry on its mission. The functional hierarchy of this sub-branch is illustrated in Figure 21.

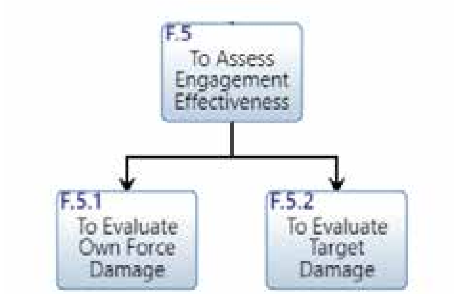


Figure 21. To Assess Engagement Effectiveness Functional Hierarchy

6. To Perform Maintenance

To be able to readily conduct field maintenance work in the event of damage after engagement is a key function that would quickly restore the system back to a high level of readiness for operations. The function of conducting repairs is supported with a diagnostic capability that would allow basic level operator level repairs to be quickly diagnosed and completed out in the field to minimize maintenance down time. In addition, other essential maintenance / logistics tasks of refuelling and resupplying of ammunition should be a function that can be conducted swiftly out in the field to enable longer periods of sustenance and ease deployment strains. The functional hierarchy of this sub-branch is illustrated in Figure 22.

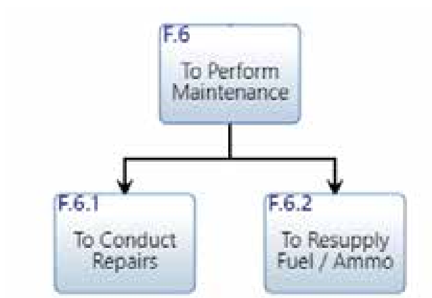


Figure 22. To Assess Engagement Effectiveness Functional Hierarchy

F. MEASURES OF EFFECTIVES DEFINITION

To determine the Measures of Effectiveness (MOEs) for the HVPGS, the author derived vital criteria from the stakeholders' objective tree to measure the effectiveness of the systems in fulfilling the effective needs of the various stakeholders and its intended mission objectives. Two main MOEs are identified.

The first MOE is the measure of Blue Force Attrition. This determines the AMD force's overall success in defending its intended locality in a combined deployment with the THAAD, HVPGS and PATRIOT systems. Within this umbrella, the objective is to maximise the survivability of the forces that are operating within its protected region. In operations, this would include Army forces in a land campaign or key operating bases/ infrastructure in forward deployments that would need the protection of the proposed AMD enterprise. For this thesis, the author has chosen a Blue Force Attrition objective to be no more than 10% of the Blue Force that is being protected. This objective is an assumption by the author and was selected over a more stringent 5% attrition (95% Survivability) to give credence to the likelihood of Red Force possessing highly capable ballistic missiles, with sophisticated decoys and signature reduction capabilities that could bypass early detection and discrimination of the defending force which are harder to defend against.

The second MOE is the measure of Cost Exchange Ratio (CER) for the combined employment of the THAAD, HVPGS and PATRIOT systems against salvo attacks versus a conventional two-tiered THAAD and PATRIOT defense system employment. The objective is to determine how the incorporation of the HVPGS against a ballistic salvo attack onto blue forces reduces the total engagement cost, in comparison to the use of just the THAAD and PATRIOT system combination. The CER is computed by dividing the cost of the total number of HVPs and THAAD / PATRIOT interceptors used over the estimated cost of the enemy munitions for comparison to determine the most cost-efficient solution.

Finally, the author decomposes the identified MOEs into Measure of Performance (MOPs) for that contributes to the defined MOEs for the system as listed in Table 5.

Table 5. MOE and MOP Summary List

MOEs	MOPs	Description
Blue Force Attrition	# HVPs Launched	This is the total number of HVPs fired against the incoming salvo of munition.
	# HVP Missed	This is the total number of HVP misses on the targeted munition.
	# HVP Hits	This is a measure of the number of Red Targets that are hit by the HVPs regardless if they were killed.
	# Red Targets Killed	This is representative of the total number of Red Targets neutralized by the HVPGS.
	# Red Force Hits	This is a measure of the number of Blue Forces being Hit by leaked Red Munitions
	# Blue Force Killed	This is a total number of Blue Forces within the protected region that are killed by the leaked Red Munitions
Cost of Engagement	# HVPs Launched	This is the total number of HVPs fired against the incoming salvo of munition.
	# PATRIOT Interceptors Launched	This is the total number of PATRIOT interceptors fired against the incoming salvo of munition.
	# THAAD Interceptors Launched	This is the total number of THAAD interceptors fired against the incoming salvo of munition.

IV. MODELING AND SIMULATION

This thesis uses ExtendSim to develop the AMD enterprise engagement model. In the following subsections the detailed composition of the model used for simulations is discussed, including the operational scenario, force structure, and the concept of operations for the red and blue forces in engagement. The assumptions underlying this model are also highlighted for the reader's awareness and understanding. Finally, for the purpose of this simulation, the author assumes that the survivability requirement is to ensure that the protected force within the AMD's protection umbrella suffers no more than 10% attrition at the 95% confidence level (CL) as discussed in chapter three for this thesis.

A. OPERATIONAL SCENARIO

The operational scenario modeled is in reference to the discussion and assertions made in an article published by the U.S. Naval War College Review Journal's Full Autumn 2010 issue, by Professor Marshall Hoyler. The article examines a scenario of employing active defenses against ballistic missile attacks on U.S. air bases in the western pacific. Specifically, the article highlighted the possibilities that could unfold in a Taiwan contingency, and how U.S. land-based aircrafts in Kadena Air base on Okinawa could be a valuable resource in the larger campaign (Marshall 2010). Therefore, the author has chosen to model this particular engagement scenario in the pacific with Chinese CSS-6 ballistic missiles attacking Kadena Air Base using salvo style attacks.

1. Red Force Concept of Operations

In this scenario, the Red Force (China) is estimated to have approximately 350–400 CSS-6 ballistic missiles in her inventory, of which, a single wave of salvo attack on Kadena is postulated to comprise about half of their entire munition inventory using 200 CSS-6 missiles. The missiles are launched from the eastern coast of China, targeting High Value Targets (HVTs) on Kadena Air Base. The primary objective is to destroy the air base's runways in order to limit Blue Forces (U.S.) ability to generate air power and secondly to destroy any unsheltered aircraft and critical infrastructure within the base.

2. Blue Force Concept of Operations

In this scenario, the U.S. Forces have deployed a Patriot battalion armed with the PAC-3 MSE interceptors, reinforced with a THAAD battery at Kadena Air Base. The two interceptor systems are employed in conjunction as part of a layered AMD strategy, with the THAAD as the first layer to engage and destroy incoming missiles in the Exo-atmospheric range while the Patriot holds the line as the second layer of defence to neutralize any leakers from the THAAD system. There is a total of six launchers for the Patriot batteries and they are deployed equally into three sectors to provide a more localized sector defence whilst the THAAD system is concentrated in the rear to provide overall defence for the incoming missiles as depicted in Figure 23. HVTs located within the base include two runways, nine aircraft hangers, six buildings and thirty-two unsheltered aircrafts.

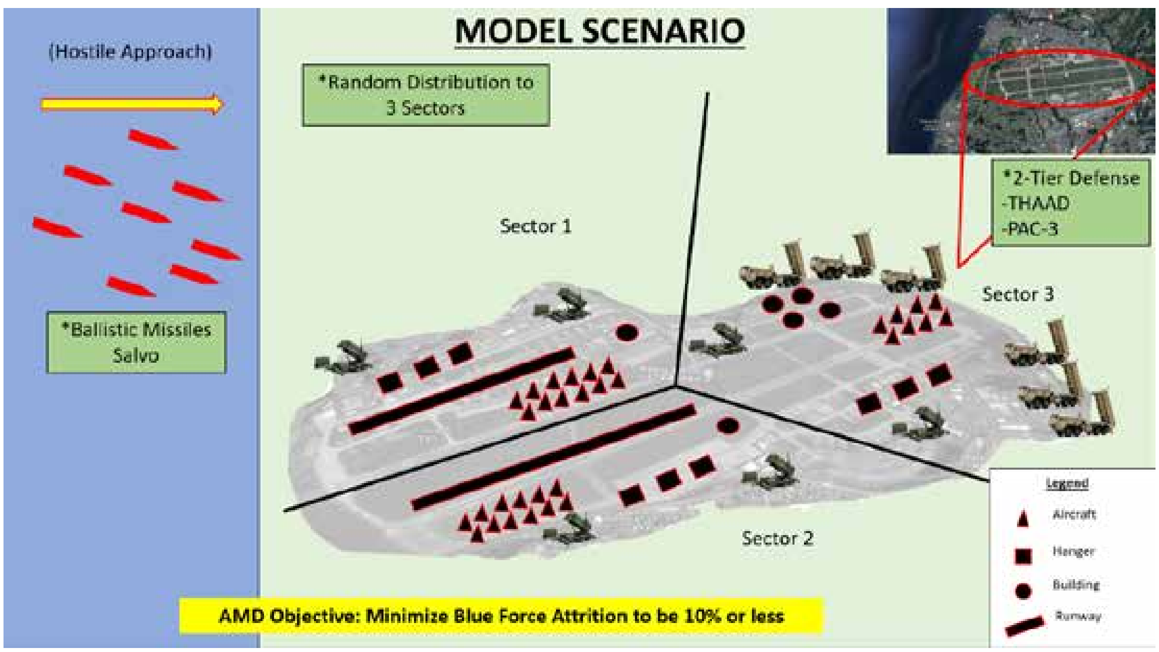


Figure 23. Model Operational Scenario.

B. MODEL ASSUMPTIONS

To model the engagement process using ExtendSim, the author needed to first establish the engagement range for the AMD systems involved as well as the characteristics of the attacking salvo. This translated to the need to model the trajectory of the ballistic missile flight from Apogee to its terminal Re-entry phase, to a simplified linear Line-of-Sight (LOS) approach where the window of intercept opens for the THAAD, HVPGS and Patriot systems. In addition, the CSS-6 missiles characteristics were also built into the process to emulate its speed and possible trajectory. Figure 24 provides a pictorial representation of the ballistic missile's flight path and the simplified engagement distance used in the ExtendSim model. The following sections elaborates on the assumptions.

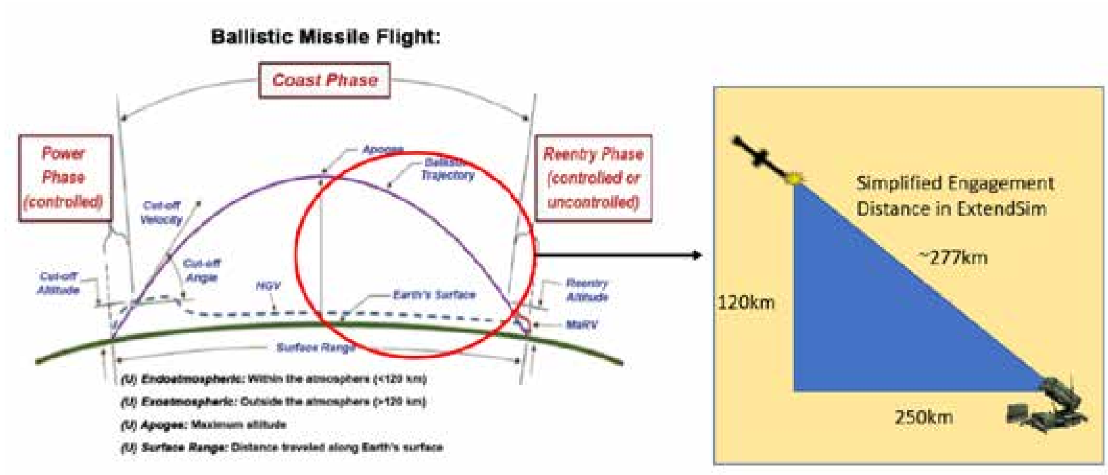


Figure 24. Ballistic Missile Flight Trajectory Assumption.

1. Ballistic Missile Characteristics

At nominal trajectory, the CSS-6 ballistic missile is estimated to have at a range of 500 km and would be able to attain an altitude of approximately 120 km with an estimated atmospheric re-entry speed of up to 2km/s (Stokes 2002). The CSS-6 is also modeled with an active radar terminal guidance which would direct it to the largest Radar Cross Section (RCS) signal detected as it approaches the base. This nominal trajectory is modeled into the simulation as the attacking salvo strike.

2. Salvo Attack Characteristics

The CSS-6 ballistic missiles are assumed to be fired as a salvo of 200 missiles in a single wave onto Kadena Base. The salvo of missiles is assumed to have a normal distribution in their launch times, resulting in a slight variation of the arrival times for each of the missiles entering the respective AMD system's engagement windows. The rationale for this assumption lies with the variability that would exists in the engagement sequence, launch propulsion systems as well as the operator delay in initiating engagement of the enemy. It would be impossible for all the missiles to be fired and travel in a uniform speed simultaneously in reality.

3. Ballistic Missile Dispersion Probability to Sectors

The CSS-6 ballistic missiles that manage to penetrate the THAAD interceptors are assumed to have an equal probability at high altitudes to be dispersed to any of the three sectors as they re-enter the atmosphere. At this stage, the author assumes that the terminal guidance seeker is not yet influenced by the various HVT RCS situation in the base compound. The three sectors are as demarcated in the scenario model and are defended by the respective Patriot launchers.

4. AMD Detection Capability

The AMD enterprise in this model is assumed to have perfect capability to identify and discriminate targets from debris, chaff and other possible forms of decoy. This allows the interceptors to perfectly target all the incoming ballistic missile without being misled by decoys that would result in the unnecessary expenditure of interceptors. This assumption is also to facilitate the author's investigation into the engagement characteristics and effectiveness of the launchers and interceptors given a perfect detection and tracking capability.

5. AMD System Initial Engagement Delay

Upon detection, the AMD systems are assumed to experience a varied engagement delay attributed to variability in the launch propulsion, operator reaction delays and system latency within the network from the radar to the respective engagement authorities. The THAAD and Patriot systems are similarly modeled with a normal distribution for their initial engagement delays.

6. Protected High Value Targets Have no Passive Defences

The HVTs protected within the umbrella of the AMD enterprise are assumed to have no other form of passive defence apart from the active AMD system in place. A single hit on the possible targets (apart from the runways) within the base compound is assumed to be a kill, depending plainly on the CSS-6 missile probability of kill which is assumed to be 0.9. Referencing from the originator of the scenario, six direct hits onto each runway by the CSS-6 ballistic missiles would make the runway completely disabled with the 3,700-meter runway being broken into three segments that would not be long enough for aircraft to land and take off (Marshall 2010).

C. BASELINE MODEL DESCRIPTION

For this thesis, the ExtendSim simulation tool is used to develop the model scenario described above with an attrition requirement of no more than 10% for Blue force HVTs. Law (2015) describes the ExtendSim software as a simulation tool, whereby “a model is constructed by selecting blocks from libraries (such as Item, Value, Plotter), placing the blocks at appropriate locations in the model window, connecting the blocks to indicate the flow of entities (or values) through the system, and then detailing the blocks using dialog boxes.” (198) The simulation tool builds upon the engagement diagram depicted in Figure 25 to emulate the engagement process that occurs from the generation of the CSS-6 missiles to its entry into the THAAD and Patriot engagement windows and the associated flight time delays between each interval.

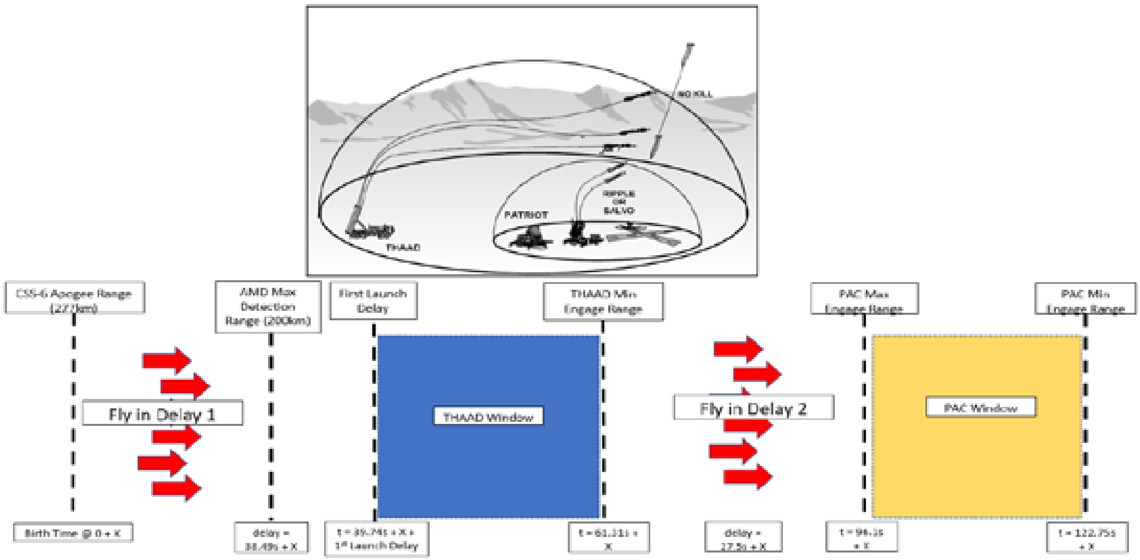


Figure 25. AMD Engagement Process.

1. ExtendSIM Model Parameters

The entire modeled engagement process in ExtendSIM is denominated in seconds and is calculated using the speed of both the incoming missile as well as the interceptor and the various distances at the key threshold intervals. With reference to Figure 25, it is depicted that the engagement model starts at Birthtime 0+X seconds, with X denoting a random value that varies with the start of the incoming CSS-6 missiles at apogee.

The first fly-in delay starts with the CSS-6 missiles at its apogee range of 277 KM to the assumed AMD enterprise's max detection range at 200 KM. The detection range employed here assumes the lower capability of the LTAMDS instead of the THAAD's organic AN/TPY-2 Radar. This gives us a range of approximately 200km which is twice as powerful as the original AN/MPQ-53 Patriot radar (Hitchens 2019). Given that the THAAD system's max engagement range is greater than the designated AMD's detection range, the 200 KM mark also denotes the earliest opportunity where the THAAD interceptors can be fired upon detection of the incoming CSS-6 missiles (Missile Defense Advocacy Alliance [MDAA] n.d.).

The THAAD engagement window then opens after an initial launch delay and closes at the designated THAAD's minimal engagement range of 90 KM. Leakers that are not neutralize by the THAAD layer then goes through a second flight delay interval before arriving at the Patriot's max engagement range of 35 KM (Gunzinger and Clark 2016). The probability of hit used in the model for the THAAD interceptor is 0.8 (Elleman and Zagurek Jr 2016), while the probability of hit for the Patriot interceptor is 0.7(Hoyler 2010). Any further leakers beyond the Patriot's min engagement range of 13 KM would have fully penetrated the AMD protection and result in impact on the HVTs for the Blue Forces.

Table 6 summarizes the key parameters designed into the model to simulate and represent the AMD characteristics for the baseline BMD engagement scenario with the THAAD and Patriot systems. The detailed baseline BMD engagement scenario with the THAAD and one sector of the Patriot system (due to space constraint) in ExtendSIM using the tool's building blocks is depicted in Figure 26.

Table 6. ExtendSIM Model Parameters

Parameters	Values	Description
Max Detection Range	200 KM	The is the maximum range of the AMD enterprise supported by the LTAMD sensor. As the LTAMD is expected to deliver an enhanced performance over the existing AN/MPQ-53 with twice the power capacity (Hitchens 2019), this thesis chose to use 200 KM which is twice the detection range of the AN/MPQ-53.
No. of THAAD Launcher	6	This is the total number of THAAD Launchers deployed for the scenario. Given that a single battery is assumed to be deployed as part of the AMD task force in the scenario, only 6 launchers are deployed on-site (Janes 2020).
No. of THAAD Interceptors	8	This is the total number of THAAD Interceptors available on each Launcher (Janes 2020).
THAAD Interceptor Speed	2800m/s	This is the THAAD Interceptor at terminal velocity at 2800 metres per second (Janes 2020). Although the interceptors are expected to accelerate over some time before achieving terminal velocity, this thesis chose to implement the terminal velocity as the constant speed travelled by the interceptors upon launch for simplification of the analysis.
THAAD Rate of Fire	2s with std.dev of 0.1s	This denotes how many seconds it takes to fire one THAAD interceptors. As there is no readily available data on this parameter, this thesis chose a larger bound rate of fire value compared to the

Parameters	Values	Description
		Patriot system but maintaining the same standard deviation.
THAAD Max Range	200 KM	This denotes the maximum engagement range of the THAAD system (Klingner 2017).
THAAD Min Range	90 KM	This denotes the minimum engagement range of the THAAD system. As the AMD enterprise operates on a layered defence concept, the engagement window will have to keep to pre-defined keep-out altitudes for firing coordination (DOD 2002). Therefore, even though the THAAD system is believed to have an even shorter minimal engagement range, this thesis chose to use 90 KM which is just slightly below the endo-atmospheric altitude.
THAAD Prob. Of Hit	0.8	This is the probability of the THAAD hitting and neutralizing each incoming CSS-6 missile (Elleman and Zagurek Jr 2016).
No. of Patriot Launcher	6	This is the total number of Patriot Launchers deployed for the scenario. Given that a single battery is assumed to be deployed as part of the AMD task force in the scenario, only 6 launchers are deployed on-site, with 2 launchers deployed in each of the three sectors (“Patriot Missile Long-Range Air-Defence System, U.S. Army” n.d.).
No. of Patriot Interceptors	32	This is the total number of Patriot Interceptors available on each Launcher. The interceptors simulated in the model are the PAC-3 MSE interceptors (“Patriot Missile Long-Range Air-Defence System, U.S. Army” n.d.).
Patriot Interceptor Speed	1406m/s	This is the Patriot Interceptor at terminal velocity in at 1406 metres per second (North Atlantic Treaty Organization [NATO] 2014). Although the interceptors are expected to accelerate over some time before achieving terminal velocity, this thesis chose to implement the terminal velocity as the constant speed travelled by the interceptors upon launch for simplification of the analysis
Patriot Rate of Fire	1s with std.dev of 0.1s	This denotes how many seconds it takes to fire one Patriot interceptors. As there is no readily available data on this parameter, this thesis chose a smaller bound rate of fire value compared to the Patriot system but maintaining the same standard deviation.
Patriot Max Range	35 KM	This denotes the maximum engagement range of the Patriot system against ballistics targets. The thesis chose the average nominal value range of 35 KM which lies between approximately 20 KM to 50 KM

Parameters	Values	Description
		engagement range as listed by Gunzinger and Clark (2016).
Patriot Min Range	13 KM	This denotes the minimum engagement range of the Patriot system. This is derived from the minimal flight time of 9 seconds that the missile needs upon launch to be armed (“Patriot Missile Long-Range Air-Defence System, U.S. Army” n.d.).
Patriot Prob. Of Hit	0.7	This is the probability of the Patriot hitting and neutralizing each incoming CSS-6 missile (Hoyler 2010).

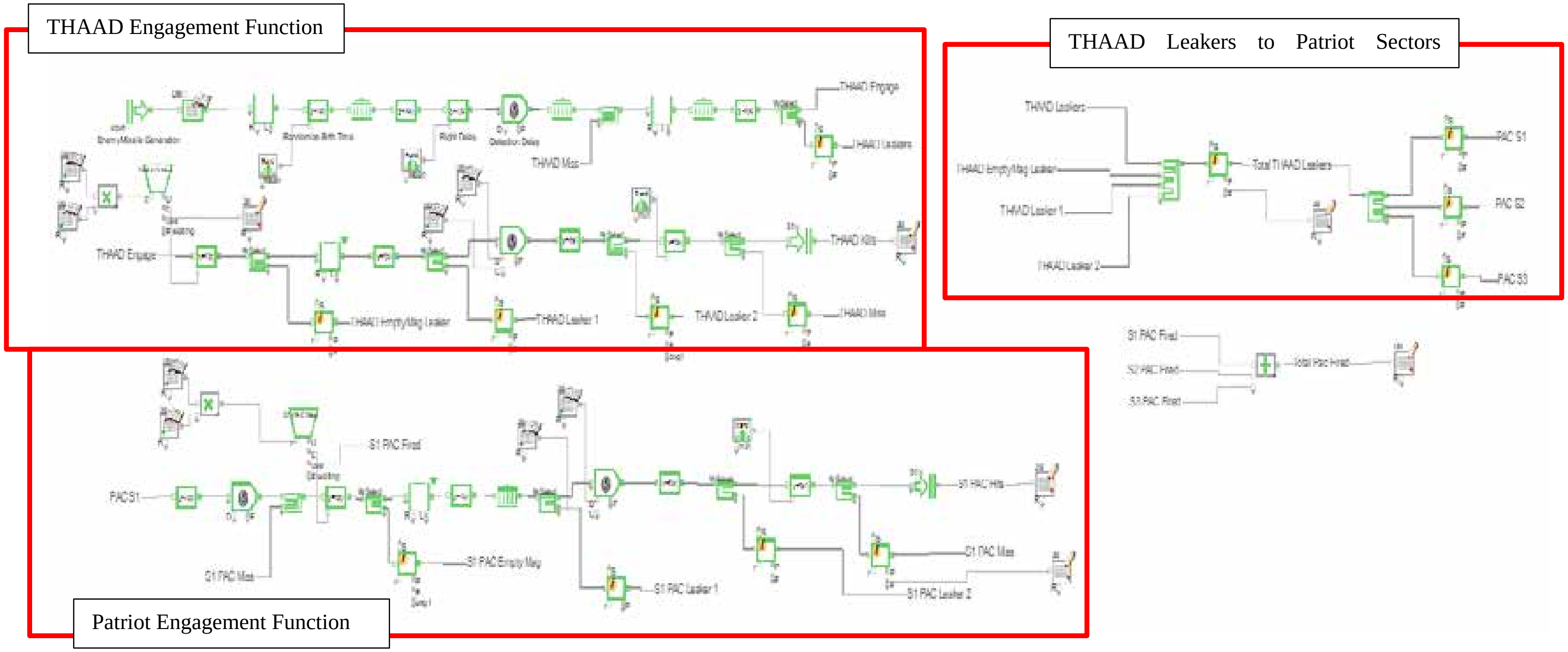


Figure 26. AMD Engagement Process.

2. ExtendSIM Model Validation

With the ExtendSIM model created, the author sought to first validate that the model is set up correctly before performing the desired detailed attrition assessment of Blue Force HVTs in an AMD scenario. This thesis demonstrates this by comparing the simulated THAAD and Patriot engagement kills to a simple back-of-envelope (BOE) result using Excel to emulate the engagement process with binomial probability distribution. Table 7 compares the results from both simulation platforms, taking the average over 100 simulation runs. From the table, one can see that the results from both simulations set ups are similar, with the number of successful intercepts by the THAAD and Patriots almost identical. This validates the author's ExtendSIM model engagement set up for a more elaborate scenario and subsequent analysis of attrition.

Table 7. ExtendSIM Model Parameters

100 Simulation Runs	ExtendSIM Model	Excel BOE
THAAD Intercept	38.64	38.5
PAC-3 S1 Intercept	21.2	22.4
PAC-3 S2 Intercept	20.28	22.3
PAC-3 S3 Intercept	20.09	22.4

D. ENHANCED MODEL SCENARIO ATTRITION ASSESSMENT

With the basis of the engagement model validated, the author moves to incorporate the proposed HVPGS and the base compound's HVTs into the baseline model. As per the earlier discussed CONOPS in Chapter III, the HVPGS will operate in the middle layer to thin out the leakers from the THAAD engagement before they enter the Patriot system's engagement window. Figure 27 depicts the modified AMD engagement process with the inclusion of the HVPGS. The modified model will then undergo a design of experiments process to further explore and investigate the design space for key parameters that are identified as significant factors that may affect the operational effectiveness of the HVPGS.

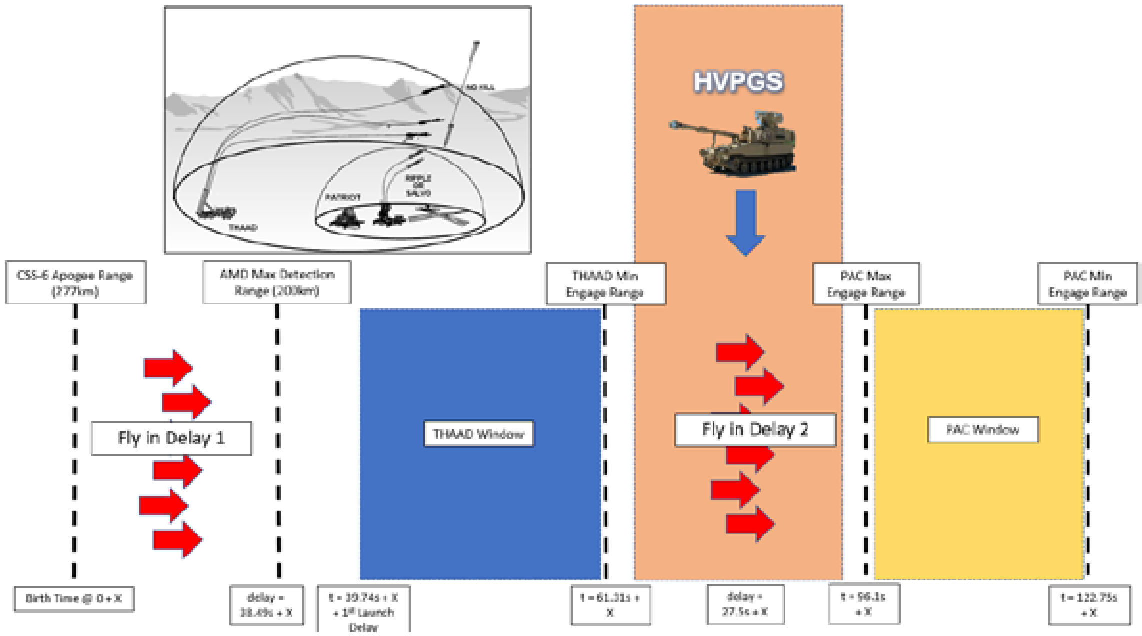


Figure 27. Modified AMD Engagement Process.

1. Incorporating the HVPGS

The HVPGS leverage the use of HVPs as an operational and cost-effective interceptor against salvo missile attacks. As discussed in Chapter II, the comparatively lower cost of the HVPs allow military planners to fire many shots successively against an incoming salvo, thereby offsetting the lower probability of hit afforded by these cheaper HVPs. The flexibility and versatility of these projectiles against a wide range of threat for various missions and its compatibility to different launcher systems prove to be an invaluable feature that would greatly lower the cost of adoption and timeline for fielding to operational units. Therefore, this thesis seeks to investigate the significance of the following key parameters as listed in Table 8 of the HVPGS launcher, and the HVPs itself using the ExtendSIM model. Figure 28 further depicts the modified ExtendSIM model with the HVPGS engagement function for sector 1. A detailed discussion of the HVP technology is reviewed in Chapter II.

Table 8. Key HVPGS and HVP Parameters

Parameters	Description
Magazine Depth	This parameter prescribes the number of HVPs that the HVPGS can accommodate on its platform. A larger HVPs magazine capacity would allow the HVPGS to fire more shots without the need for reload. This would increase the engagement capacity of each launcher and reduce the overall down time due to reloading in operations especially against large salvos attacks.
Munition Speed	This parameter prescribes the HVP engagement velocity in flight. A higher velocity should reduce the flight time needed for the HVP to reach its intended target at an identified / detected distance. This should increase the engagement window thresholds for the HVPGS, allowing it to fire more shots in a limited engagement window.
Firing Interval (Rate of Fire)	This parameter prescribes the time interval taken between each shot fired by the HVPGS. Accordingly, this translates to Rate of Fire which means the number of rounds fired within a given time period. Therefore, a higher rate of fire or a smaller Firing interval should increase the number of HVPs fired within the HVPGS engagement window.
Max Engagement Range	This parameter prescribes the max engagement range of the HVPs when fired by the HVPGS. A greater engagement range should allow the HVPGS to engage targets at further distances, increasing the engagement window opportunity.
Probability of Hit	This parameter prescribes the probability of hit for each HVP. Given that the HVP is designed with limited guidance technology due to its small size and low cost, it is expected that the HVP possess a lower probability of hit compared to conventional interceptors. However, it is necessary to determine what are the lower and upper bound limits for the probability of hit that would limit the operational effectiveness of the HVP.
No. of Launchers	This parameter prescribes the number of HVPGS launchers deployed as part of the AMD taskforce. This parameter aims to provide some insights to the ideal number of HVPGS to be employed in conjunction to the other AMD systems.

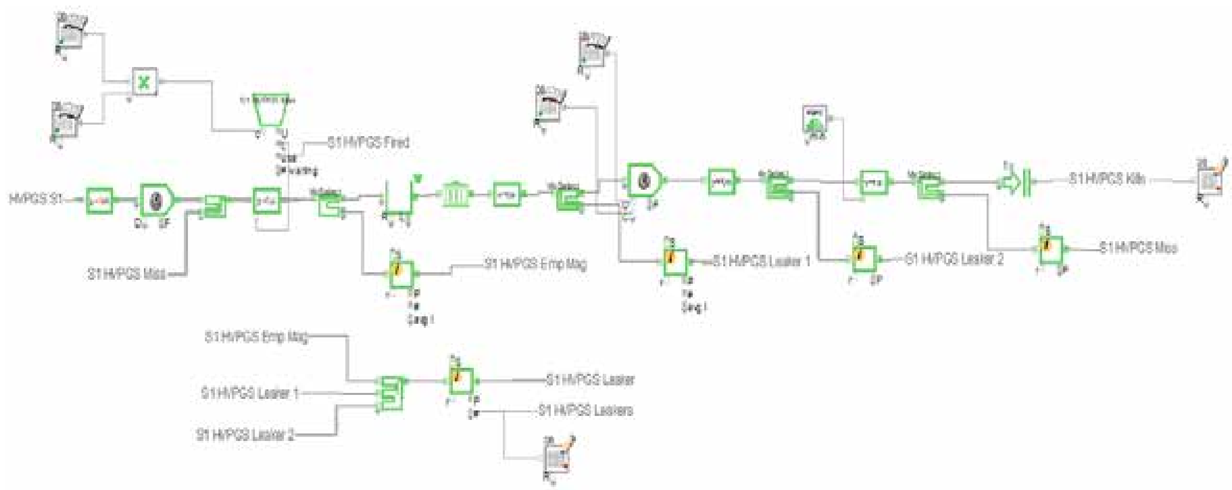


Figure 28. HVPGS Engagement Function in ExtendSIM.

2. Incorporating the Blue Force HVTs

For the model scenario, Kadena Air Base is split into three sectors with each sector housing different HVT quantities. To model the Blue Force HVTs susceptibility to each incoming CSS-6 missile that successfully penetrates the AMD enterprise's protective layers, an RCS value is assigned to each target classification. The larger the RCS signature of the target the higher the probability for each leaker CSS-6 missile to be directed to it within the particular sector. A select block is used in the model to select the target based on a computed probability using the target's RCS values. This thesis models the CSS-6 as having an active seeker in its terminal phase to guide it towards a target. Table 9 lists the number of targets within each sector and its associated RCS value. Figure 29 depicts the targeting function of the CSS-6 leaker missiles in the ExtendSIM model for sector 1.

Table 9. Blue Force HVT Parameters

Sector	Targets	RCS Value	Qty
1	Aircraft	1	12
	Building	3	1
	Hangar	2	3
	Runway	8	1
2	Aircraft	1	12
	Building	3	1
	Hangar	2	3
	Runway	8	1
3	Aircraft	1	8
	Building	3	4
	Hangar	2	3

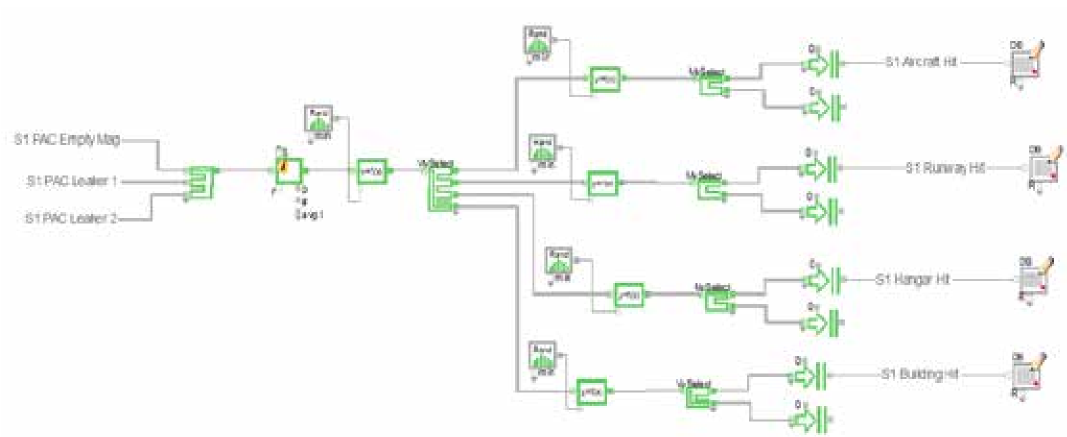


Figure 29. RCS Targeting Function in ExtendSIM.

3. Nearly Orthogonal Latin Hypercubes (NOLH) Design

To assess how the various factors / parameters of the HVPGS as listed in Table 8 affects the AMD enterprise's ability to meet the attrition objective, a design of experiments approach is employed to determine how these variables affect the response variable (Attrition Objective) which is investigated in this thesis. The basic approach would involve the use of a factorial DOE to examine the effects and the interactions between each factor. However, such a design set up using a two-level factorial design would consist of m^k combinations, where m refers to the number of levels and k refers to the number of factors. This number of combinations is usually exponentially large and may not be an efficient design for experimentation. Hence, although factorial DOE demonstrates good space-filling properties, they are in fact "not good experimental designs for more than a handful of factors because of their massive data requirements." (52) according to Sanchez (2006). Figure 31 shows the factorial designs point requirements as m and k change.

No. of factors	10^k factorial	5^k factorial	2^k factorial
1	10	5	2
2	$10^2 = 100$	$5^2 = 25$	$2^2 = 4$
3	$10^3 = 1{,}000$	$5^3 = 125$	$2^3 = 8$
5	100,000	3,125	32
10	10 billion	9,765,625	1,024
20	*don't even*	9.5×10^9	1,048,576
40	*think of it!*	9.1×10^{21}	1.0×10^9

Figure 30. Factorial Design Point Requirements. Source: Sanchez (2006).

To mitigate the above issues and challenges arising from full factorial design and the associated requirements, Sanchez (2006) recommends another method using Latin Hypercubes (LH) as an alternative. The use of LH provides good space-filling properties with a smaller number of design points. This is achieved by spreading the design points evenly throughout the design region. This yields a design space with minimal unsampled spaces within the region. However, for experiments that have a smaller number of factors in consideration, the use of Nearly Orthogonal Latin Hypercubes (NOLH) methodology as described by Cioppa and Lucas is proposed as a better fit for DOE (Sanchez 2006). Figure 31 illustrates the number of design points that is generated using this NOLH methodology which is dependent on the value of the number of factors (k).

No. of Factors	No. of Design Points
2–7	17
8–11	33
12–16	65
17–22	129
23–29	257

Figure 31. Design Point Requirements for NOLH. Source: Sanchez (2006).

Orthogonality denote independent design points; this means that the response variable of a particular design point would not be influenced by another set of design point in the experiment. To determine the orthogonality of the design points, one can compare the pairwise correlation value of two factors. The values should lie in the range between -1 to 1, with values being closest to 0 as the most desirable. However, according to Tng (2014) in his thesis, he mentions a discussion with Professor Thomas W. Lucas, who stated that a correlation value less than +/-0.05 is also sufficient to demonstrate orthogonality between design points (Tng 2014). Therefore, using the six design parameters/factors as listed in Table 8 and the design point requirement shown in Figure 32, using just 17 design points would have been adequate for this thesis's analysis. However, for the purpose of this experimental design, the author has chosen to simulate using 33 design points instead of 17 to improve the design's orthogonality. Another reason for this is because of the smaller range of high low values that is applicable for some of the factors, these would inevitably result in higher pairwise correlation values. Therefore, using a larger number of design points mitigate the impact of this and improve the overall design's orthogonality (Wong 2016). Finally, to generate the required design points, the high and low factor values for each design parameter must first be defined. The author based these values for the experiment on a list of four weapon systems, namely the Advanced Gun System (AGS), MK 45 Mod 4, 155mm Paladin Artillery Gun and the Electro-Magnetic Rail Gun (EMRG) that have been assessed to be capable of firing the HVPs (O'Rourke 2016). An elaboration of the chosen values is described in Table 10.

Table 10. NOLH High and Low Factor Values

Design Parameters	High Value	Low Value	Description
Magazine Depth	750	95	The high value here is based on the magazine storage capacity of the AGS which employs an automated below-deck weapon handling and storage system (Janes 2017). The low value is derived from the Paladin artillery system which is supported by the M992 field ammunition supply vehicle (Janes 2018).
Munition Speed	2503 m/s	1029 m/s	The high value here is based on the HVP velocity fired from the EMRG system which approaches Mach 7 speeds in flight, while the low value is based on the HVP fired from conventional powdered gun systems. In this case, the assumption is that the HVP fired by the Paladin artillery gun would reach speeds of up to Mach 3 (O'Rourke 2016).
Firing Interval (Rate of Fire)	1s	10s	As there is no clear available data on the Firing Interval (Rate of Fires) for the four weapon systems firing the HVP, a broad range from 1s to 10s to fire a single round is assumed in this thesis and used as the high and low values for analysis.
Max Engagement Range	90 KM	40 KM	According to O'Rourke (2016), the engagement ranges for the four systems span from 17 Nautical Miles (31 KM) to 100 Nautical Miles (185 KM). However, as this thesis proposes the integration of the HVPGS to the wider AMD enterprise, the author has chosen the High and Low values of 90 KM and 40 KM which is between the engagement ranges for both the THAAD and Patriot systems as described in the CONOPS. The values chosen are deemed realistic and attainable within the current technology capability limits as described by O'Rourke (2016).
Probability of Hit	0.7	0.1	For the probability of hit, this thesis used 0.7 as the high value which takes reference to the Patriot System interceptor capability. However, this thesis assumes a lower bound probability of hit value of 0.1 with the assumption that given the low cost of these HVP interceptors, it would be associated with a much lower probability of hit (Sydney 2018).
No. of Launchers	10	1	For this parameter, this thesis assumes that military planners have the ability to leverage a large inventory of compatible launchers (i.e almost 800 paladin guns) to support the AMD enterprise (O'Rourke 2016). Therefore, an arbitrary range of 1 to 10 HVPGS launchers in support of two Patriot launchers in each sector is used to investigate the impact of this factor on the operational outcome.

Based on the described low and high levels in Table 10, a total of 33 design points is then generated using the NOLH spreadsheet which can be downloaded from the Seed Center for Data Farming website, Naval Postgraduate School. As a total of 11 factors are needed to generate the desired 33 design points, the five additional factors are left empty. The 33 design points are depicted in Figure 32.

Magazine Depth	Munition Speed	Rate of Fire	Max Range	Prob. Hit	No. of Launchers					
750	1167	6.06	49375	0.63	7	0	0	0	0	0
689	2503	8.88	58750	0.38	3	0	0	0	0	0
668	1674	1.84	47813	0.12	6	0	0	0	0	0
463	2319	1	60313	0.66	2	0	0	0	0	0
709	1075	5.78	50938	0.51	7	0	0	0	0	0
730	2411	7.19	54063	0.36	3	0	0	0	0	0
545	1720	1.28	52500	0.1	7	0	0	0	0	0
443	2042	1.56	57188	0.64	3	0	0	0	0	0
525	1398	8.03	66563	0.53	4	0	0	0	0	0
586	1996	7.47	74375	0.23	6	0	0	0	0	0
566	1351	3.25	88438	0.31	2	0	0	0	0	0
607	2088	4.09	86875	0.55	10	0	0	0	0	0
484	1259	8.31	68125	0.46	2	0	0	0	0	0
648	1904	6.63	83750	0.19	6	0	0	0	0	0
504	1305	2.41	85313	0.33	1	0	0	0	0	0
627	1950	4.66	90000	0.59	9	0	0	0	0	0
423	1766	5.5	65000	0.4	6	0	0	0	0	0
95	2365	4.94	80625	0.18	4	0	0	0	0	0
156	1029	2.13	71250	0.42	8	0	0	0	0	0
177	1858	9.16	82188	0.68	5	0	0	0	0	0
382	1213	10	69688	0.14	9	0	0	0	0	0
136	2457	5.22	79063	0.29	4	0	0	0	0	0
115	1121	3.81	75938	0.44	8	0	0	0	0	0
300	1812	9.72	77500	0.7	4	0	0	0	0	0
402	1490	9.44	72813	0.16	8	0	0	0	0	0
320	2135	2.97	63438	0.27	7	0	0	0	0	0
259	1536	3.53	55625	0.57	5	0	0	0	0	0
279	2181	7.75	41563	0.49	9	0	0	0	0	0
238	1444	6.91	43125	0.25	1	0	0	0	0	0
361	2273	2.69	61875	0.34	9	0	0	0	0	0
197	1628	4.38	46250	0.61	5	0	0	0	0	0
341	2227	8.59	44688	0.48	10	0	0	0	0	0
218	1582	6.34	40000	0.21	2	0	0	0	0	0

Figure 32. NOLH 33 Design Points.

Prior to using the generated design points for further simulation analysis, the author needed to verify that the design points demonstrate good space filling properties and orthogonality levels before the actual simulation. To do so, the author conducted the correlation test by generating a correlation matrix of the six parameters using Microsoft Excel. A Scatter Plot Matrix was also generated using JMP PRO V15 (JMP) software for analysis. Figure 33 and 34 depicts the Correlation Matrix and Scatter Plot Matrix results respectively.

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Column 1	1					
Column 2	8.7E-05	1				
Column 3	0.00064	0.00023	1			
Column 4	9.8E-05	-0.00037	0.00033	1		
Column 5	-0.02285	0.00545	0.02366	0.00518	1	
Column 6	0.01186	3.8E-05	0.05455	0.03093	-0.00637	1

Figure 33. Correlation Matrix Results.

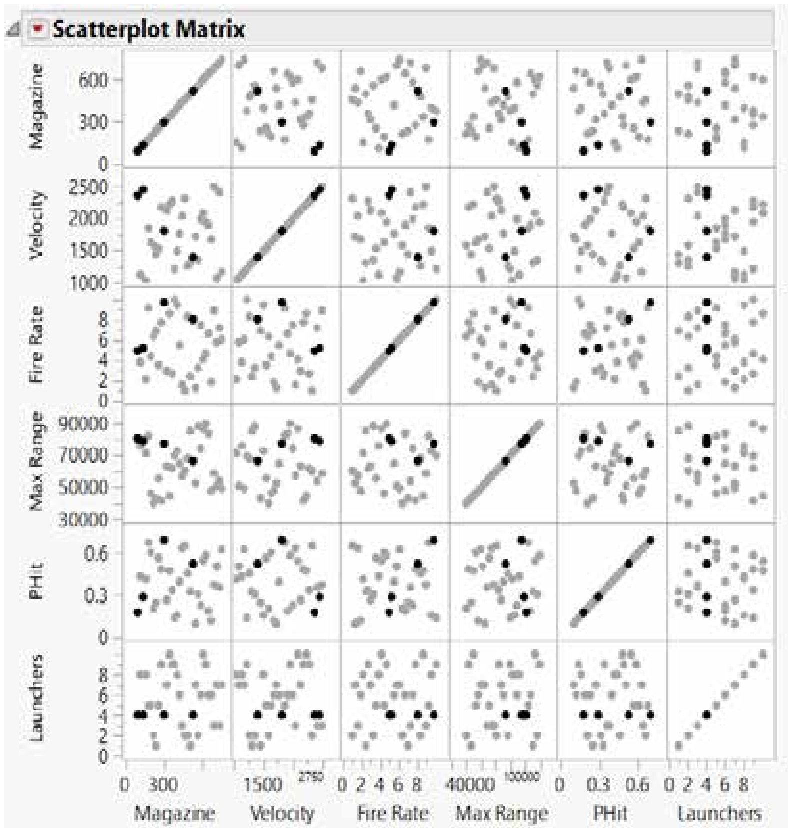


Figure 34. Correlation Matrix Results.

From the results shown in Figure 33, we can ascertain that the design points are tested and found to be independent with sufficient orthogonality between each other. This is understood from the correlation values of the six factors seen in Figure 33, which all fall within the +/- 0.05 guideline as described by Tng (2014). From the scatterplot matrix in Figure 34, we can also ascertain that there are no large empty spaces within the scatterplot for any of the six factors investigated. This also supports our assertions that the generated design points possess good space-filling properties. With this result, the author can now proceed to use the design points for simulation and analysis.

4. Simulation results

With the 33 generated design points, this thesis simulated each design point 100 times using ExtendSIM. The aim was to determine if any of the 33 design points was able to meet the Blue Force HVTs attrition objective of less than 10% for the AMD engagement. Figure 35 shows the results of the simulations. It can be seen that out of the 33 design points, only five are able to meet the 10% or less attrition objective. These are namely design points #4, 8, 12, 16 and 30 which are highlighted in green in Figure 35. The five design points simulation results are then calculated to derive a 95% upper bound Confidence Interval (CI) for all five design points as depicted in Table 11. For this scenario, the author used an upper bound CI for a stricter and more stringent distinction point because the attrition requirement is that the number of Blue Force HVTs cannot exceed 10%. Therefore, using the upper bound gives this thesis a higher level of confidence that each of the design points actually meet the stated attrition objective.

S/N	NOLH Design						Attrition
1	750	1167	6.06	49375	0.63	7	0.7033
2	689	2503	8.88	58750	0.38	3	0.8141
3	668	1674	1.84	47813	0.12	6	0.6700
4	463	2319	1	60313	0.66	2	0.0169
5	709	1075	5.78	50938	0.51	7	0.7384
6	730	2411	7.19	54063	0.36	3	0.8080
7	545	1720	1.28	52500	0.1	7	0.5718
8	443	2042	1.56	57188	0.64	3	0.0804
9	525	1398	8.03	66563	0.53	4	0.6676
10	586	1996	7.47	74375	0.23	6	0.7182
11	566	1351	3.25	88438	0.31	2	0.7192
12	607	2088	4.09	86875	0.55	10	0.0002
13	484	1259	8.31	68125	0.46	2	0.7778
14	648	1904	6.63	83750	0.19	6	0.7290
15	504	1305	2.41	85313	0.33	1	0.7151
16	627	1950	4.66	90000	0.59	9	0.0055
17	423	1766	5.5	65000	0.4	6	0.5992
18	95	2365	4.94	80625	0.18	4	0.7641
19	156	1029	2.13	71250	0.42	8	0.2014
20	177	1858	9.16	82188	0.68	5	0.6120
21	382	1213	10	69688	0.14	9	0.7547
22	136	2457	5.22	79063	0.29	4	0.7331
23	115	1121	3.81	75938	0.44	8	0.3543
24	300	1812	9.72	77500	0.7	4	0.6986
25	402	1490	9.44	72813	0.16	8	0.7445
26	320	2135	2.97	63438	0.27	7	0.3949
27	259	1536	3.53	55625	0.57	5	0.4782
28	279	2181	7.75	41563	0.49	9	0.6443
29	238	1444	6.91	43125	0.25	1	0.7718
30	361	2273	2.69	61875	0.34	9	0.0669
31	197	1628	4.38	46250	0.61	5	0.5798
32	341	2227	8.59	44688	0.48	10	0.6678
33	218	1582	6.34	40000	0.21	2	0.7876

Figure 35. Simulation Results.

Table 11. 95% Attrition Upper Bound CI Results.

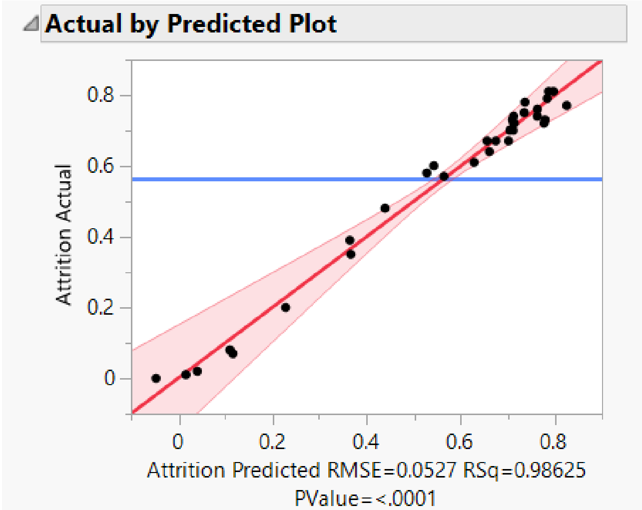
Design Point #	95% Upper Bound CI for Attrition
4	Mean: 0.0169 Upper Bound CI: 0.0256
8	Mean:0.0804 Upper Bound CI: 0.0976
12	Mean: 0.0002 Upper Bound CI: 0.0006
16	Mean: 0.0055 Upper Bound CI: 0.0097
30	Mean: 0.0669 Upper Bound CI: 0.0828

V. DATA ANALYSIS

This thesis employs two types of data analysis methods to investigate and analyzse the simulation results obtained, namely regression analysis and partition tree analysis. Using these two methods of analysis, the author seeks to identify the significance of each of the six identified factors for the HVPGS and how the variation of design points would impact the attrition objective for Blue Force HVTs. The mean percentage results of Blue Force HVT attrition from 100 simulation replications were used for both methods of analyses.

A. REGRESSION ANALYSIS

Using JMP Pro 15, regression analysis was conducted on the derived results from the simulation. The regression model predicting how the overall Blue Force Attrition percentage varies with the six design parameters is depicted in the Actual by Predicted Plot shown in Figure 36. The individual dots (data points) in the predicted plot of Figure 36 represents the simulated data points. Given that a large majority of the data points fall within this lower and upper range, which is represented by the dotted lines, this signals a good fit of the data to the predicted linear model. This is also substantiated by the relatively high R-square value of 0.986252, meaning the model is able to account for up to 98.6% of the variation in the percentage of Blue Force HVT attrition. Figure 36 also shows the analysis of variance (ANOVA) result for the analysis. The extremely small p-value (0.0001) obtained from the ANOVA, supports the alternate hypothesis and hence allows us to reject the null hypothesis, which specifies that none of the design parameters pose any significance on the Blue Force Attrition percentage.



Summary of Fit

RSquare	0.986252
RSquare Adj	0.960007
Root Mean Square Error	0.052665
Mean of Response	0.56303
Observations (or Sum Wgts)	33

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	21	2.1887869	0.104228	37.5780
Error	11	0.0305101	0.002774	**Prob > F**
C. Total	32	2.2192970		<.0001*

Figure 36. Actual by Predicted Plot Result.

Therefore, to investigate the significance and rank of each of the six design parameters, the sorted parameter estimates function in JMP is used to rank the design parameters in their respective order as depicted in Figure 37.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Fire Interval	0.0614055	0.00345	17.80	<.0001*
PHit	-0.630363	0.051882	-12.15	<.0001*
Launchers	-0.037226	0.003453	-10.78	<.0001*
Max Range	-3.181e-6	6.21e-7	-5.12	0.000[illegible]*
Velocity	-0.000102	2.113e-5	-4.81	0.000[illegible]*
(Velocity-1766.03)*(Launchers-5.51515)	-7.519e-5	4.416e-5	-1.70	0.116[illegible]
Magazine	7.5577e-5	0.000049	1.54	0.151[illegible]
(Fire Interval-5.50061)*(Max Range-65000.2)	[illegible]	[illegible]	-1.41	[illegible]
(Velocity-1766.03)*(PHit-0.40061)	-0.002465	0.00227	-1.09	0.300[illegible]
(Magazine-422.515)*(PHit-0.40061)	-0.003292	0.003388	-0.97	0.3321
(Magazine-422.515)*(Launchers-5.51515)	0.0003174	0.000678	0.47	0.6490
(Max Range-65000.2)*(Launchers-5.51515)	-8.275e-7	1.879e-6	-0.44	0.6682
(PHit-0.40061)*(Launchers-5.51515)	-0.153881	0.386536	-0.40	0.6982
(Magazine-422.515)*(Fire Interval-5.50061)	-0.000159	0.000534	-0.30	0.7721
(Velocity-1766.03)*(Max Range-65000.2)	-1.441e-8	5.392e-8	-0.27	0.7942
(Magazine-422.515)*(Velocity-1766.03)	-9.374e-8	1.223e-6	-0.08	0.9403
(Velocity-1766.03)*(Fire Interval-5.50061)	-4.017e-6	7.554e-5	-0.05	0.9585
(Fire Interval-5.50061)*(Launchers-5.51515)	0.0003131	0.007352	0.04	0.9668
(Max Range-65000.2)*(PHit-0.40061)	3.0834e-7	2.045e-5	0.02	0.9882
(Fire Interval-5.50061)*(PHit-0.40061)	-0.001564	0.147033	-0.01	0.9917
(Magazine-422.515)*(Max Range-65000.2)	-2.77e-10	3.132e-8	-0.01	0.9931

Figure 37. Effects Analysis Result.

From the results, one can see that the HVPGS's Rate of Firing has the greatest effect on the overall Blue Force HVT attrition. This is followed by the Probability of Hit, Number of Launchers, Max Engagement Range and the HVP velocity in order of significance. The outcome is largely expected, as a higher rate of fire allows the HVPGS to launch more HVPs against the incoming salvo attack to thin out the CSS-6 missiles within its engagement window before they reach the Patriot system. The exception here is the result for Magazine Capacity. The p-value of the Magazine Capacity parameter found is significantly higher than the test significance level (0.05) at 0.151, falling within in the rejection region. This provides insufficient statistical evidence to reject the null hypothesis of Magazine Capacity having no significant effect on the overall attrition outcome. However, this author assessed that this could be due to the significantly smaller number inbound CSS-6 missiles leakers entering the HVPGS engagement window compared to the Magazine Capacity value used in the test, resulting in limited impact on the response variable due to this factor. Figure 37 also shows that apart from the Firing Interval (Rate of Fire), the predicted coefficients for all the other significant factors are negative. This means that these factors with negative coefficients generate a higher probability of Blue Force HVT Attrition as their values decrease. On the contrary for Firing Interval (Rate of

Fire), the longer the time taken between shots, the higher the probability of the overall Blue Force Attrition.

B. PARTITION ANALYSIS

Using the Partition Tree Hierarchy for analysis allows one to see the optimal split of the collected data with respect to the measured outcome. The partition tree categorizes the data and breaks down the key threshold values for specific parameters, providing designers with more tangible threshold values when evaluating system constraints and trade-offs. From Figure 38, one can see that the R-Square value obtained from the analysis is 0.834. This demonstrates that the partition tree is able to account for 77.7 percent of the variability with regard to the Blue Force HVT attrition outcome after performing four splits.

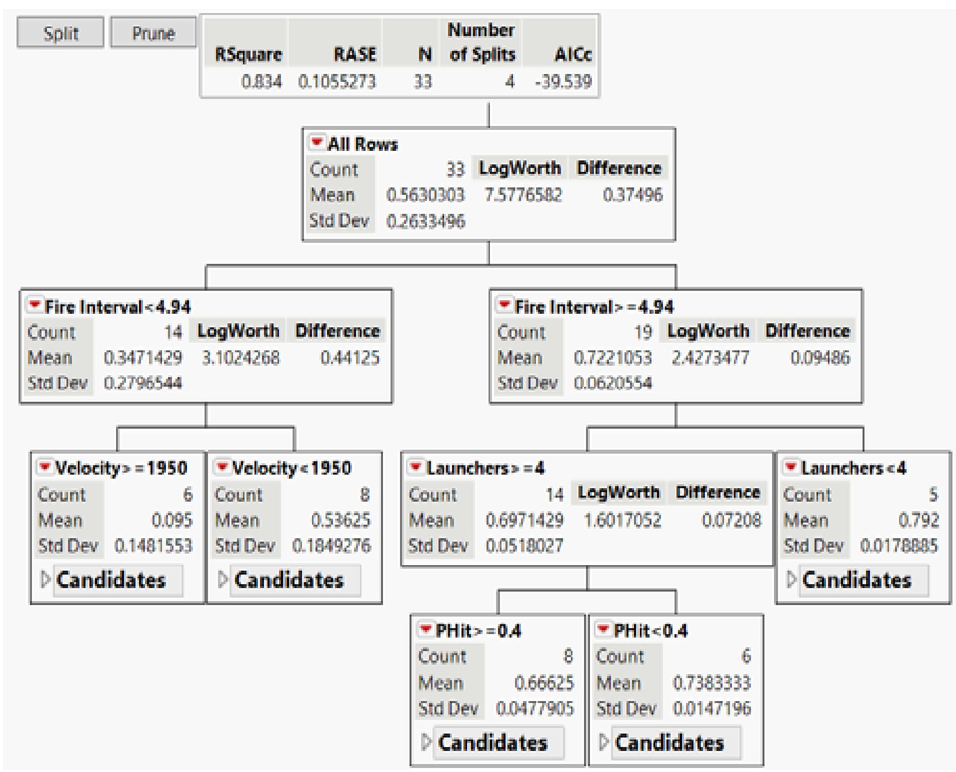


Figure 38. Partition Tree Analysis.

A further analysis of the results shows us that a mean attrition value of 56.3% is obtained over 33 design points. In the first split, one can see that if the Rate of Fire is above 4.94 seconds (meaning that time between fires takes more than 4.94 seconds), the mean attrition percentage increases to 72.2% as simulated in 19 of the design points. Conversely, when the Rate of Fire is below 4.94 seconds (meaning that time between fires takes less than 4.94 seconds), the mean attrition percentage decreases to 34.7% as simulated in 14 of the design points. Next, in the case when a Rate of Fire below 4.94 seconds is achieved, a second level of decomposition shows that the next most significant factor, namely the HVP's velocity is examined. In this level of decomposition, one can see that if the HVP velocity is below 1950 m/s, the mean attrition percentage increases to 53.6%, while having an HVP velocity above or equal to the 1950 m/s threshold brings the mean attrition percentage down to 9.5% which is within this thesis's state maximum attrition objective.

Alternatively, from the partition tree analysis, one can also see that if the most significant parameter threshold for the HVPGS Rate of Fire is not achievable by design or other identified limitations, a system engineer can consider the emplacement of at least 4 or more HVPGS launchers, employing HVPs with a probability of at least 0.4 and above as a trade-off to the other factors. However, from the partition tree analysis, it is shown that this alternative design parameter threshold values would still yield a mean attrition percentage of 66.6% and is unable to deliver the desired 10% attrition or below as stated in this thesis.

C. MISSILE COST EXCHANGE ANALYSIS

As highlighted in Chapter II, a key challenge faced by U.S. forces against the large inventory of Chinese missiles lies with the cost exchange factor for missile to missile engagement. For every incoming missile that is fired onto U.S. targets, an equal or more expensive counter missile interceptor is needed to neutralize the threat before it impacts its target. Therefore, to investigate the improvement in CER with the incorporation of the HVPGS into the AMD Enterprise, this thesis also simulated the base model AMD Enterprise (Without HVPGS) scenario 100 times to determine the base-line CER incurred to achieve an average Blue Force Attrition percentage of no more than 10%. In this base-line model simulation, only the cheaper Patriot missiles was varied to achieve a Blue Force

Attrition percentage of no more than 10%. The investigation revealed that at least five Patriot Launchers (Compared to two launchers originally) with a total of 80 PAC-3 interceptors were needed to bring the Blue Force Attrition percentage to no more than 10%. The THAAD interceptors was kept unchanged. The CER is computed by dividing the cost of the total number of HVP, THAAD and PATRIOT interceptors used over the estimated cost of the enemy CSS-6 missiles. The computed CER is then compared to the CER obtained from the modified AMD Enterprise (With the HVPGS) as seen in Figure 39.

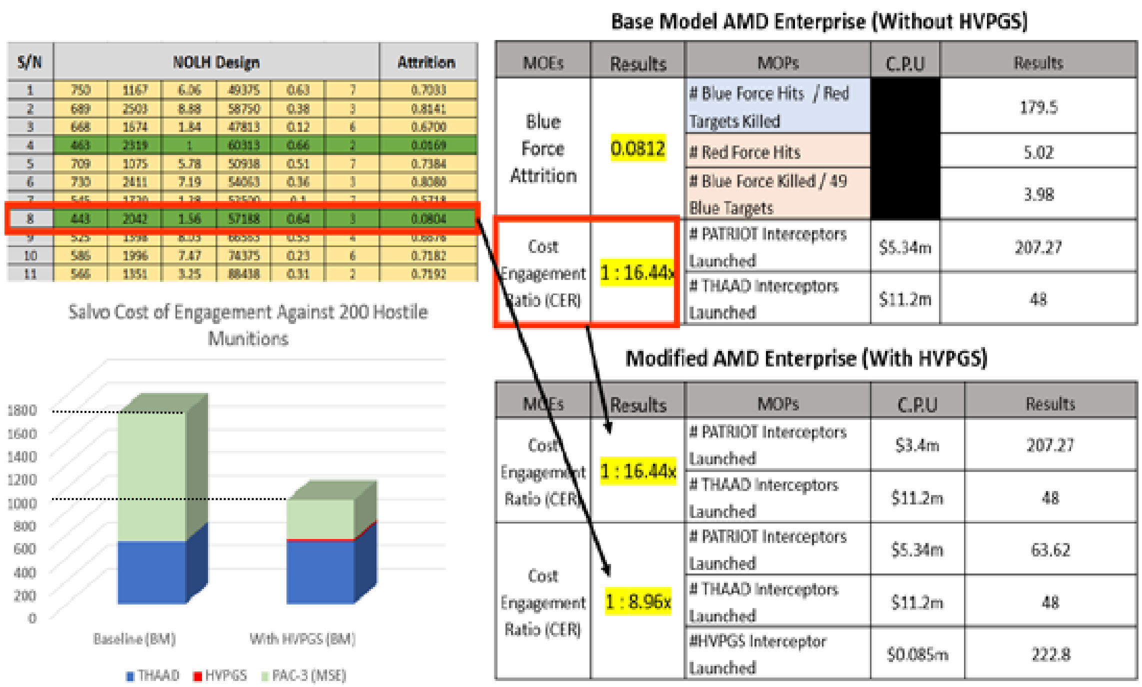


Figure 39. Partition Tree Analysis.

Design point 8 of the modified AMD Enterprise (With HVPG) is used in this comparison as the mean Blue Force Attrition percentage of 8.04% obtained is most similar to the Blue Force Attrition percentage of 8.12% by the base model AMD Enterprise (Without HVPGS), when the number of Patriot Launchers employed in each sector was increased to five. On the whole, from the results seen in Figure 39, one can see that base model AMD Enterprise (Without HVPGS) yields a CER of 1:16.44, while the modified AMD Enterprise (With HVPG) yields a CER of 1:8.96. This represents a 45.4%

improvement in the overall CER when the HVPGS is incorporated into the AMD Enterprise, greatly improving the overall cost exchange factor and sustainability for missile defense.

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VI. CONCLUSION AND FUTURE RESEARCH

The parameters for the AMD systems studied in this thesis are based on open source references. Although the values used may vary from the true performance parameters of the aforementioned AMD systems, the observations and findings from the modeled simulation should still offer valuable insights into the proposed incorporation of a HVPGS into the U.S. Army's existing AMD Enterprise. Nonetheless, it is clear that the results demonstrated should only be limited to the investigation yielded from this thesis and may not necessarily reflect the actual system performances in a real-world scenario adequately.

A. INSIGHTS

From the results obtained, one can see that having a small Firing Interval (Rate of Fire) for the HVPGS is a key design criterion in meeting the desired minimal attrition objective. This is verified in both the regression analysis as well as the partition tree analysis. The results show a significant 37.5% improvement when the threshold is varied above and below 4.94 seconds. It is assessed that the high rate of fire is able to mitigate the HVP's disadvantage of a significantly lower probability of hit compared to other conventional interceptors and deliver a heavier barrage to effectively thin out an incoming salvo attack in line with the author's proposed CONOPS for the AMD Enterprise. Therefore, if permitted, system designers / engineers should prioritize this as a key parameter in the design selection and trade-off consideration process when incorporating the HVPGS.

The next consideration in the employment of the HVPGS lies with the number of launchers that should be deployed in support of the AMD Enterprise for optimality. From the partition tree analysis, one can see that at least four launchers should be employed in tandem with two Patriot systems for a single defended sector to achieve a visible improvement in performance. This author assess that four launchers should only be used as a basis for reference and military planners should not be limited by this threshold. The employment of more HVPGS in support of the AMD mission would indirectly increase the rate of fire, putting more HVPs downrange and thereby increasing the probability of hit against each incoming enemy missile. With an abundance of existing powder guns such as the 155 MM M109A6 Paladin self-propelled howitzer that is capable of firing HVPs, the idea of having a large HVPGS force to complement a single Patriot battery should be a feasible proposal that can be readily adopted for AMD forces. This revelation should provide military planners with more tangible planning guidance to formulate doctrinal and TTP adjustments to meet the AMD mission requirement.

Lastly, as the production costs of each TBM decreases through economies of scale to the advantage of potential adversaries, the continued pursuit of long range and highly accurate AMD systems may not be sufficient to tilt the cost exchange in favor of U.S. AMD forces. From the CER analysis, one can see that the employment of low cost HVPs that offers a lower probability of hit is capable of effectively lowering the cost of engagement for U.S. force whilst still optimizing AMD performance. However, this author assesses that the effectiveness offered by the use of low cost HVPs without advance guidance systems onboard may be limited to TBMs or munitions with a fixed trajectory flight path. In the case of more agile and maneuverable threats such as long-range cruise missiles systems, the existing state of HVPs may not be a viable interceptor solution and more developmental work on the technology is required to improve the capability.

B. FUTURE WORK

The race to develop and field more advanced missile engagement and defense systems is an enduring challenge for many nations. However, in today’s increasingly constrained fiscal environment, cost and sustainability will also persevere as significant considerations to be taken into account in the missile defense calculus for military planners. The arms race is likely to swing in favor of one nation or another over time as technology progresses and become iterative in nature as newer technologies emerge. Therefore, it must be acknowledged that while the study conducted by this thesis is not exhaustive, it provides a relevant context for other possible follow-on research topics as listed below.

(1) Study on Effectiveness of HVPs for Cruise Missiles Defense

Cruise missiles are an increasingly potent threat against U.S. forces and allies. A key area to be explored on this topic is how HVPs with a varied low to high guidance capability would be able to effectively intercept a long-range cruise missile's flight trajectory and neutralize the threat. Such a test and investigation should also include more fidelity in terrain features as long-range cruise missiles usually skim the surface of the earth's curvature and take cover behind high relief feature in their flight path to avoid radar detection (Harney 2004). This would likely entail the use of other modeling tools beyond ExtendSIM to effectively simulate terrain features for the research.

(2) Study on Effectiveness of HVPGS on Ships for Naval Missile Defense.

HVPs offer the potential for a multi-mission capability. As such, further research can be conducted to determine the operational effectiveness of a HVPGS onboard navy ships to augment existing missile defense systems such as the Aegis Ballistic Missile Defense system as well as the Close-In Weapon System (CIWS) against surface and air threats. With the build-up of Anti-Ship Ballistic Missile capability by potential adversaries, more research into the HVP technology should offer significant operational and tactical advantages to the Navy if deemed applicable.

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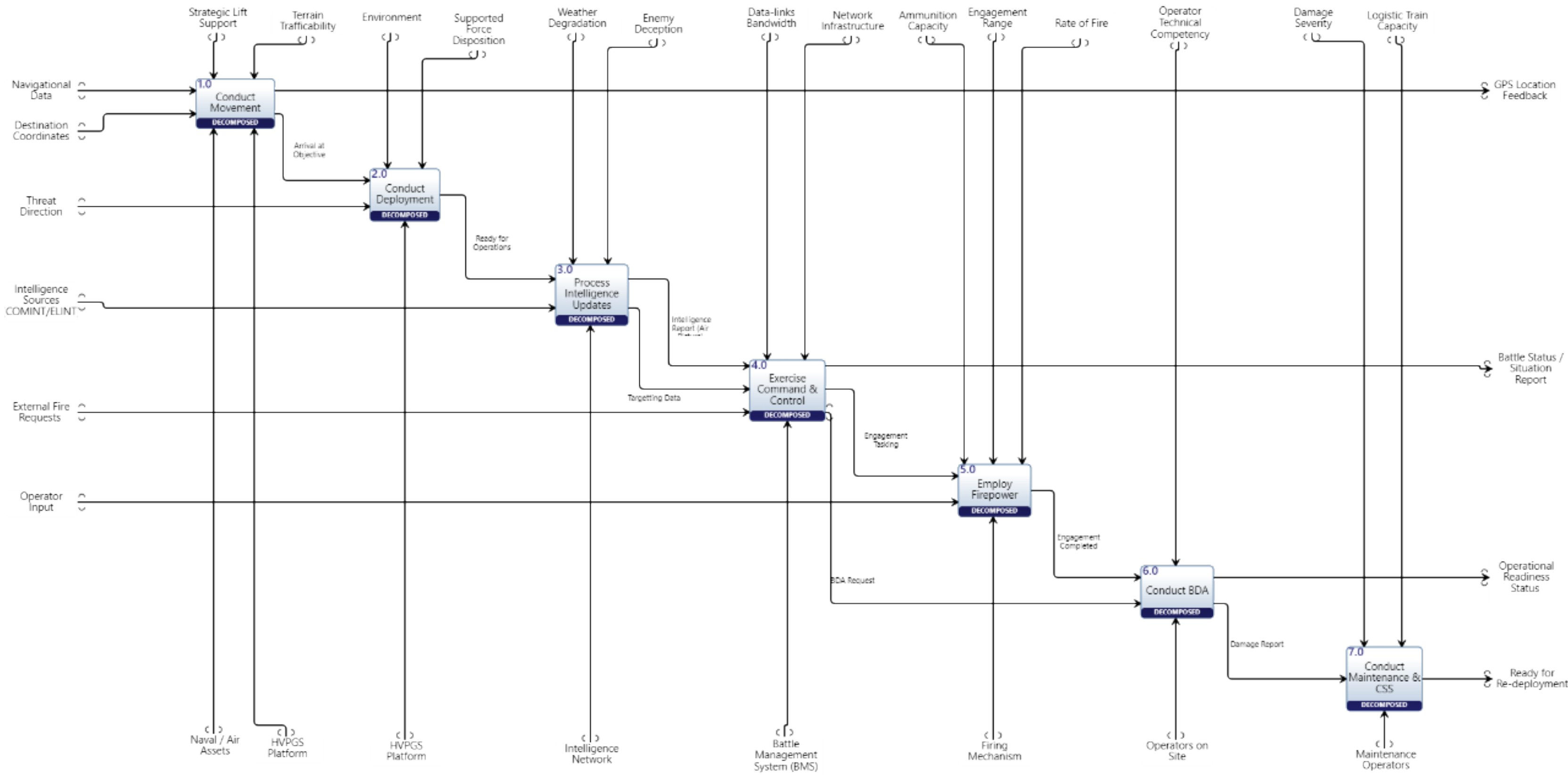
APPENDIX. INNOSLATE ARCHITECTURE PRODUCTS



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