QUANTIFYING RESILIENCY RISK METRICS THROUGH FACILITY DISPERSION

THESIS

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AFIT-ENV-MS-19-M-170

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENV-MS-19-M-170

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THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

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March 2019

AFIT-ENV-MS-19-M-170

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Abstract

During the last century, airbases were attacked at least 26 times in an effort to destroy the enemy at its base. Attacks on military airbases impose prohibitive losses to critical infrastructure, which in turn impacts the maintenance of air power projection. The primary enemy threat facing critical infrastructure today is the use of ballistic and land-attack cruise missiles to disrupt an airbase's ability to launch and recover aircraft. Over the last decade, ballistic and cruise missile technology has grown to allow the world's most powerful countries to achieve a nascent threat to forward operating bases used in theater security campaigns worldwide. Planners can reduce the impact of ballistic and cruise missile attacks on aircraft projection platforms by incorporating a number of resiliency measures, including dispersal of critical infrastructure assets, such as aircraft fuel containment and conveyance equipment. The integration of resiliency measures increases construction costs; therefore, planners need to identify an optimum balance between maximizing airbase resiliency and minimizing site costs. This research presents an airbase resiliency assessment capable of quantifying facility dispersal and risk tolerance levels in an environment threatened by missile attack. Model performance was evaluated using a case study from Osan AB, Republic of Korea. The model's distinctive capabilities are expected to support planners in the critical task of analyzing and selecting the design strategy that maximizes airbase resiliency against the threat of ballistic and cruise missile attack.

Acknowledgments

First and foremost, I would like to thank my wife for her endless support while I conducted this research. Thank you for your inspiration and wrangling our children while I spent long days in the computer lab and traveling to conduct research. I could not have done this without you. Furthermore, I would like to thank my peers for the shared laughter and misery that has created life-long bonds of friendship. And finally, I would like to thank my advisor, Major Steven Schuldt, for his wisdom and guidance that was a breath of fresh air. You helped get me to a level I thought I’d never reach. I’m thankful for my time here at AFIT, but am looking forward to the future and yearning to find out what it holds.

Branden D. DeLong

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QUANTIFYING RESILIENCY RISK METRICS THROUGH FACILITY DISPERSION

I. Introduction

Background

"*Our forces face the very real possibility of arriving in a future combat theater and finding themselves facing an arsenal of advanced, disruptive technologies that could turn our previous technological advantage on its head – where our armed forces no longer have uncontested theater access or unfettered operational freedom of maneuver.*"

Robert Work, Deputy Secretary of Defense

Airfields have been strategic targets within adversary shot doctrine dating back to the first recorded account of a German airfield attack by a British aircraft in 1914 (Vick, 2015). Continuing through the last century, airbases were attacked at least 26 times, proving that strategic reliance on infrastructure and support assets is critical to the generation of air superiority (Vick, 2015). Giulio Douhet, an early airpower pioneer, institutionalized the idea that the most effective way to achieve airpower is to destroy the enemy at its bases (Conner, 2017; Douhet, 1998). Furthermore, within the last decade, ballistic and cruise missile technology has grown to allow peer adversaries of the United States (U.S.) to achieve a nascent threat to forward operating bases used in theater security campaigns (Conner, 2017; Luebert et al., 2016; Vick, 2015). The technological advancements in short range ballistic missile accuracy has been demonstrated to be achievable to within a circular error probable (CEP) of 5-45 meters from the desired mean point of impact (DMPI) (Nuclear Threat Initiative, 2012; Vick, 2015). This assertive threat is now forcing the idea that sanctuary basing, the belief that assets are outside of an effective threat range for missile attack, is no longer a military strategy for planners (Conner, 2017; Vick, 2015). Instead, the United States Department of Defense (DoD) has been tasked to investigate and define airbase resiliency.

In 2018, Pacific Air Forces (PACAF) headquarters employed strategic discussions aimed at reducing the risk of operating within the threat of missile attack. The resulting PACAF Agile Combat Employment (ACE) strategy follows the National Defense Strategy of "forward force maneuver and posture resilience" by studying airbase resiliency from multiple levels in order to determine how to appropriately defeat attack from adversaries (Levin, 2018; Mattis, 2018). Bases in the PACAF area of responsibility have transitioned to fighting positions in which military operations are now ongoing, even as the risk to the mission and personnel have increased (Levin, 2018). Therefore, quantifying and understanding risk has become a critical element to how geographically threatened areas are used, to include how facilities and assets are dispersed.

Problem Statement

The People's Republic of China maintains the capability to launch a high precision, ground launched ballistic missile from an area near Beijing to locations extending passed the Korean peninsula, where the DoD currently sustains multi-service operations (Conner, 2017). This brings to light the significant need to study the quantitative measures of resiliency in order to better understand the risk involved with any mission throughout the world.

The need to create a resilience strategy for “stand-in basing” within ballistic and cruise missile threat rings is becoming an ever present requirement for the next generation of airpower (Conner, 2017). Therefore, assessing risk of a stand-in base has received growing attention within the highest levels of the U.S. political spectrum. This can be seen in The National Security Strategy published in December of 2017, which highlights the need for military response to competitors around the world. To further campaign the issue of resilience and risk, the National Security Strategy provoked a response from the DoD. In the National Defense Strategy, the focus is clearly on forward resilience, with investments in assets that can survive, as well as regenerate in all domains, while under attack. It then continues to specifically identify the priority to disperse infrastructure within these forward postures (Mattis, 2018). Ted Lewis confides that it’s currently not possible to “know in advance where, when, and what the next attack is,” and thus, instilling the ability to prepare for, respond to, and recover from an attack on critical assets on an airfield is essential (Lewis, 2006). The direction from the highest ranks underpins the budgeting of all military departments to embrace a culture transitioning from a large, robust basing structure, to small locations that are resilient to attack (Mattis, 2018).

A drawback to the defense of critical infrastructure is that it is often built in concentrated areas, which leads to vulnerabilities against attack (Lewis, 2006). To help reduce asset vulnerabilities the DoD has sponsored many studies into how military assets can become more resilient. A report published in early 2017 by the Air Force Civil Engineer Center (AFCEC) demonstrated that “the application of engineering capabilities to support Airbase Resiliency requirements are multi-faceted and not yet qualitatively defined attack (Air Force Civil Engineer Center, 2017). The purpose of the study was to identify the engineering functions needed to inform the discussion on Airbase Resiliency. This AFCEC resilience study is one example of how the DoD would like to quantify risk and has been a spring board for many studies in the genre.

Headquarters PACAF has also begun to explore risk tolerance over risk aversion when force presence in forward locations is analyzed (Levin, 2018). Yet the discussions fall short of any calculations or measurable computations. Unfortunately, measuring resiliency at a forward operating base, or any location, is not a simple task and can be measured from multiple lens and functions (Air Force Civil Engineer Center, 2017). Therefore, by focusing on the prioritized issues that drive resiliency, a designer and decision-maker can begin to determine a resiliency score for that location and operation.

Research Objectives

This research begins to study the descriptive functions of resiliency to better understand the risk associated with facility destruction at a location threatened by missile attack. By studying the dispersion of asset location, the designer can impart the decision-makers risk tolerance level with the optimum facility dispersion resiliency measure. The development of risk profiles help the designer to quantitatively assess the resiliency level at a location and leads to better advocacy of military planning choices and project funding.

The objective of this research is to provide a mathematical lens to the analysis of emerging airbase resiliency strategies. The research uses dispersion methodologies coupled with known missile characteristics to quantify the risk profiles of facility siting in a location that has a constant threat of missile attack. By studying the adversary weapon characteristics and combining the analysis with research in optimal facility dispersion, a risk profile is generated to allow for decision-maker risk tolerance to be quantified. This research objective is to better understand how the DoD might defend combat power generation against future enemy attacks on airfields. Ultimately, the research goal is to determine the optimal layout for assets and systems, using weapon capabilities, to achieve maximum effective dispersion.

Research Focus

The scope of this research is defined to the analysis of facility dispersion of assets within a geographically bounded area that are within the constant threat of adversary missile attack. The research is a study of how different weapon characteristics can change the risk level of facility locations. The approach to this research is to study the question: "what is currently going on?" (Lunday, 2018). It is also employed to describe the metrics used in dispersion analysis. This research is focused on establishing the risk metric for the designer and decision-maker to quantitatively measure risk associated with facility dispersion, and therefore ultimately increase base resiliency.

Methodology

To quantify the level of risk associated with facility location, dispersion methodologies are used. The coverage of destruction areas is based on weapon characteristics and is analyzed with a multi-phase approach. First, the anti-covering based methodology is used to show that a facility can be located in an area where more than one weapon has the chance of destroying it. The second phase allows for maximum weapon capability coverage, and analyzes how the risk to a facility located within the coverage area is affected by the weapon characteristics.

Assumptions

In order to quantify risk in facility dispersion, some assumptions have been made and are used to establish the groundwork analysis for the problem. This research assumes that all weapons fired will impact within the geographical bounds of the targeting grid. No weapon will destruct by neither self-elimination, nor physical destruction and will always reach the intended destination. It is also assumed that the facility coordinates used in the analysis of impact locations of the weapon are facility locations. Therefore, the adversary will never target a location not occupied by a facility, such as an empty field. This technique assumes that the least amount of weapons are used to destroy the maximum amount of geographical area. Finally, the destruction radius for all weapons is assumed to be 900 feet.

Significance

This research presents an assessment model capable of efficiently quantifying the impact of infrastructure dispersal on airbase resiliency. The performance of the model was evaluated using a case study from Osan AB, Republic of Korea. The distinctive capabilities of the model are expected to support planners in the critical task of analyzing and selecting the design strategy that maximizes airbase resiliency against the threat of ballistic and cruise missile attack as mandated by the National Defense Strategy.

Preview

The following chapter summarizes a comprehensive literature review to establish a thorough understanding on facility dispersal. The literature review establishes requirements for the development of improved analysis of facility dispersion based on quantity dispersal and redundancy within a threatened environment. Chapter 3 presents the methodology used to develop the dispersal risk profiles as well as the dispersal analysis. It contains discussion on how the data is collected, and an explanation of the methods and procedures used to generate the research results. This methodology can be used for further analysis of the base resiliency problem definition and clarity for decision-makers. Chapter 4 presents the assessment of risk associated with facility dispersion within a threatened environment. The risk metric is developed using a five-stage analysis for multiple blast types and weapons. Chapter 4 also develops the model to quantify storage potential given the boundary and system constraints within the geographic area. Chapter 5 serves as a final discussion of the study. Conclusions along with pertinent findings and the identification of future research opportunities are presented and summarized.

II. Literature Review

Introduction

The Department of Defense (DoD) has spent over $1.9 billion dollars in support of global contingency operations in the previous two decades (Cordesman, 2017). Contingency operations often require an expeditionary means of construction in order to meet the demands of military forces, yet still today, the DoD is plagued by the problem of installing new facilities for stability operations in locations that are threatened by attack from peer and near-peer adversaries (Air Force Civil Engineer Center, 2017). Accordingly, decision-makers must analyze multiple factors when planning for new facilities. Dispersion of facilities is among the most influential of these factors. Dispersion within a geographic area can be influential on facility survivability when the location is attacked (Owen & Daskin, 1998; Snyder, 2006).

In order to meet the needs of mission evolution, planning for facility construction, even temporary facilities, can lead to long timelines in funding acquisition, facility location determination and operational support generation (Owen & Daskin, 1998). To better understand the difficult task of siting a facility, several studies have conducted research on the effects of facility dispersal within a range of community types. These studies have given designers the ability to minimize facility quantities. This ability stems from the optimization of new facility layouts that reduce duplication of service and maximize effectiveness. Researchers have been interested in facility location problems for over four decades because the study has given decision-makers the ability to link the maximum service coverage of a facility dispersion plan with the lowest cost.

Ultimately, the facility dispersion problem is pared down to the identification and minimization of future risk (Aven, 2012). Through focused and purposeful analysis of the placement metrics of new facilities, designers can better articulate the risk associated with facility location selection and how it pertains to accomplishing the mission in a threat-constrained environment. This chapter summarizes a comprehensive literature review to establish a thorough understanding on facility dispersal. For the purpose of this research, the siting of a facility is constrained to within a hostile environment and is bounded by the damage potential of ballistic and cruise missiles (Conner, 2017).

Background

Demand nodes & servicing nodes

A key component in the study of facility dispersal is the role of the demand node. A demand node is used to describe the geographic location that generates the requirement for the siting of a facility, the servicing node. Figure 1 shows a representation of demand nodes, shown by “x”, with the servicing node, the inner circle, and the prescribed area of service capability of the servicing node.

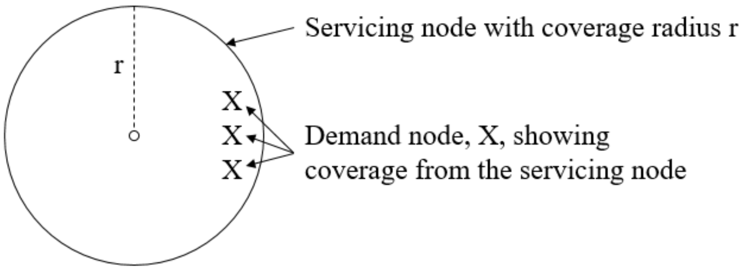

Figure 1: Servicing node facility radius of coverage to a demand area, annotated by "X." Adapted from Toregas et al., 1971

DMPI & CEP

The desired mean point of impact (DMPI) is used by military analysts to estimate the point where a missile will impact a target (Joint Staff, 2017). DMPI is used to describe a point "associated with a target and assigned for a specific weapon impact," as shown in Figure 2 (Joint Staff, 2017). DMPI can also be used to describe the center location of multiple missiles hitting a geographic area. Similarly, the circular error probable (CEP) is used to estimate the precision targeting capabilities of a missile. The most advanced capability that has been published in unclassified sources show that missiles can be very precise. In fact, the CEP for the most advanced missile is known to be as accurate as 5 meters, meaning that based on the damage radius of any missile, the intended target will be destroyed (Nuclear Threat Initiative, 2012). CEP allows analysts to differentiate between the actual location of a target and the DMPI coordinates, as shown in Figure 2 (Joint Staff, 2014). CEP is useful during the study of attack effects in which the target destruction is statistically analyzed. CEP is calculated by how much instrumentation and technology is associated with the operation of the missile and is outside the scope of this research.

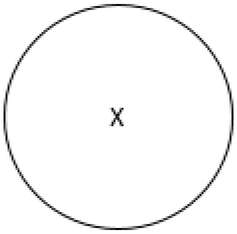

Figure 2: The desired mean point of impact, annotated by “X” shown with the circular error probable area (Joint Staff, 2017; Joint Staff, 2014)

Damage radius & threat rings

Designers must investigate the survivability of a mission within an environment threatened by attack. Missiles have a prescribed damage radius, in which the target and any unintended target collateral within the damage radius will be damaged or destroyed (Nuclear Threat Initiative, 2012; Vick, 2015). Therefore, it is important to plan and design facilities in locations that optimize dispersion from the center point of the missile and its associated impact location. By optimizing the dispersion of a facility set, the survivability of a mission is increased by: (1) maximizing the dispersal distance of assets from intended targets to reduce damage to critical infrastructure; and (2) reducing the time needed for mission regeneration post-attack (Air Force Civil Engineer Center, 2017).

In an environment threatened by attack, designers are interested in minimizing the threat to mission success. Therefore, the survivability of the mission is linked to the missile range from outside the area of geographic responsibility. Some locations are threatened by missiles with the lethal capability of traveling up to 15,000 kilometers from the point of origin (Nuclear Threat Initiative, 2012).

Intended damage and unintended damage

Adversaries of the US are actively pursuing technology that will meet or exceed the defense capabilities of operating locations around the world (Krepinevich et al., 2003). This study considers two types of damages associated with the analysis of dispersal of facilities. The first and most destructive, is the damage caused by a missile hitting the facility as an intended target. The term “intended target” is used when the adversary strategically employs a missile to destroy and/or disable the facility and the functions associated with the facility. This study assumes that the missile hitting an intended target associated with a fuel storage or conveyance capability destroys the facility and renders the facility useless as a servicing node to a demand node.

The second type of damage associated with the analysis of dispersal of facilities is the “unintended damage.” Unintended damage is used by this study to describe the damage a facility receives when located in close proximity to the intended target. In this case, the intended target is destroyed and resultantly projects damage on the unintended facility through projectiles and shrapnel. This study assumes that if a facility is within the damage radius of the missile hitting an intended target, the unintended facility associated with a fuel storage or conveyance capability destroys the facility and renders the facility useless as a servicing node to a demand node.

Noxious facilities

Researchers have developed frameworks that analyze the linkages in dispersion and hazardous facility explosions such as fuel tanks (Daskin, 2013; Jung et al., 1987). These studies have demonstrated that dispersion methods can be used to site noxious or hazardous facilities *a priori* an explosive event or attack. Designers can use facility dispersion principles to reduce the risk to the mission by siting facilities that are essential for successful operations yet pose a threat to other facilities. The threat can be from hazardous operations at the facility to the damage potential endured by other facilities if an explosive event were to take place. Designers have sited munitions bunkers, fuel storage tanks and other facilities with undesirable characteristics away from critical operations to reduce the threat of sequential facility damage when an accident or attack on a facility happens. As Buchanon and Wesolowsky (1993) state in their *Locating a Noxious Facility with Respect to Several Polygonal Regions Using Asymmetric Distances*, “the distinguishing characteristic of noxious facility problems…is that the optimum location is ‘as far as possible’ from the set of demands.” This study will account for hazardous facilities as “noxious facilities” to identify facilities that pose a threat to operations.

Development of Risk

Risk is inherent to any mission, and therefore must be analyzed by designers at all levels. Terje Aven (2012) describes risk as an additive process of consequences and uncertainties that cannot be entirely accounted for. Others describe risk as something that needs to be balanced in order to achieve the desired performance of a facility to meet the organization’s objectives (ISO, 2014).

While risk is difficult to quantify with a high level of certainty, it is critical to the management of decision-making. Therefore, the ability to define risk and plan for necessary avoidances of risk is imperative for designers as they site noxious facilities in a threat-constrained environment. The risk that a critical facility has to the mission must be reduced as much as possible in order to reduce the exposure to loss (Aven, 2012). Furthermore, designers must also be able to communicate any risk reduction measures to decision-makers when analyzing the siting of new facilities (Aven, 2012).

Dispersal

Several methods were developed to predict the dispersion of facilities. The dispersion analysis dates back to Pierre de Fermat, a student to Galileo, and French mathematician who studied analytic geometry relating to curved lines (Farahani et al., 2010). Within the scientific community, it is accepted that the original work in dispersion was first introduced by Alfred Weber in 1909, where he studied a single facility location problem to minimize the distance between where an industrious facility was located in relation to the demand nodes and the customers (Daskin, 2008). Weber based his analysis on three variables: (1) location of raw materials; (2) location of the market; and (3) transportation costs of the materials to the industry and the market (Weber, 1909). The result of Weber's work produced a method of calculating the ideal facility location based on the transportation costs between raw materials markets and consumer markets. A representation of Weber's work is shown in Figure 3, where, C1 and C2 are the source locations for raw material; M is the consumer market location; and, P is the optimum facility location.

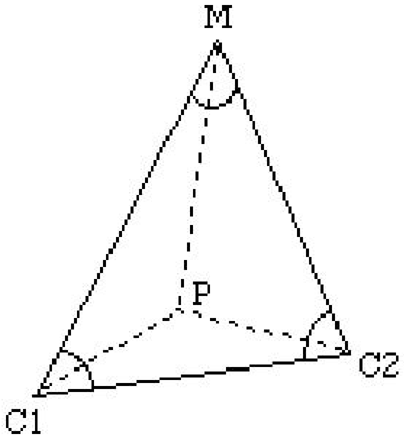

Figure 3: Alfred Weber's Least Cost Theory of Industrial Transportation, showing the optimal location of an industrial facility that relies on two raw materials markets and the consumer market (Weber, 1929)

Weber used his facility location triangle for Euclidean (straight-line) distance analysis to predict the best location of an industry by reducing transportation costs (Drezner & Suzuki, 2004). The location of the manufacturing facility, P, would be sited in the ideal location to reduce costs. The method was simple, but it generated a high amount of interest into the economical perspectives of facility siting.

There has been a sustained interest in the application of location theory over the last century because designers continue to optimize facility locations for business and industry growth (Farahani et al., 2010). Although the application of location theory in dispersion science continues to grow as more tech and industry growth occurs, dispersion science remains grounded to three genres: (1) covering-based methods; (2) median-based methods; and (3) other dispersion methods such as the siting of noxious facilities to maximize the distance between any two facilities (Daskin, 2008). Figure 4 illustrates the three different dispersion problem contributions.

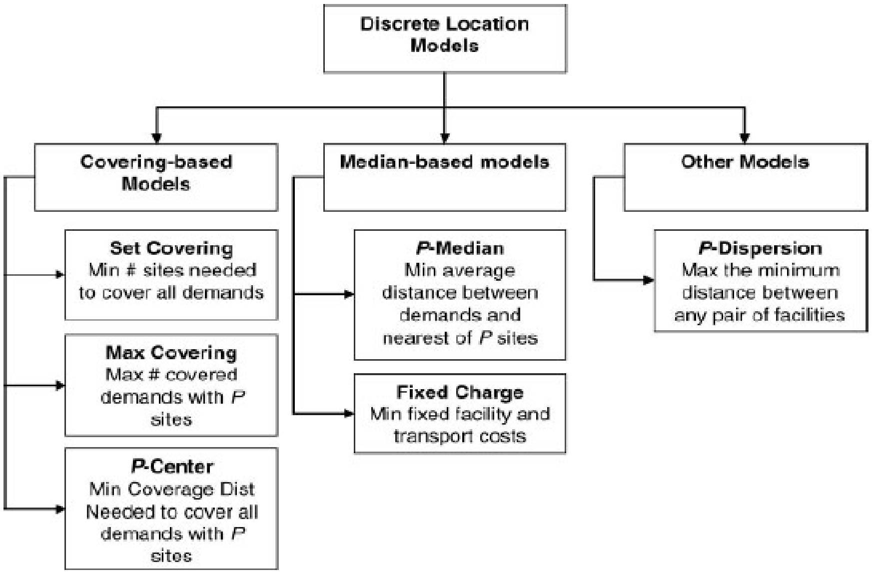

Figure 4: Breakdown of discrete location models (Daskin, 2008)

When using covering-based methods, designers need to plan for facility location with a dispersed criterion. The covering problem ensures that a facility is close enough to the demand node yet far enough from the same or similar servicing node to generate a need for the facility siting (Emir-Farinas & Francis, 2005). Covering models are seen most in the siting of emergency services vehicle facility locations (Emir-Farinas & Francis, 2005; Kvet & Janáček, 2018; Serra & Marianov, 2004).

When using median-based methods, designers locate a known number of facilities with an objective function of minimizing the distance between the nearest facility and its demand node (Daskin, 2013). This methodology reduces facility requirements and associated costs of facility development (Daskin, 2013). Other location problems include the siting of noxious facilities in which the designers are interested in siting the facilities farthest a part to reduce the probability that simultaneous reactions will result when threatening events such as accidents, explosions, or attacks occur at a single facility location.

Covering Methods

Facility location problems that involve covering seek to arrange the facility dispersion in one of two fashions: (1) covering; and (2) anti-covering. Covering allows the designer to minimize facilities in the region of service by maximizing the coverage area of each new servicing facility sited within the region. By reducing the overlap of facility coverage as much as possible, designers are able to maximize the amount of demand nodes being serviced by the least amount of facility nodes. With anti-covering strategies, the designer can maximize the number of facilities such that each facility is constrained by a specified distance of minimum separation from the closest like or similar neighboring facility (Emir-Farinas & Francis, 2005; Niblett & Church, 2015).

Covering

The facility covering dispersion problem is viewed as a binary consideration. The demand node is within the servicing capability, or coverage, of the servicing node, or is otherwise outside the maximum value of coverage offered by the servicing facility (Daskin, 1997). Covering dispersal analysis is useful when a designer would like to ensure the locations demanding service from the covering facility are all within the service radius capabilities, and therefore minimize the maximum distance between a demand node and the closest facility, as illustrated in figure 5 (ReVelle & Hogan, 1989).

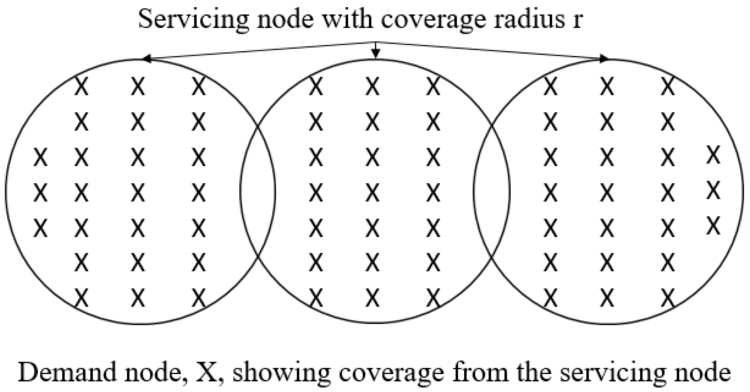

Figure 5: Facility coverage problem that disperses servicing facilities in order for the demand nodes to be covered by only one servicing node (ReVelle & Hogan, 1989)

Many studies have been performed using location methods to mathematically solve the demand node coverage of servicing nodes (Bélanger et al., 2018). Hakimi (1964) shows the first attempt at location coverage methods. The author uses absolute centers to find the minimum distance to the farthest point of a switching center within a communications network. Hakimi shows that finding the absolute center between a set of points is used to conclude that a radius can be generated to cover demand nodes within a service area.

To build upon the work of Hakimi, Toregas et al. (1971) show that a demand area can be covered by only one servicing facility to reduce the facility requirement and associated costs. The study was influential enough to enact legislation and mandate a response time requirement as a part of the Emergency Service Medical Act of 1973 (Daskin, 1982). Toregas identified potential facility locations so that the demand area is covered by only one emergency service vehicle facility and call this approach the location set covering model (LSCM). The study analyzed the servicing facility locations based on a maximum time or distance between the demand node and the servicing node. The result of their findings provided a solution that indicated “the number and location of the facilities that provide the desired service”. In order to determine the servicing node locations for emergency services, the response time from the servicing node to the demand node is constrained to a maximum value. Coverage for the servicing node is denoted by all values within the response time to the demand node. The nature of the problem creates a binary consideration by rejecting all other facilities from the coverage area if a solution already exists for that facility.

Toregas et al. (1971) formulate the LSCM problem analysis by using static variables. A known maximum for vehicle response time to a demand node is used with integer programming to determine a set of nodes within the response time. Ultimately, the total number of service facilities is minimized subject to: (1) only one service facility can support a demand node; and (2) only one facility can be located at a site. (Toregas et al., 1971).

Seeking to expand the work by Toregas at al. (1971) and incorporate aspects of real-life problems, Brotcorne et al. (2003) showed that multiple coverage scenarios can be used to develop a methodology that accounts for coverage being diminished throughout the demand area when a service vehicle is employed to another node on the network. In this case, there may not be adequate coverage as vehicles become too busy. Although this study has advanced the dispersion analysis methodology for coverage of demand nodes by service nodes, the deterministic approach to the problem's solution is not in line with the static nature of this study and will not be considered.

Anti-covering

Another methodology used in dispersion analysis is the anti-covering methodology. Anti-covering can be used to mathematically quantify dispersal at a location by representing "the largest number of facilities that can be simultaneously located while keeping each of them at least a minimum distance, r, from each other" (Niblett & Church, 2015). Designers can use the boundary constraints of a location and anti-covering principles to formulate a discrete quantity of dispersal (Niblett & Church, 2015).

Anti-covering was first developed by Moon and Chaudhry (1984). The authors used a standardized minimum separation distance that allowed for the maximum amount of facilities to be sited in a discrete geographical area. The study used linear programming to solve the problem with an objective solution that (1) ensured maximum site selection criteria for a facility; and (2) all other facility locations are either too close to the boundary constraint, or too close to an existing facility in which both violate the separation constraints (Niblett & Church, 2015).

Figure 6 demonstrates the anti-covering methodology on a plane (Niblett & Church, 2015). It illustrates the anti-covering dispersion method by showing three sites, A, B and C. Site A has two radii associated with it showing the radius r, for the minimum separation between sites, and radius s, for the coverage of site A if it were a demand node. Conversely, site C is too close to the location of both sites A and B (as it is shown to be in the shaded area and not constrained by the minimum separation distance) and cannot be considered a location for a facility. Since site B is located at the minimum separation distance away from site A, it is located in the optimum location for the site layout and facilities should be chosen at both sites A and B. Otherwise, site C can be chosen, without placing facilities and either of sites A or B.

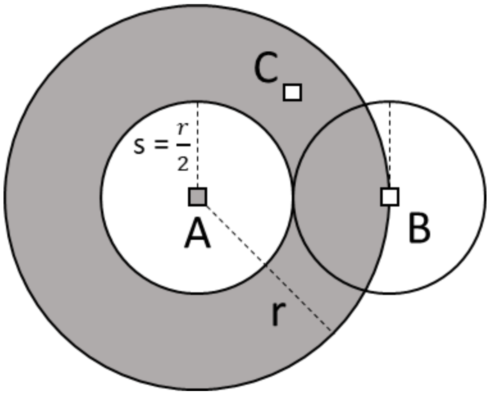

Figure 6: An example site layout for an anti-covering dispersion in which A, B, and C are all sites that have been dispersed on a plane. The radius, r, shows the minimum separation distance between site A and site B. The coverage radius, s, is shown as not overlapping between site A and B. Adapted from Niblett & Church (2015).

Moon and Chaudhry (1984) maximized the possible facility locations by using the following formulae notation to setup the anti-covering analysis problem (Moon & Chaudhry, 1984; Niblett & Church, 2015):

N = a discrete set of potential facility sites;

i,j = indices used to represent specific sites;

d_{ij} = the shortest distance between sites i and j;

r = minimum acceptable separation distance between any two new facilities;

Qi = $\{ j \in N | d_{ij} < r \text{ where } j \neq i \}$, defined for each $i \in N$;

x_j = $\begin{cases} 1, if\ site\ j\ is\ selected\ for\ a\ facility \\ 0, otherwise \end{cases}$; and

M = a large positive number.

$Maximize\ Z = \sum_{j \in N} x_j$ to maximize the possible facility locations.

Others have built upon the first look at anti-covering from Moon and Chaudhry (1984). Grubesic and Murray (2008) used anti-covering analysis to test policy that regulates the maximum amount of sex offender residencies in a specific geographic region. Carrizosa and Tóth (2015) show the anti-covering solution can also be bounded by a continuous region instead of only a discrete boundary. Others have used anti-covering methodologies to study the impact and compute the largest density of merchandizing stores that can be placed in a geographic area without sharing customers between stores (Grubesic et al., 2012).

Niblett and Church (2015) expand on Moon and Chaudhry (1984) anti-covering methodologies by showing how disruptive configurations to a network can change the effectiveness of anti-covering, to which the authors asked the question: “what configurations disrupt [optimal anti-covering] the most” (Niblett & Church, 2015). Niblett and Church (2015) were the first to define the number of facilities on the lower bound of the optimal solutions without violating the separation constraints of anti-covering (Niblett & Church, 2015). This application is attributable to real-world scenarios. As such, anti-covering solution techniques show how maximum separation distances can be maximized; in the sex offender case, the residential options are never exactly where they need to be and therefore the optimum anti-covering solution can never be obtained (Grubesic & Murray, 2008).

Median-Based Methods

Many studies have followed in the studies of Alfred Weber, one of which was Hakimi (1964). While Weber (1909) developed his problem around facility location in the Euclidean plane, Hakimi (1964, 1965) studied the location problem on a network to locate a specified number of facilities. Hakimi’s work is important to designers as it solves the question of how many facilities to site within a specified geographic area. He minimized a distance objective function between the nearest facility and demand nodes (Daskin, 2013; García-Palomares, Gutiérrez, & Latorre, 2012) using the following constraints: (1) a known number of facilities must be provided for siting analysis; (2) all demand points must be known and input into the problem; and (3) a facility has a set capacity for service or storage as defined by the facility (Pirkul et al., 1999).

From Hakimi (1964), the objective for using the p-median approach to facility siting is easily explained by noting that the distance between the demand node and the servicing nodes are reduced as much as possible. For analysis, the problem setup entitles the designer to input a set number of facilities. Hakimi has determined that since the problem is a discrete location problem, the assets and infrastructure are analyzed as nodes of a network. Therefore, within a p-median problem, Hakimi (1965) has shown that as least one optimal solution will be created.

Serra et al. (2004) review four decades of facility location modeling and trends to optimize discrete space for public facility locations. The analysis is emphasized with a description within the dispersal network using p-median modeling (Serra & Marianov, 2004). Pirkul et al. (1999) introduced a decision support tool, “VisOpt,” to show the decision-maker a visual representation of the p-median problem. Furthermore, J. Reese (2006) provided a survey of the p-median problem, focusing on the applied techniques of the p-median problem (Reese, 2006).

Further research in the field of median-based methods of facility location analysis came from Garcia et al. (2011), who introduced an algorithm that allows analysis of large input values of facility sets. This important work allows for faster analysis for the decision-maker on large-scale location determination for a given variable. Other notable research is drawn from the recent work by Kvet & Janáček (2018), who used the p-median to minimize the disutility of emergency services.

Other Dispersion Methods

Many facility analysis problems site the location analysis of desirable facilities such as stores, public services, and worksites. Other forms of dispersion analysis take the form of the maximization objective model, which is a technique used in the siting of noxious facilities (Erkut & Neuman, 1989). In such an analysis, the objective is to locate a given number of facilities to maximize the (population-weighted) distance between population centers and the nearest sites (Church & Garfinkel, 1978; Daskin, 2013; Minieka, 1983). Such a model is useful for designers in the critical analysis of facility siting for noxious facilities *a priori* a hazardous event. The methodology of siting a noxious facility was first developed by Moon and Chaudhry (1984). The authors studied the effects of using the lower distance bounds between facilities to approach the facility siting problem from a minimization perspective (Moon & Chaudhry, 1984).

Accidents involving flammable materials have prompted urgent need for designers to allocate facility footprint separation in such a way as to minimize the consequences of fire and explosion to other facilities (Jung et al., 2011). The 2005 Buncefield fire (Hailwood et al., 2009) and Texas City Refinery explosion (Jung et al., 2011) prompted action by safety organizations such as the Occupational Safety and Health Administration (OSHA) and the Dow Fire and Explosion Index (Dow F&EI) to regulate the facility siting for facilities that hold large inventories, or potential ignition sources (Jung et al., 2011).

Geographic Information System Modeling

Geographic information systems (GIS) have proven to be a significant resource to facility location analysis because of its ability to retrieve, analyze, and store a considerable amount of data from multiple sources (Gbanie et al., 2013; Murray, 2010). As such, the use of GIS has surged and is now at the forefront of spatial analysis capabilities (Murray, 2010). Many developments have occurred in the study of location of facilities within a network using GIS (García-Palomares et al., 2012). The distribution of potential demand node locations has lead researchers to use GIS-based multi-criteria analysis for dispersal problems. Of the different scenario types, bike-sharing program analysis has been studied to evaluate what number of stations should be introduced to a network (García-Palomares et al., 2012). Furthermore, Gbanie et al. (2013) show that the use of GIS technologies is crucial to the quick and efficient spatial analysis. They use the capabilities of GIS to locate the optimal siting location of landfill sites.

Limitations to Dispersal Studies

Little research is available regarding the analysis of dispersion methods within the threat of ballistic and cruise missile attack. However, the static nature of a lingering threat of attack makes the facility planning strategic in nature. Despite the significant contributions of the aforementioned research studies, these dispersion models only tend to maximize a measure of distance a population is from a facility or the distance between facilities (Ratick & White, 1988). They are incapable of: (1) quantifying a dispersal coefficient that provides a safe operating distance for noxious facilities based on threat analysis; (2) investigating the objective function of survivability within a quantifiable threat ring to a dispersal coefficient; and (3) implementing redundancy in terms of mission effectiveness and survivability.

Accordingly, there is an urgent need to apply single facility quantity authorizations dispersal with the added consideration of facility redundancy to efficiently analyze the survivability of dispersal effects on facilities with the effectiveness of facility dispersion. This will help designers in there critical task of identifying the most effective treatment for facility siting.

Quantified Risk

Risk is classically defined as the additive relationship of consequences and uncertainties (Aven, 2012). Therefore, risk management is critical to decision-making and includes a number of variable considerations for analysis. Unfortunately, the variables that are relevant to an area threatened by adversary attack are always changing. As such, the decision-maker must adjust to the environment and use the following simple decision-making framework to aid in the decision-making process: (1) analyze the problem and alternatives; (2) consider the stakeholder values and goals; (3) analyze countermeasures and evaluations; (4) perform constant review and judgement of the considered decision to be made; and (5) make the decision (Aven, 2012).

Quantified Risk Limitations

Current literature is incapable of quantifying the decision-making risk associated with fuel facility locations in a threatened environment. The statistical analysis on dispersion of noxious facilities lacks the ability to predict the consequential damage received by the missile damage radii. Therefore, this study has organized the research around binomial dispersion considerations, where the probability of attack on a fuel facility is analyzed based on the distance from the DMPI and associated damage radius.

III. Methodology

Introduction

The literature review established requirements for the development of improved analysis of the dispersion of facilities and assets based on quantity dispersal and redundancy within a threatened environment. This chapter presents the methodology used to develop the dispersal risk profiles as well as the dispersal analysis. It contains discussion on how the data is collected, and an explanation of the methods and procedures used to generate the research results. This methodology can be used for further analysis of the base resiliency problem definition and clarity for decision-makers.

This thesis defines risk tolerance levels for decision-makers to consider when siting a facility in a hostile environment. It identifies the risk acceptance levels decision-makers must consider when facilities are within the missile threat range of adversaries. In identifying the risk, the decision-maker will generate the most informative and constructive information of the facility siting analysis (Vose, 2008). This research will establish the methodology of identifying risk in areas that are threatened by destructive attack when facilities are still required for mission success. This thesis defines destruction as a direct hit from a ballistic and/or a cruise missile, or the potential of destruction from unintended target damage due to the proximity of the facility to a targeted object.

Data analysis considers four levels of modeling: descriptive, diagnostic, predictive, and prescriptive. The data analysis framework is presented in Figure 7. The first step in the dispersion analysis is created by using a descriptive approach to study the question: “what is currently going on?” It is also used to describe the metrics used to analyze dispersion. In this study, the research is focused on establishing the risk metric for the development of follow-on research within the model (Lunday, 2018).

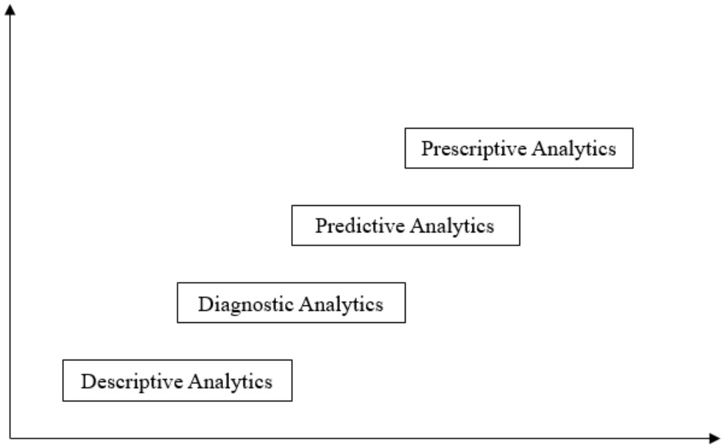

Figure 7: Paradigm model for data analytics (Brian J. Lunday, personal communication, November 20, 2018)

Data

Data has been collected for this study through multiple sources. The geospatial data was collected through the Air Force internal GIS system operated by the Air Force Civil Engineer Center (AFCEC). The Air Force Petroleum Office provided the fuel facilities location data, in conjunction with the Logistics Readiness Squadron from Osan Air Base, South Korea. The weapons data was provided through multiple intelligence reports, mainly the Nuclear Threat Initiative.

The DoD maintains installations worldwide with differing threat environments. In an effort to conduct this research as close to reality as possible and establish an accurate baseline for analysis, field data was collected. The Pacific Air Forces (PACAF) command has many installations that are currently operating under the constant threat of adversary attack. Of these installations, Osan Air Base (AB) is well within the range of a ballistic and cruise missile from adversaries such as Russia, China, and North Korea (Mattis, 2018). Therefore, the dispersion implementation of facilities at Osan AB is used in this research for a case study analysis.

Instrumentation

Microsoft Excel 2013 is used to conduct this research, including the statistical analysis of the risk and efficiency metrics. The software is a part of the Microsoft Suite that is paid for and provided by the Air Force Institute of Technology. Microsoft Excel has many add-on packages that can provide robust capability and is therefore commonly used in research studies. The add-on packages used for this research were Solver, data analysis toolpak, and data analysis toolpak - VBA.

Dispersal Development

From the literature review, it is determined that this research must build upon the work already performed in the field of facility dispersion analytics. Therefore, the dispersal methodology used in this research employs characteristics of covering and anti-covering methodologies. Covering methods are used to assess the risk of a facility in geospatial analysis. It is known that missiles are capable of producing a 900-foot damage diameter on a coordinate plane after detonating (Nuclear Threat Initiative, 2012). Figure 8 shows weapon impact dispersion based on a 900-foot damage diameter. The center point of each damage potential zone serves two purposes: (1) to show the location of the facilities being targeted within the dispersed geospatial environment; and (2) to show the DMPI and associated missile damage potential zone, as represented by the circles. Each damage potential zone is placed on a Euclidean distance of 900 feet from centerline.

Figure 8 shows a perfect shot pattern where all three weapons that are deployed by the adversary hit the intended target perfectly. Figure 8 shows the highest achievable effectiveness of deploying three missiles to destroy a linear distance of up to 2,700 feet. If the missile does not strike at the coordinates of the intended target, covering overlap occurs, the maximum efficiency of target engagement is reduced, and a reduction of effectiveness over a Euclidean distance is seen.

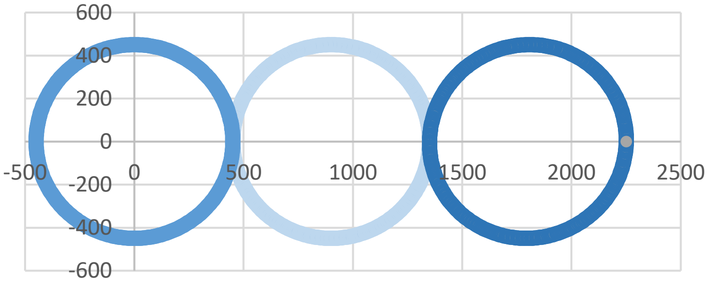

Figure 8: Representation of the highest achievable destruction over a Euclidean distance

Figure 8 also indicates that facility placement of dispersed capabilities must be placed outside the damage potential zone in order to be effective. If facility placement is less than 450 feet and within any arc, dispersal is not achieved, and the facility will be destroyed due to the weapon's damage potential zone. If facility placement is more than 450 feet, minimum dispersion is achieved, requiring more weapons from the adversary to complete resource destruction.

Considerations for Risk Development

By using a geographic coordinate for the missile DMPI and the associated CEP (Nuclear Threat Initiative, 2012), a designer has the ability to disperse facilities according to a risk tolerance in Table 1. Table 1 defines the risk of facility dispersal based on facility coordinates in relation to the coordinates of the initial missile impact location.

Figure 9 is oriented on an x,y axis with a (0,0) coordinate center point, and is therefore the DMPI coordinate. Furthermore, the development of risk zones is used to provide an understanding of how designers can plan for facilities in a threat-constrained environment.

Table 1: Risk Tolerance Levels for Facility Dispersal

Risk Zone	Location of Facility In Relation to Missile Impact Location
Low Risk Zone	Facility has coordinates **OUTSIDE** of the missile impact damage radius and **OUTSIDE** the missile circular error probable
Medium Risk Zone	Facility has coordinates **OUTSIDE** of the missile impact damage radius but **INSIDE** the missile circular error probable
High Risk Zone	Facility has coordinates **INSIDE** the missile impact damage radius

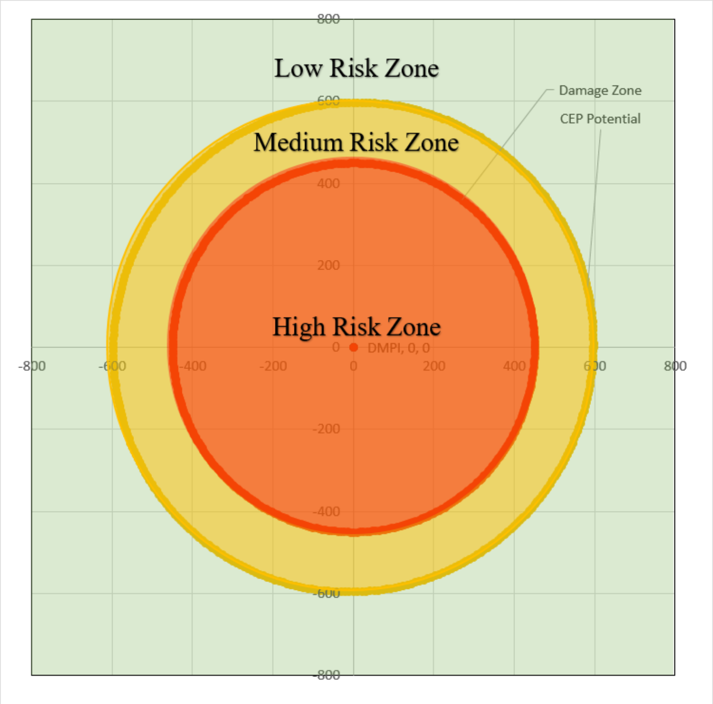

Figure 9: Risk zones showing the damage zone and the CEP of the weapon

The “high risk zone” in Figure 9 shows the radius of 450 feet and was adapted from the original work by Stillion and Orletsky (1999). Analysis completed by the RAND Corporation further quantifies the destructive capabilities of ballistic and cruise missiles and determined the effective lethal radius of a Type 1 cruise missile loaded with 132 bomblets to be 900 ft (Vick, 2015). Therefore, if the weapon impacts a geographic location, the resultant damage zone will be 450 feet in any direction from the impact area.

The “medium risk zone” is defined by the damage radii extension from the DMPI according to the CEP of the weapon. As the weapon impact location is analyzed along a Euclidean distance from the DMPI, the “medium risk zone” is derived as a range covering an area just outside the “high risk zone” to, and including, the maximum distance a facility can be located from the DMPI and still be considered within the lethal capability of the weapon.

The furthest zone from the center point of the impact of the weapon is the “low risk zone”. The “low risk zone” is defined as the best dispersal location for a facility when only one weapon DMPI is being analyzed. In a threat-constrained environment, the criticality of the “low risk zone” is increased when multiple weapons are simultaneously analyzed. The interaction between each weapons DMPI and associated damage potential zone effect the location of “low risk zone.”

Dispersal and Redundancy Methodology

When a designer is interested in the analysis of facility dispersion, risk measures are calculated with the weapon DMPI and CEP, and the Euclidean distance between facilities. In a threat-constrained environment, the adversary remains unpredictable and therefore a multi-level analysis is needed. The analysis is initiated by baselining the effectiveness of a single weapon attacking a geographic area. After developing the weapon's baseline, a more robust analysis that involves a multi-weapon attack scenario can be generated (Stillion & Orletsky, 1999). To determine the best approach to facility dispersion, a multi-weapon attack scenario is used.

To begin the assessment, the designer must first analyze the DMPI and CEP of a single weapon to understand the effects on a geographic location. Additional analysis of facility dispersal using multiple facilities and multiple weapons follows this framework: (1) a single weapon impacting a single target; (2) two or more of the same type of weapon impacting a single target; (3) two or more different types of weapons impacting a single target; (4) the same type of weapon impacting multiple targets; and, (5) two or more different types of weapons impacting multiple targets. Table 2 shows the framework for analysis and includes the weapon characteristics used.

Table 2: Facility Dispersal Analysis Framework Based on Weapon Type. Adapted from (Nuclear Threat Initiative, 2012)

Analysis Level	Weapon Use	Weapon Type
1	Single weapon impacting a single target	DF-15A
2	Two or more of the same type of weapon impacting a single target	DF-15A
3	Two or more different types of weapons impacting a single target	DF-15A DF-11 (M-11)
4	Same type of weapon impacting multiple targets	DF-15A
5	Two or more different types of weapons impacting multiple targets	DF-15A DF-11 (M-11)

Level 1

The analysis of Level 1 is driven by only one weapon and its associated DMPI and CEP. For the purpose of developing a dispersion distance that represents the defense against all adversary weapons, the Level 1 analysis uses the DF-15A short-range ballistic missile (SRBM) with a maximum CEP of 147 feet from the intended target. If using two facilities, and the Euclidean distance is less than 450 feet, the facilities do not have dispersion and fall within the “high risk zone.” If the facilities have a distance between them that is greater than 450 feet, but less than 597 feet, they have some dispersal with a medium risk. This is because the CEP of the DF-15A short range ballistic missile (SRBM) is 147 feet and therefore effects the DMPI location over a range from an impact coordinate of (0,0) to 147 feet away from the intended target. Level 1 analysis is represented in Figure 10.

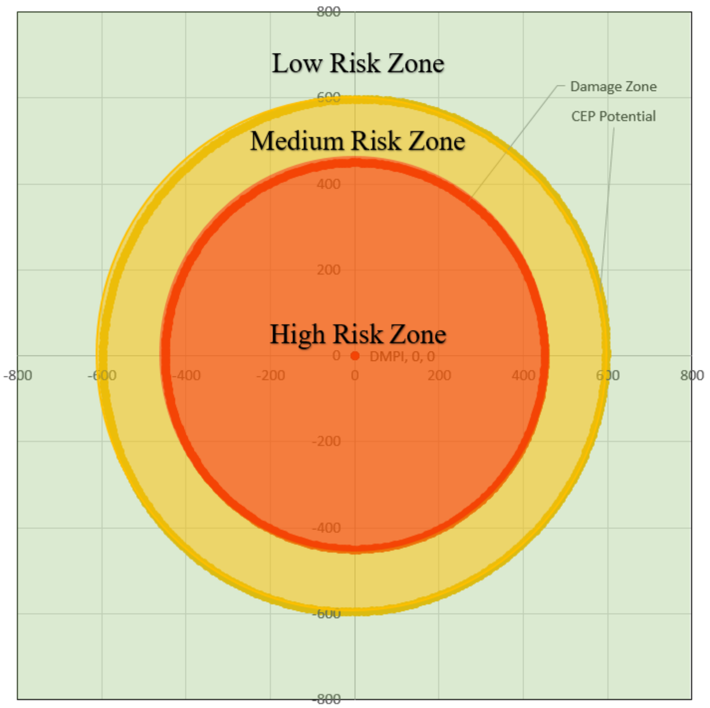

Figure 10: Representation of Level 1 analysis

Not all geographic locations have the luxury of vast spaces for maximum dispersion. Therefore, to determine the probability of risk associated with the placement of a facility within the "medium risk zone," a normal distribution with random sampling is used. A normal distribution with a mean equal to 0 and a standard deviation of 49 feet to account for 99.74% of the total missile impact possibilities. The range of 0-147 feet is used to determine the location of weapon DMPI and a risk range is developed for the probability of destruction, P(D), of a facility within the "medium risk zone." The analysis of Level 1 dispersion only considers the P(D) within the "medium risk zone." It is assumed that the P(D) associated with the "high risk zone" in Level 1 analysis is 100%, and the P(D) associated with the "low risk zone" in Level 1 analysis is 0%.

Level 2

The analysis of Level 2 is driven by more than one iteration of the same weapon type with the same coordinates, and the associated DMPI and CEP. In Level 2 analysis, the designer is concerned with the P(D) of a facility that is dispersed to outside the “high risk zone”. Therefore, a normal distribution with a mean equal to 0 and a standard deviation of 49 to account for 99.74% of the total missile impact possibilities. The Level 2 analysis involves an additive equation that adds one normal distribution with another to simulate a multi-weapon attack using the same weapon characteristics. The range of 0-147 feet is used to determine the location of the impact location of each weapon. As with the Level 1 analysis, Level 2 only considers the P(D) in the “medium risk zone” because of the maximum CEP of the weapon. It is assumed that the P(D) associated with the “high risk zone” in Level 2 analysis is 100%, and the P(D) associated with the “Low Risk Zone” in Level 2 analysis is 0%. Level 2 analysis is represented by Figure 11.

Figure 11: Representation of Level 2 analysis

Level 3

The analysis of Level 3 involves more than one weapon type used for an attack on a target coordinate. In Level 3 analysis, the designer calculates the P(D) of a facility based on dispersion and differing weapon characteristics. This level of analysis assumes that the adversary may attempt to destroy a target without any state of the art geospatial guidance systems, but with a larger CEP value. Level 3 analysis assumes that the adversary will follow the first munition with another missile to guarantee the target destruction by deploying a precision munition on the same target coordinates.

Therefore, a normal distribution is performed in Microsoft Excel to analyze the location of a DF-11 (M-11) DMPI within a large CEP range of 0-

1,969 feet, as well as a follow-on DMPI from a DF-15A salvo with the same targeting coordinates and a much smaller CEP range of 0-147 feet. Figure 12 represents the DMPI and CEP range of both the DF-15A and DF-11 (M-11) weapons. In this analysis the “Low Risk Zone” from earlier iterations is no longer a safe-haven for facility dispersal as the DF-11 (M-11) CEP reduces the precision targeting capabilities and assumes destruction potential up to 2,419 feet from the target coordinates. . The dotted red line shows the potential weapon destruction location based on the CEP of a non-precision weapon. In this extreme case, the weapon impacts the outer boundary area of the circular error probable.

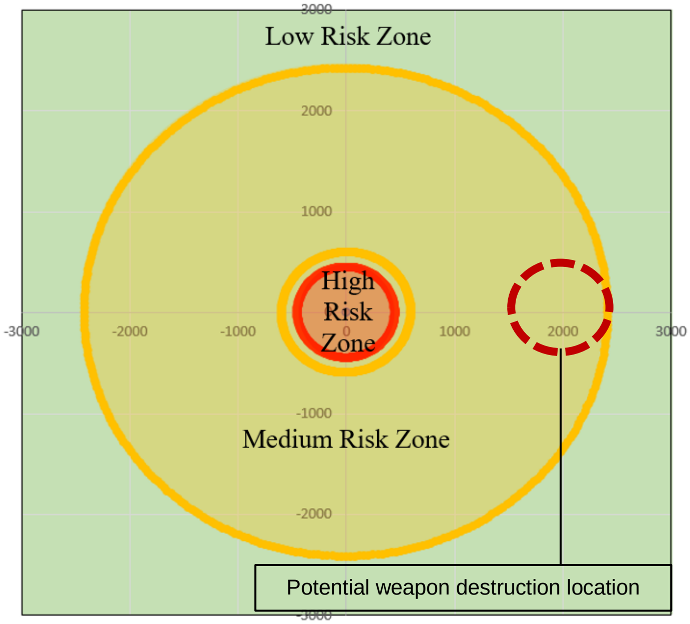

Figure 12: Level 3 analysis - DMPI and CEP range of both the DF-15A and DF-11 (M-11) weapons targeting the same coordinates

Level 4

In Level 4 analysis, the designer calculates the P(D) of a facility based on dispersion and the same weapon characteristics effecting more than one target. This level of analysis assumes that the adversary may attempt to destroy multiple targets with the same technology. Therefore, a normal distribution is performed in Microsoft Excel to analyze the P(D) of three dispersed facilities. The analysis includes the DMPI and CEP of a DF-15A SRBM with a precision range of 0-147 feet from the intended target. Two DF-15A's are used to analyze the P(D) of facilities dispersed within a geographically defined area.

The DF-15A is first analyzed in the same way as the Level 1 analysis, where the facility location is determined based on the weapon's CEP. Within this analysis the medium and low risk zones are considered for dispersed capabilities only, as the P(D) in the "high risk zone" is assumed to be 100%. Thereafter, the Level 4 analysis then examines a nearby facility targeted by the same weapon capabilities. Level 4 is intended to analyze one more facility then weapons used by the adversary. This consideration can be used to develop redundancy of a resource, or dispersion.

In a two-weapon analysis of Level 4 dispersal, the designer disperses two facilities greater than 900 feet apart for the third facility P(D) development in the "medium risk zone." The "medium risk zone" with a Euclidean distance of facilities is developed using the CEP of a DF-15A SRBM with a precision range of 0-147 feet within a target coordinates. Level 4 analysis differs from the analysis of Level 1 by extending the range of the potential "medium risk zone." In a condensed analysis, the CEP range from two DF-15As shows the "medium risk zone" is greater than 450 feet up to and including 597 feet in any direction from the DMPI of either weapon. Figure 13 shows a representation of this Level 4 dispersion.

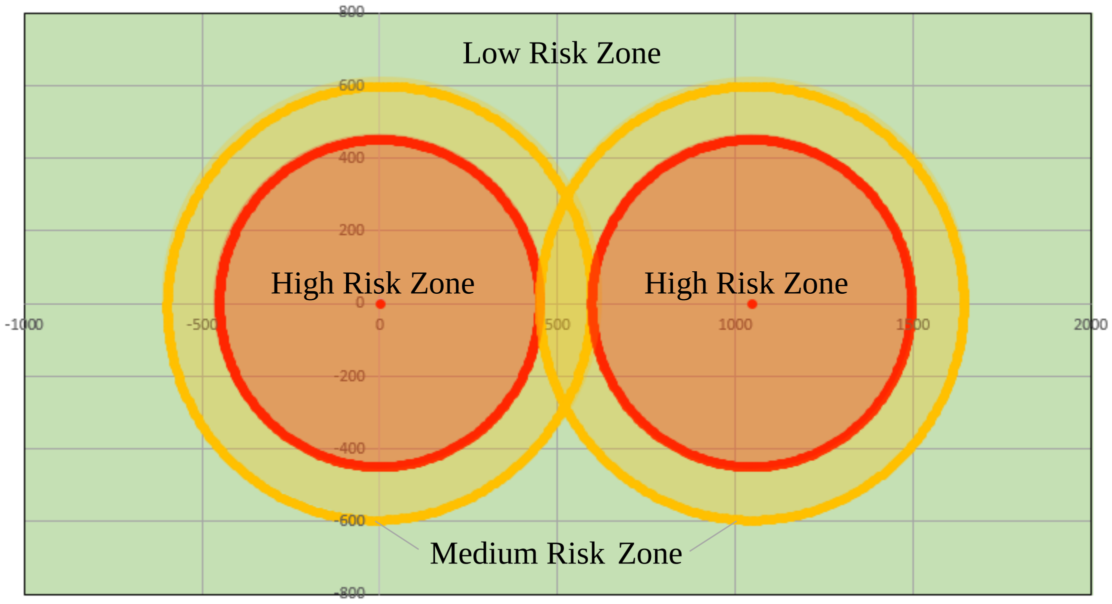

Figure 13: Level 4 analysis – The minimum DMPI and CEP range of two DF-15A weapons targeting multiple target coordinates

By using covering methodologies to show a Euclidean distance serviced by only one weapon damage potential zone, the destruction area is maximized. Therefore, Figure 14 shows that the "medium risk zone" can be extended in the Level 4 analysis to include any point within a range of greater than 450 feet up to and including 744 feet in any direction from the weapon's DMPI. This representation is used in the Level 4 analysis of this study as the baseline for the "medium risk zone."

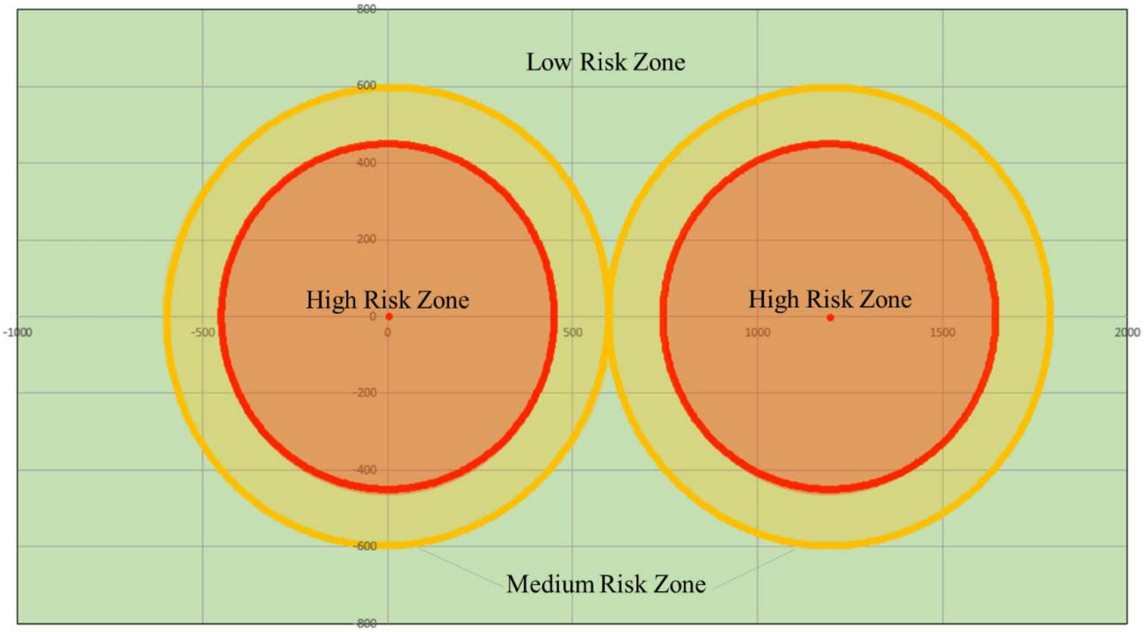

Figure 14: Level 4 analysis – The maximum DMPI and CEP range of two DF-15A weapons targeting multiple target coordinates

The analysis of Level 4 dispersion only considers the P(D) within the "medium risk zone." It is assumed that the P(D) associated with the "high risk zone" in Level 4 analysis is 100%, and the P(D) associated with the "low risk zone" in Level 4 analysis is 0%. Therefore, the additional facility that is located outside the damage potential zone of both weapons is located either in the "medium risk zone" or the "low risk zone" within the geographical area.

Level 5

In Level 5 analysis, the designer calculates the P(D) of a facility based on dispersion and the characteristic of more than one weapon effecting more than one target. This analysis assumes that the adversary will attempt to destroy targets within a geographical area with both precision and non-precision weapons. The analysis includes the DMPI and CEP of: (1) a DF-15A SRBM with a precision range of 0-147 feet from the intended target; and (2) a DF-11 (M-11) SRBM with a non-precision range of 0-1,969 feet from the intended target. One DF-15A and one DF-11 (M-11) are used to analyze the P(D) of facilities dispersed within a geographically defined area. Because of the uncertainty in the target and weapon selection, the risk profile is developed by incorporating a two-sided analysis by striking each side of the bounded area with each weapon.

The DF-15A is first analyzed in the same way as the Level 1 analysis, where the facility location is determined using the CEP of the weapon. Within this analysis the medium and low risk zones are considered for dispersed capabilities only, as the P(D) in the "high risk zone" is assumed to be 100%. It is intended to analyze one more facility then weapons used by the adversary. This consideration can be used to develop redundancy of a resource, or dispersion.

In the two-weapon analysis of Level 5 dispersal, the designer disperses two facilities greater than 2,869 feet apart for the third facility P(D) development in the "medium risk zone." The "medium risk zone" is developed using the DMPI and CEP of both the DF-15A SRBM and the DF-11 (M-11). The CEP range from one DF-15A overlaps the CEP range of the DF-11 (M-11) and shows the "medium risk zone" is greater than 450 feet up to and including 2,419 feet in any direction from the DMPI of either weapon. Figure 15 shows a representation of this Level 5 Phase I dispersion.

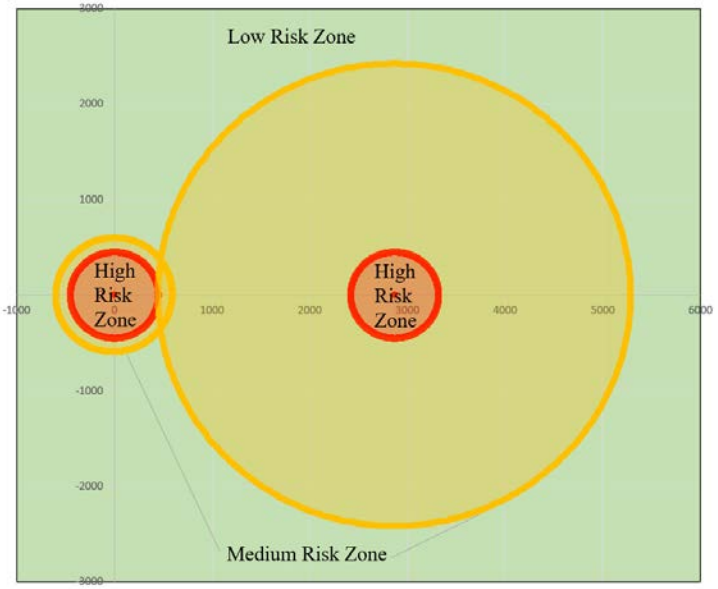

Figure 15: Level 5 Phase I Analysis - DMPI and CEP range of both the DF-15A and DF-11 (M-11) weapons targeting multiple target coordinates in an anti-covering analysis

By using anti-covering methodologies to show a Euclidean distance serviced by only one weapon damage potential zone, the destruction area is maximized. Therefore, Figure 16 shows that the “medium risk zone” can be extended in the Level 5 Phase II analysis to include any point within a range of greater than 450 feet up to and including 3,016 feet in any direction from the weapon’s DMPI.

The analysis of Level 5 dispersion only considers the P(D) within the “medium risk zone.” It is assumed that the P(D) associated with the “high risk zone” in Level 5 analysis is 100%, and the P(D) associated with the “low risk zone” in Level 5 analysis is 0%. Therefore, the additional facility that is located outside the damage potential zone of both weapons is located either in the “medium risk zone” or the “low risk zone” within the geographical area.

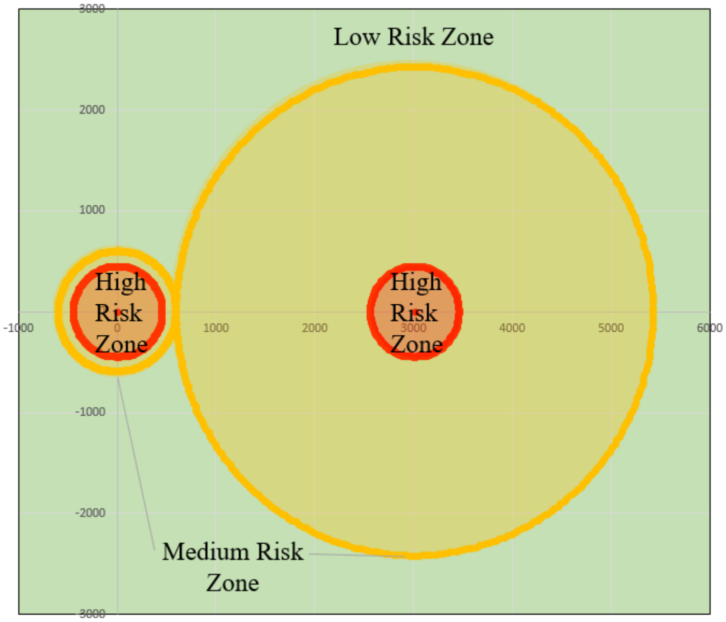

Figure 16: Level 5 Phase II Analysis - DMPI and CEP range of both the DF-15A and DF-11 (M-11) weapons targeting multiple target coordinates in a covering analysis

Combined Analysis

The combined analysis of this research can follow multiple optimization methods. In order to conclude with the best representation of risk for a decision-maker in a threat constrained environment, the highest, and lowest values are used. A midpoint risk value is also achieved. The high risk represents the most risk available to the decision-maker and the most dangerous facility dispersion distance. The low risk represents the least risk available to the decision-maker and is the least dangerous facility dispersion distance. The midpoint value demonstrates the midpoint risk value available to the decision-maker.

Case Study

Osan AB in the Republic of South Korea is oriented in a region roused with continuous threats from adversaries (Stillion & Orletsky, 1999). Therefore, Osan AB is used as the geographic area for a case study to illustrate the model capabilities and demonstrate its ability for risk analysis of dispersion. In particular, four locations on the AB are considered for the case study analysis. Each area considered is a parking ramp used for mission aircraft ranging in size of usable area. The Euclidean distance of each ramp is: (1) 1,250 feet; (2) 700 feet; (3) 700 feet; and (4) 1,300 feet. Each ramp is analyzed for dispersal operations on the ramp, as well as analyzed for the combined total space between ramps. The total distance used in the analysis was 7,000 which is the total distance between and including parking ramp 1 and parking ramp 4. Figure 17 illustrates the analyzed space.

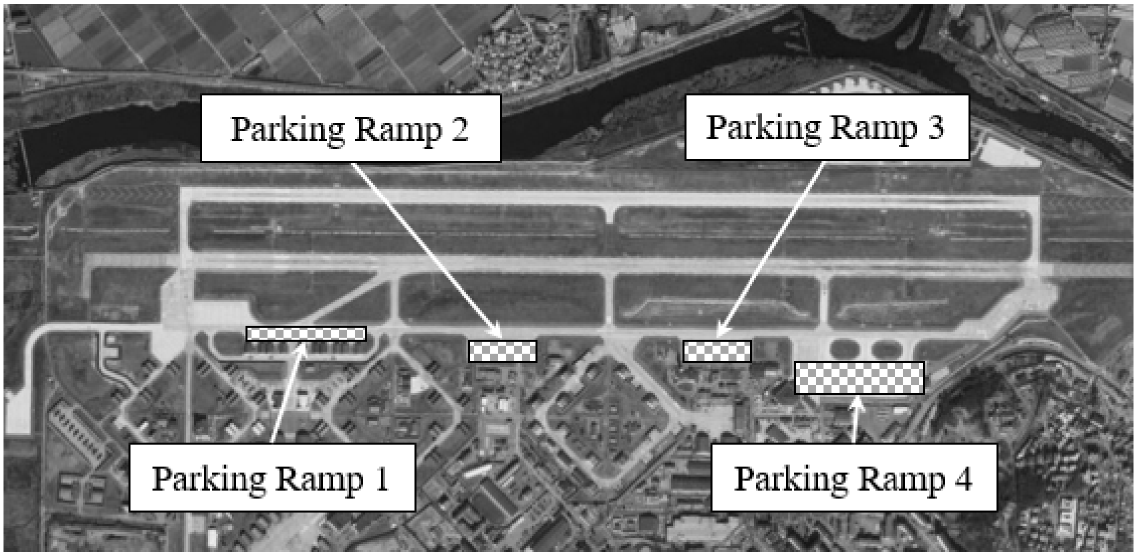

Figure 17: Geographic area representation of the case study

Once the linear distance is determined for the application of the geographical area, the quantitative measures of risk tolerances can be applied. Along with applying the length and capacity of the storage system, the total quantity of fuel able to be dispersed with the risk tolerance level is obtained. This process can be applied to multiple iterations of analysis, as long as the dispersion distance remains a constraint.

IV. Results and Analysis

Introduction

This chapter presents the assessment of risk associated with facility dispersion within a threatened environment. The risk metric was developed using a five-stage analysis for multiple blast types and weapons: (1) a single weapon impacting a single target; (2) two or more of the same type of weapon impacting a single target; (3) two different types of weapons impacting a single target; (4) the same type of weapon impacting multiple targets; (5) two different types of weapons impacting multiple targets.

The contribution of this research is to define the risk metric used to disperse facilities within the threatened environment. By identifying the risk metric associated with the dispersal of facilities, the designer and decision-maker can make the most appropriate dispersion decisions. The analysis of facility dispersal based on weapon type is described with further detail in Chapter 3.

Level 1 Analysis

Level 1 analysis is driven by a single DF-15A impacting a single target to baseline the analysis. The distribution represents the CEP of a DF-15A missile with a range of target impact locations from coordinates (0,0) to (147,0) over a Euclidean distance. The output shows a normal distribution, centered on zero, with three standard deviations allowing for analysis of 99.74% of the data. The Microsoft Excel probability distribution function gives the output probability percentage for each input value spanning away from (0,0) with a cumulative total adding to 0.5. This shows a 50% probability distribution of a weapon impacting a distance between 0 and 147 feet – the right side of the normal distribution. The analysis uses a standard deviation of 49 and a mean of 0. Level 1 is represented by Figure 18.

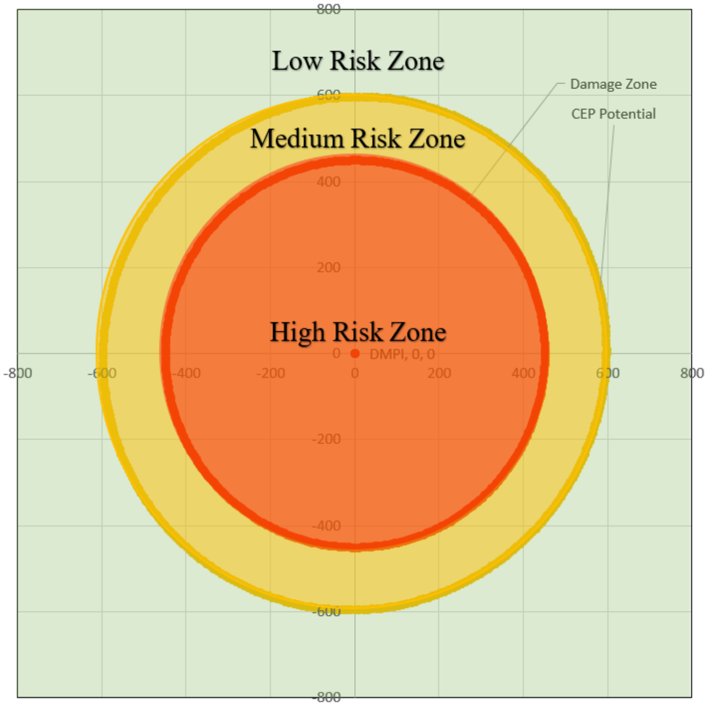

Figure 18: Representation of Level 1 analysis

The output of the Level 1 analysis shown in Figure 19 categorizes the level of risk into three risk profiles: (1) the high risk of siting a facility while only considering a missile will impact the target directly, or within 49 feet away, is equal to a 34.79% probability over any given number of missile impact iterations; (2) the medium risk of siting a facility while considering a missile will impact the target directly, or within a range of 49-98 feet from the target coordinates, is equal to 13.89% probability over any given number of missile impact iterations; and (3) the low risk of siting a facility while considering a missile will impact the target directly, or within a range of 98-147 feet from the target coordinates, is equal to 2.09% probability over any given number of missile impact iterations.

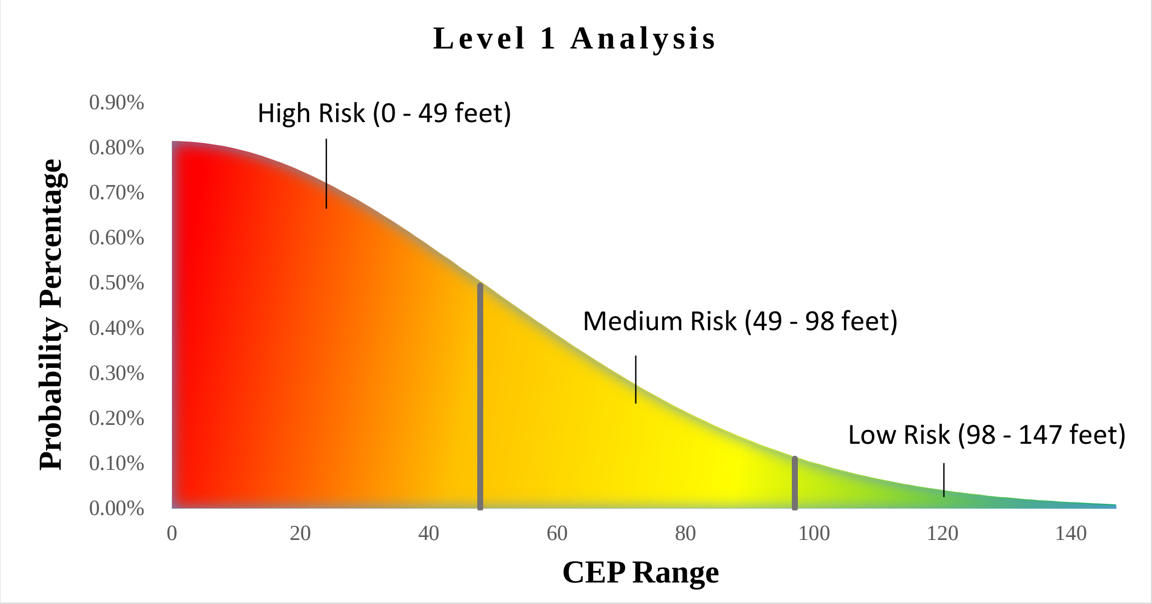

Figure 19: Probability distribution of a DF-15A SRBM over the CEP range

The objective of the Level 1 analysis is to determine the best location for a facility. By accounting for to a precision missile impact location within the 147-foot weapon error probable range, and a 450-foot damage potential radii, the best location to site a facility in the Level 1 analysis is 597 feet away from any facility, in any direction. The P(D) of a facility decreases as it is sited further away from the impact and damage potential zone. Level 1 uses covering methodologies for noxious facilities to keep the siting of a facility outside the coverage range of a weapon destruction zone.

Level 2 Analysis

Level 2 analysis is driven by covering dispersion methodologies. The servicing node P(D), used in this analysis as the precision weapon impact location, is developed by overlaying the risk profile of two precision weapons targeting the same facility. The curve representing the risk profile of two precision weapons targeting the same coordinates is shown in Figure 20. The analysis uses a standard deviation of 49 and a mean of 0. The resulting risk is categorized into three risk profiles: (1) the high risk of siting a facility while only considering a missile will impact the target directly, or within 49 feet away, is equal to a 34.79% probability over any given number of missile impact iterations; (2) the medium risk of siting a facility while considering a missile will impact the target directly, or within a range of 49-98 feet from the target coordinates, is equal to 13.89% probability over any given number of missile impact iterations; and (3) the low risk of siting a facility while considering a missile will impact the target directly, or within a range of 98-147 feet from the target coordinates, is equal to 2.09% probability over any given number of missile impact iterations.

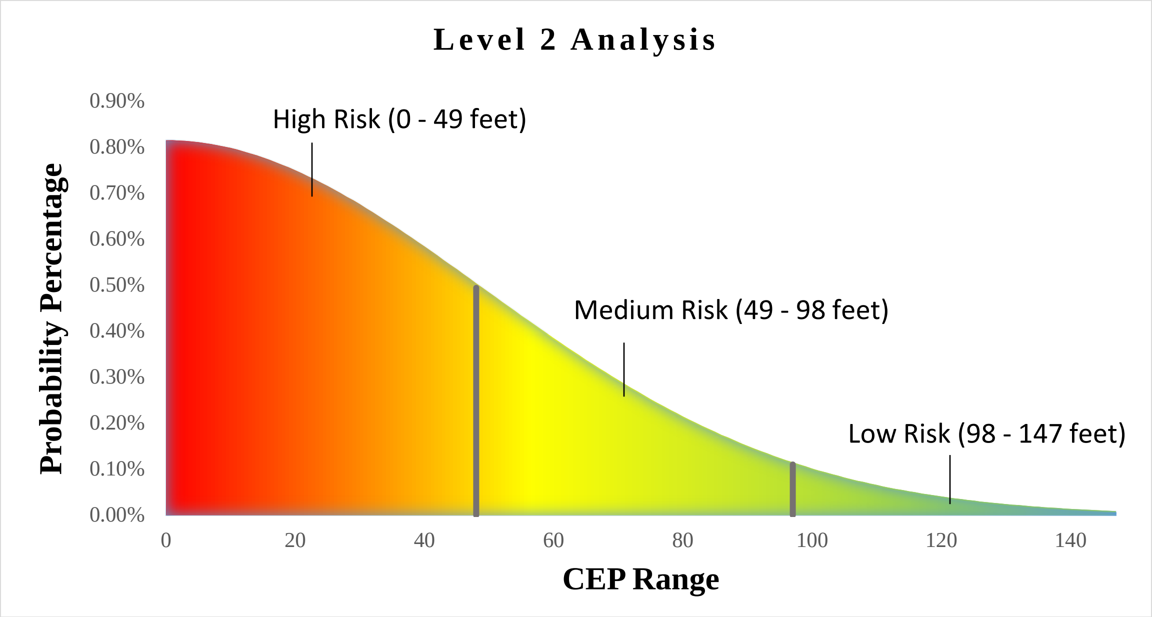

Figure 20: Probability distribution of a DF-15A SRBM over the CEP range

The output analysis of Level 2 is identical to Level 1. This is because the characteristics of the weapons used is the same. Level 1 uses only one precision weapon, while Level 2 uses more than one. The outcome of the analysis remains the same because the CEP doesn’t change. This analysis replicates the adversary employing more than one weapon to cover the intended destruction zone. The redundancy of the weapon usage does not affect the dispersion of the facilities relative to the baseline.

Level 2 analysis determines the best location for a facility accounts for a 450-foot blast radius and a 147-foot weapon error, or 597 feet away from any facility, in any direction. The P(D) of a facility decreases as it is sited further away from the impact and damage potential zone. Level 2 uses covering methodologies for noxious facilities to keep the siting of a facility outside the coverage range of a weapon destruction zone.

Level 3 Analysis

Level 3 analysis studies two or more different types of weapon characteristics impacting a single target. One DF-15A missile and one DF-11 (M-11) missile are used to impact a single target and represent a precision missile, and a non-precision missile, respectively. The intent of the study in Level 3 analysis is to determine the risk associated with both missile types targeting the same coordinates. In this environment, the use of precision weapons has less of an effect on the facility dispersal. Figure 21 is the CEP of the precision missile striking a target at a (0,0) coordinates and remains the same as the first two analyses.

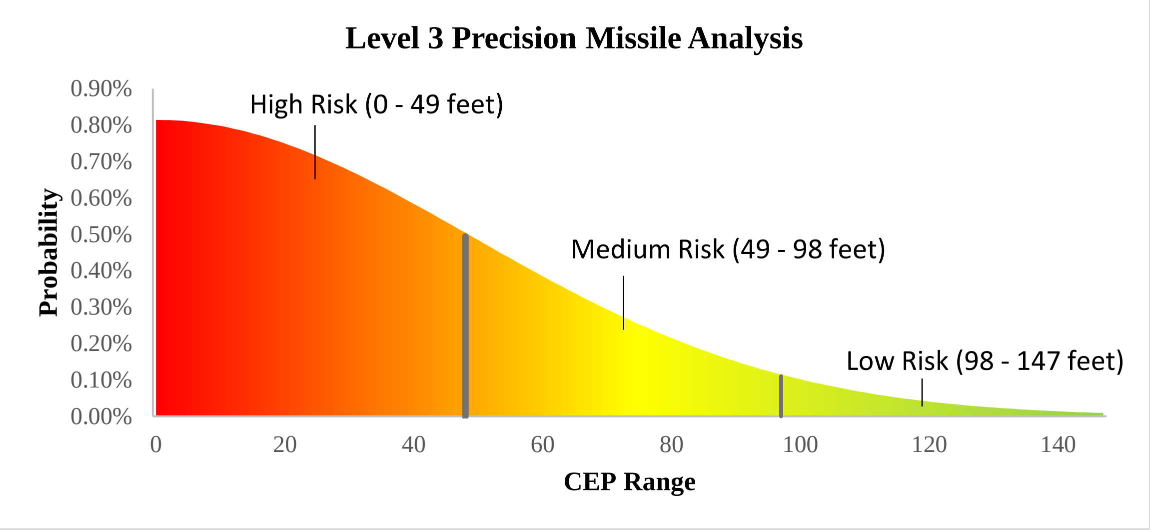

Figure 21: Probability distribution of a DF-15A over the CEP range

Following the precision missile analysis, the risk profile of the non-precision missile was developed and is shown in Figure 22. The analysis was performed independent to the characteristics of each missile, and therefore only represents the probability of destruction associated with the non-precision missile targeting the (0,0) coordinate. Furthermore, it shows that the CEP of the non-precision missile extends the risk profile distance by over thirteen times the distance of the precision missile.

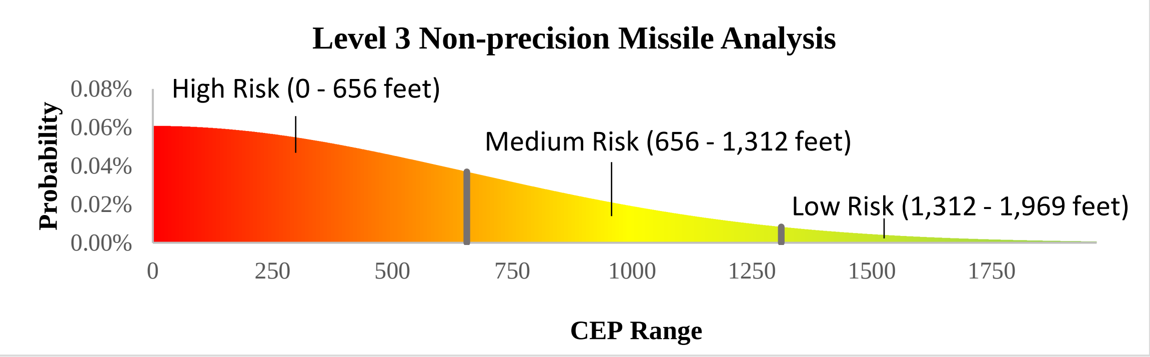

Figure 22: Probability distribution of a DF-11 (M-11) SRBM over the CEP range

The total risk profile distance was developed by combining the characteristics of both weapon capabilities. The output of the combined analysis is shown in Figure 23. When the risk profiles from both weapons are combined, the high risk zone increases 50% over the baseline study of only one precision weapon impacting the target coordinates. Because of the high error potential of the non-precision weapon, the analysis distance is extended to include all risk from the precision weapon within the first standard deviation. Therefore, siting a facility within the high risk zone equates to 84.45% probability that the facility will be destroyed over any given number of impact iterations.

The medium risk associated with the combined risk profiles of both weapons is shown in Figure 23 and has a CEP range of 656 to 1,312 feet from the DMPI. When siting a facility in the medium risk zone, the risk decreases to only 13.62% facility destruction probability. Furthermore, the best scenario for siting a facility within the Level 3 design of experiments (DOE) is within the low risk CEP range of 1,312 to 1,969 feet from the targeted coordinates. Within this range, the probability of destruction of a facility decreases to only 2.14% over any given number of missile impact iterations.

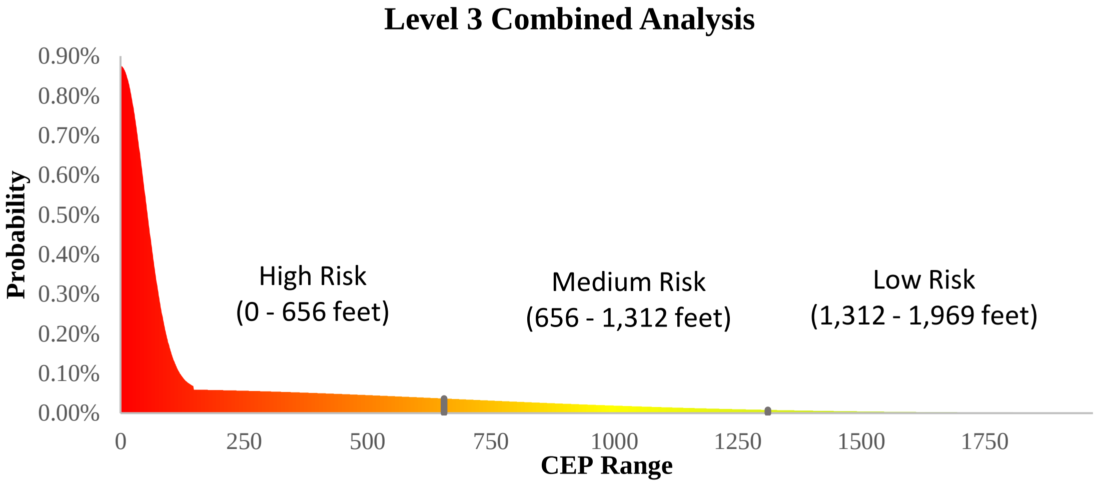

Figure 23: Probability distribution of a DF-15A and DF-11 (M-11) SRBM over the CEP range

The safest dispersion distance as determined by the Level 3 analysis accounts for a 450-foot blast radius and a 1,969-foot weapon error, or 2,419 feet away from any facility, in any direction. The P(D) of a facility decreases as it is sited further away from the DMPI and associated damage potential zone. Level 3 employs covering methodologies for noxious facilities to keep the siting of a facility outside the coverage range of a weapon destruction zone.

Level 4 Analysis

Level 4 analysis quantifies risk by focusing on targeting two separate facilities. The first facility remains the same as the baseline and is analyzed similarly with the same weapon characteristics input and the same output risk profile. The analysis then studies two phases of weapon impact scenarios as the DMPI is adjusted between anti-covering and covering methodologies. The results from both phases are combined to produce the overall risk profile that allows designers to quantify the risk associated with dispersion of multiple facilities in defense from precision weapons.

The second phase is analyzed with no overlap in the “medium risk zone,” representing full coverage of a facility dispersion model. The area of interest in this study is the decrease in facility destruction probability as covering methodologies transfer from anti-covering and overlapped CEP potential, to a covering methodology that maximizes the destruction capabilities of each weapon targeting each facility.

Level 4 Phase I

The first phase of analysis allows for potential overlap of the “medium risk zones” of both weapons by using the anti-covering methodologies of Moon and Chaudhry (1984).. Phase I develops the CEP range of two facilities targeted by the same weapon characteristics. Because of the anti-covering methodology used in this analysis, the facility dispersion is limited to the precision weapon CEP range and is represented by the medium risk zone shown in Figure 24.

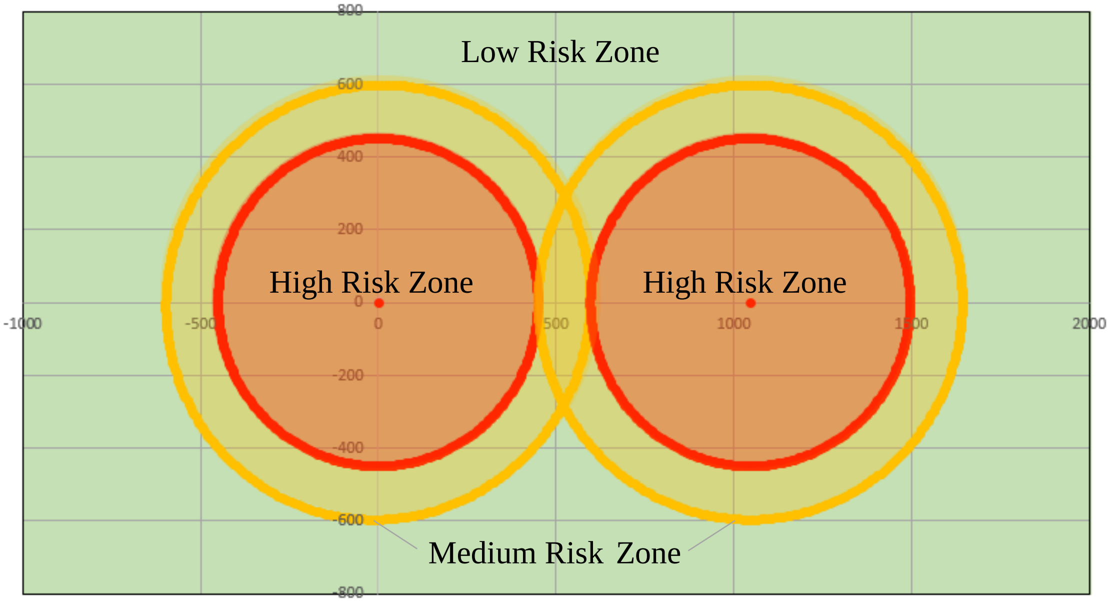

Figure 24: Level 4 Phase I Analysis – The minimum DMPI and CEP range of two DF-15A weapons targeting multiple target coordinates

The output shows the missile impact probability over a range of 147 feet along the x-axis, with a cumulative total adding to 1.0. Because the curves are inverse to each other and intersect at the midpoint of the overall 147-foot distance, the probability distributions of each curve add together to produce the cumulative total at each point. Therefore, the dispersion analysis gives designers the capability to quantify risk at locations that are geographically constrained.

Within the medium risk zone of Figure 24, the risk for facility destruction is developed into three separate categories: (1) the high risk of siting a facility while only considering both missiles will impact each target directly, or within 49 feet away, is equal to a 36.98% probability over any given number of missile impact iterations; (2) the medium risk in siting a facility while considering both missiles will impact within a range of 49-98 feet from the target coordinates, is equal to 27.79% probability over any given number of missile impact iterations; and (3) the low risk in siting a facility while considering both missiles will impact within a range of 98-147 feet from the target coordinates, is equal to 36.98% probability over any given number of missile impact iterations. The output of Phase I is represented by Figure 25.

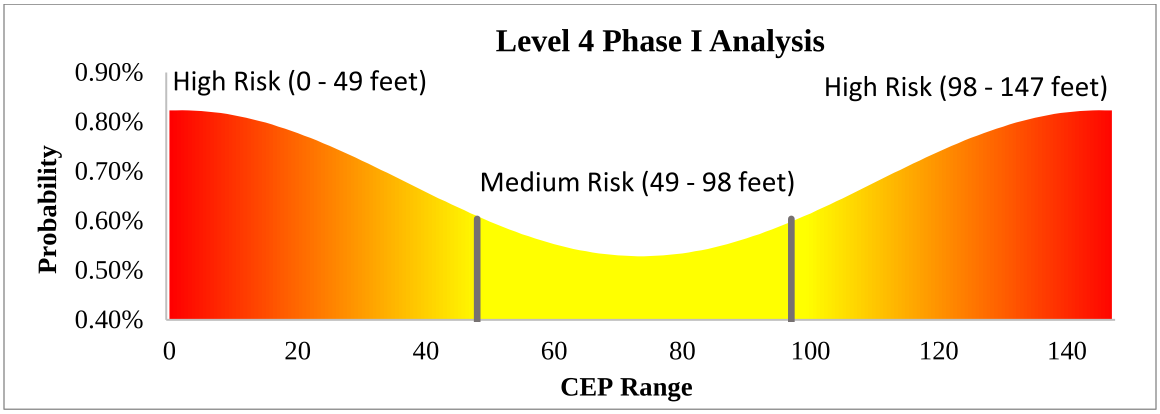

Figure 25: Level 4 Phase I Analysis - Probability distribution of two DF-15A SRBMs over the CEP range

The best location of a facility in the Phase I analysis accounts for a 450-foot blast radius and a 73.5-foot weapon error, or 523.5 feet away from any facility, in any direction. The risk tolerance level for this location is quantified as medium based on the standard deviations within the analysis. This is because of the risk profiles intersect with each other, which increases the P(D) of the facility as the distance between facilities is maximized. Phase II will examine the maximum covering of the missile destruction radii, resulting in a transition from anti-covering aspects from Phase I to covering methodologies in Level 4 Phase II analysis.

Level 4 Phase II

In the Phase II analysis, the risk profile was developed for a maximum coverage with precision weapons scenario. The facility location on one side of the analysis remains the same as the baseline. The DOE of Phase II changes by moving the second DMPI coordinates to a location that prohibits the additive CEP and destruction radii of each weapon from intersecting. Phase II analysis develops a risk profile distribution accounting for maximum coverage of the weapon impact zone, including any potential to miss the target and impact at a location within the CEP range of each weapon. Figure 26 displays the distance for siting a facility within the “medium risk zone” along the x-axis.

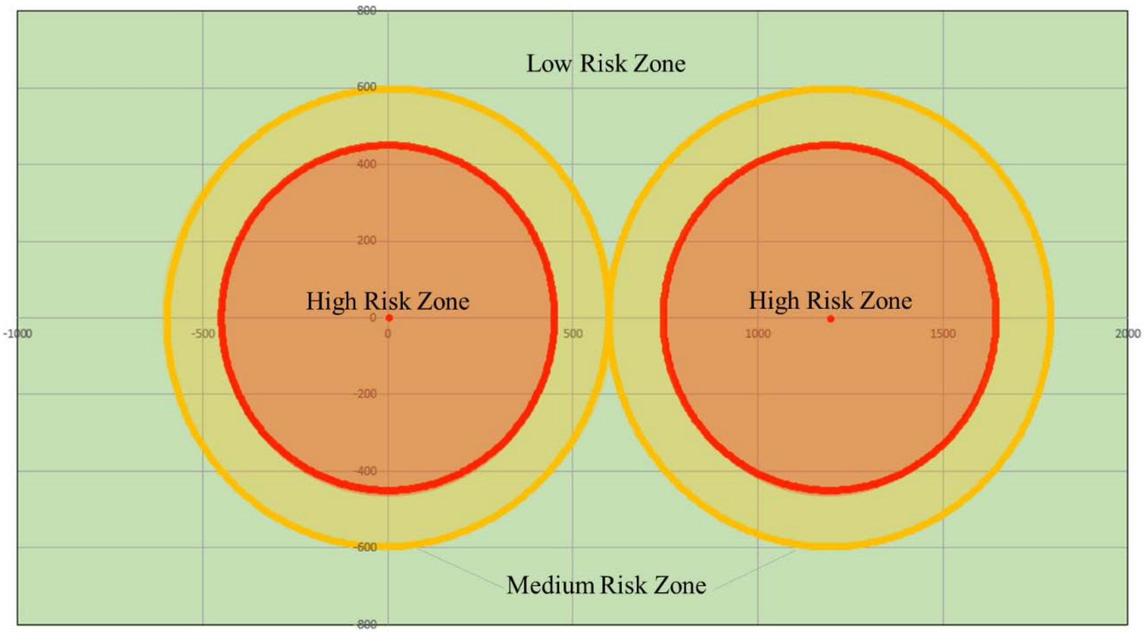

Figure 26: Level 4 Phase II Analysis – The maximum DMPI and CEP range of two DF-15A weapons targeting multiple target coordinates

The output of Phase II shows the missile impact probability over a range of 147 feet along the x-axis. The analysis is categorized by level of risk into three standard deviations over the maximum destruction distance: (1) the high risk of siting a facility while only considering both missiles will impact each target directly, or within 49 feet away, is equal to a 34.79% probability over any given number of missile impact iterations; (2) the medium risk of siting a facility while considering both missiles will impact within a range of 49-98 feet from the target coordinates, is equal to 13.40% probability over any given number of missile impact iterations; and (3) the low risk of siting a facility while considering both missiles will impact within a range of 98-147 feet from the target coordinates, is equal to 2.09% probability over any given number of missile impact iterations. Figure 27 represents the risk profile of facility dispersion of three facilities.

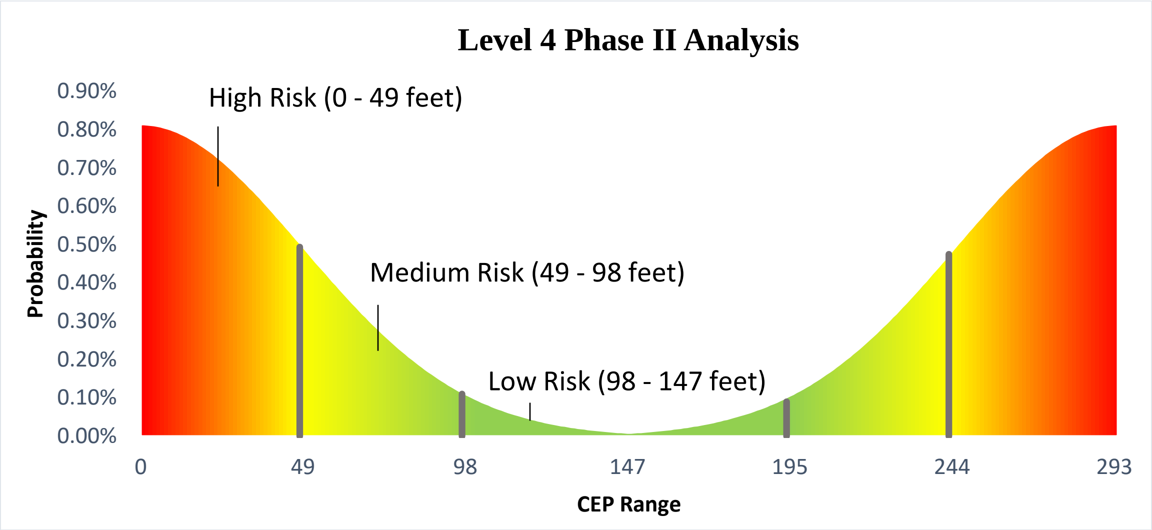

Figure 27: Level 4 Phase II Analysis - Probability distribution of two DF-15A SRBMs over the CEP range

The Phase II analysis shows that the best facility dispersion accounts for a 450-foot blast radius and a 147-foot weapon error potential, or 597 feet away from any facility, in any direction. This is because there is no intersection between the weapon CEPs resulting in the safest conditions at the lowest probability. The P(D) of a facility decreases as it is sited further away from the DMPI and associated damage potential zone.

Level 4 Combined Analysis

When considering the combined risk profile of the Level 4 Phase I and II analysis, the risk factors change according to the distance from the intended target. Level 4 Phase I shows that the best location to disperse a facility is 523.5 feet away from any facility in any direction. As the methodology transforms from an anti-covering based model, to a covering based model, the risk reduces. Level 4 Phase II shows that the best location to disperse a facility is 597 feet away from any facility in any direction. Therefore, the combined analysis results in the most accurate risk profile and is categorized into three results: (1) the high risk is categorized as dispersing a facility 450-523.5 feet away from any other facility in any direction; (2) the medium risk is categorized as dispersing a facility 523.5-560 feet away from any other facility in any direction; and (3) the low risk is categorized as dispersing a facility 560-597 feet away from any other facility in any direction. The risk profiles are for the combined Level 4 analysis is shown in Table 3. Ultimately, as the CEP radii move away from each other on the x-axis, the amount of risk is reduced.

Table 3: Level 4 Combined Analysis - Risk profile for facility dispersion against DF-15A SRBM impact locations

Risk Level	Dispersion Distance Between Facilities (ft)	Probability of Destruction
High Risk	450-523.5	50.0%
Low Risk	523.5-560	6.31%
Medium Risk	560-597	1.08%

Level 5 Analysis

The Level 5 analysis is driven by more than one type of weapon effecting more than one target within a geographically defined area. The analysis involves characteristics of both a precision missile (DF-15A) and a non-precision missile [DF-11 (M-11)]. It has two phases of analysis over a distance of 2,116 feet, as discussed in Chapter 3. The first phase of analysis allows for potential overlap of the “medium risk zones” of both weapons by using the anti-covering methodologies of Moon and Chaudhry (1984). The second phase is analyzed with no overlap in the "medium risk zone," representing full coverage of a facility dispersion model.

Level 5 Phase I

The first analysis produces the output shown in Figure 28, representing the CEP and associated damage potential of a DF-15A and DF-11 (M-11) missile with two range distributions for target impact locations: (1) coordinates (0,0) to (147,0); and (2) coordinates (900,0) to (2869,0), respectively. Figure 28 represents the orientation for siting a facility within the "medium risk zone" along the x-axis.

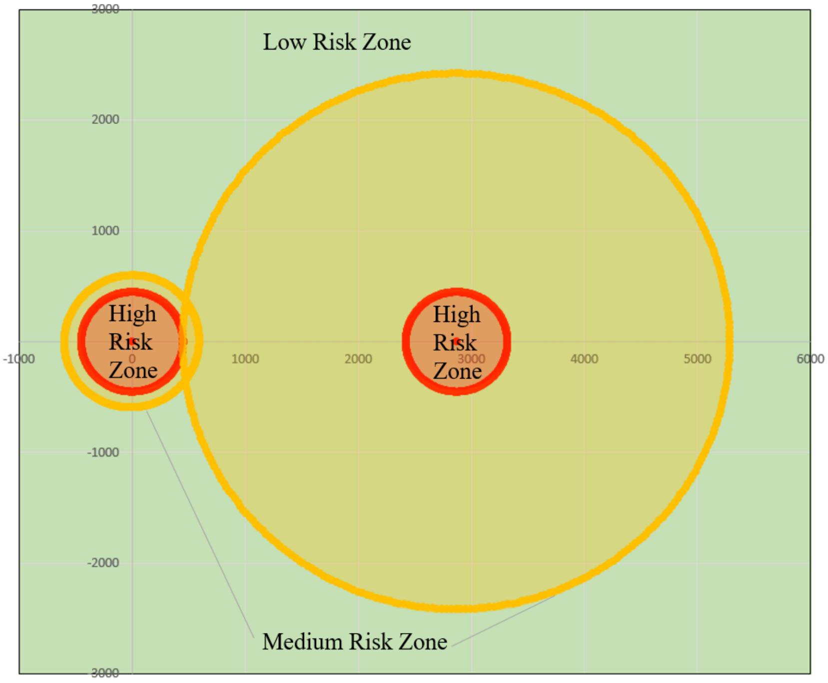

Figure 28: Level 5 Phase I Analysis - DMPI and CEP range of both the DF-15A and DF-11 (M-11) weapons targeting multiple target coordinates

The output shown in Figure 29 represents the missile impact probability over a range of 1,822 feet along the x-axis, with three standard deviations. Figure 29 also represents the risk of not knowing the adversary shot doctrine for missile characteristics. Because the missile characteristics can be applied to both sides of the analysis, the risk profile curves are inverse to each other and intersect. This shows that the probability distributions of each curve must be combined to produce the cumulative total of risk at each point.

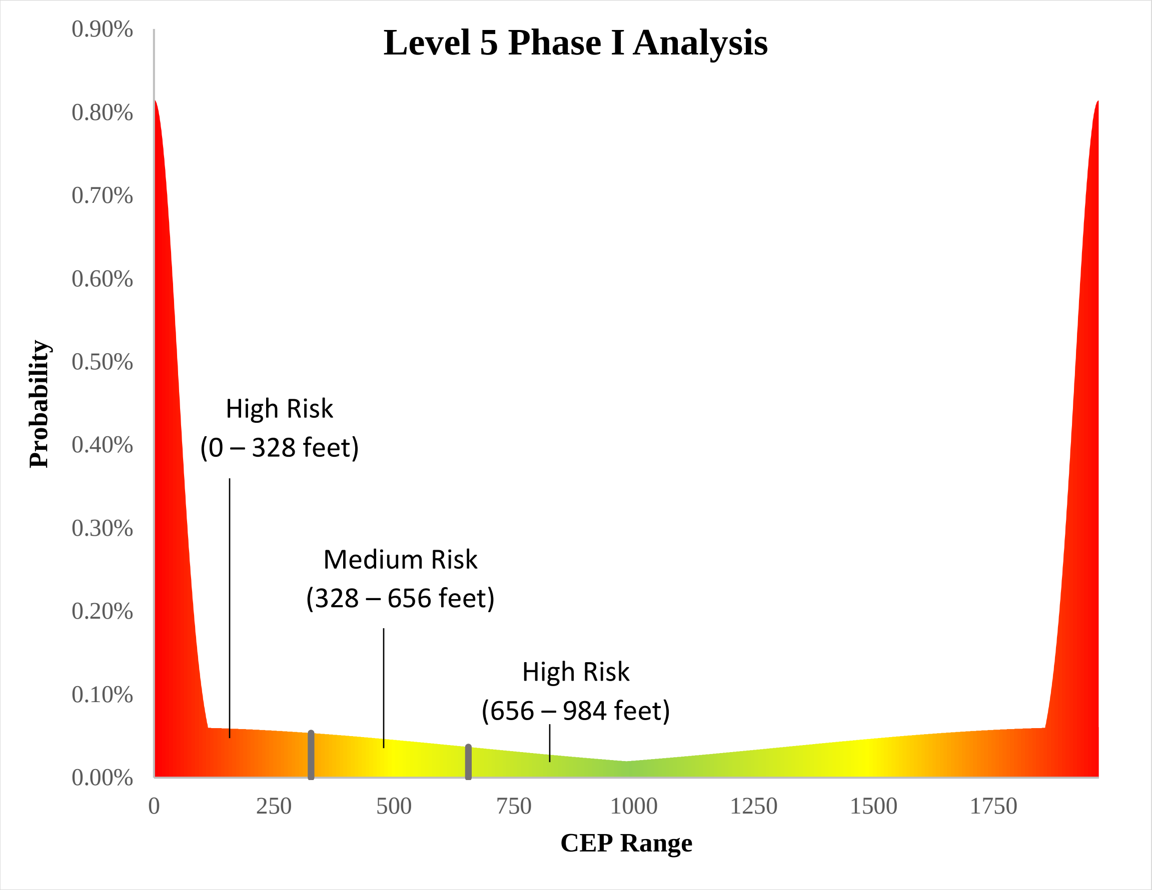

Figure 29: Level 5 Phase I Analysis - Probability distribution of DF-15A and DF-11 (M-11) SRBMs over the CEP range

In the Phase I analysis configuration, the risk profile is categorized into three levels for decision-maker tolerance considerations and dispersion distances. The risk profile considers the anti-covering methodologies of maximum coverage and produce the following results: (1) the high risk of siting a facility while only considering both missiles will impact each target directly, or within 328 feet away, is equal to a 69.96% probability over any given number of missile impact iterations; (2) the medium risk in siting a facility while considering both missiles will impact within a range of 328-656 feet from the target coordinates, is equal to 16.72% probability over any given number of missile impact iterations; and (3) the high risk in siting a facility while considering both missiles will impact within a range of 656-984 feet from the target coordinates, is equal to 13.49% probability over any given number of missile impact iterations.

The precision weapon CEP also influences this model because with the low range in error, the covering model is never obtained. Therefore, the risk level is reduced to three standard deviations from the target coordinates to the center point between each facility, making the dispersion distance of 984 feet the safest over the CEP range, or 1,434 feet away from any facility, in any direction. This accounts for the missiles hitting from either side of the analysis area. Phase II will examine the maximum covering of the missile damage area, resulting in a transition from anti-covering aspects from Phase I to covering methodologies in Phase II of the Level 5 analysis.

Level 5 Phase II

Phase II of Level 5 analysis represents the impact potential of both precision and non-precision weapons. The two range distributions are: (1) from coordinates (0,0) to (147,0); and (2) from coordinates (1047,0) to (3016,0) over a Euclidean distance, and as shown in Figure 30, where the distance for siting a facility within the “medium risk zone” is annotated along the x-axis.. The inverse analysis is also applied to this orientation and is shown in the risk profile for P(D) in Figure 31. The risk profile accounts for maximum coverage of the weapon impact zone, including any potential to miss the target and impact at a location within the CEP range of each weapon. The covering methodology used for this scenario accounts for the maximum possible destruction potential.

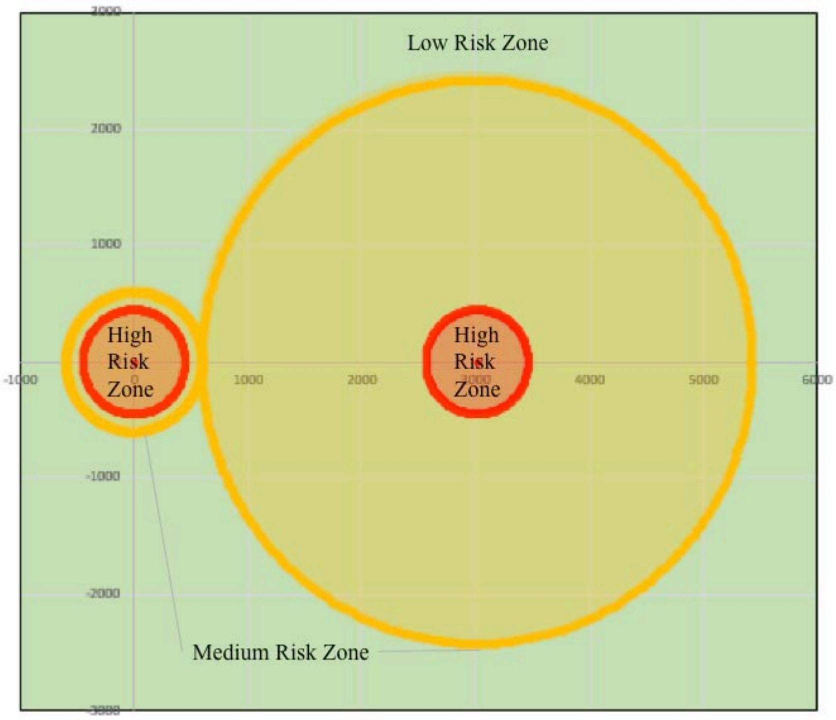

Figure 30: Level 5 Phase II Analysis - DMPI and CEP range of both the DF-15A and DF-11 (M-11) weapons showing maximum coverage

The output of Phase II shows the missile impact probability over a range of 147 feet along the x-axis from one direction and 1,969 feet along the x-axis from the other direction. The analysis does not allow for the intersection of the medium risk zone radii from any direction. A standard deviation of 49 and a mean of 0 produce the left side curve, and a standard deviation of 656 and a mean of 2116 produce the right side curve to show the non-precision weapon impact probability along the x-axis in a maximum covering scheme. The resultant intersection of the non-precision risk profile from each direction shows the safest location for a facility according to the P(D).

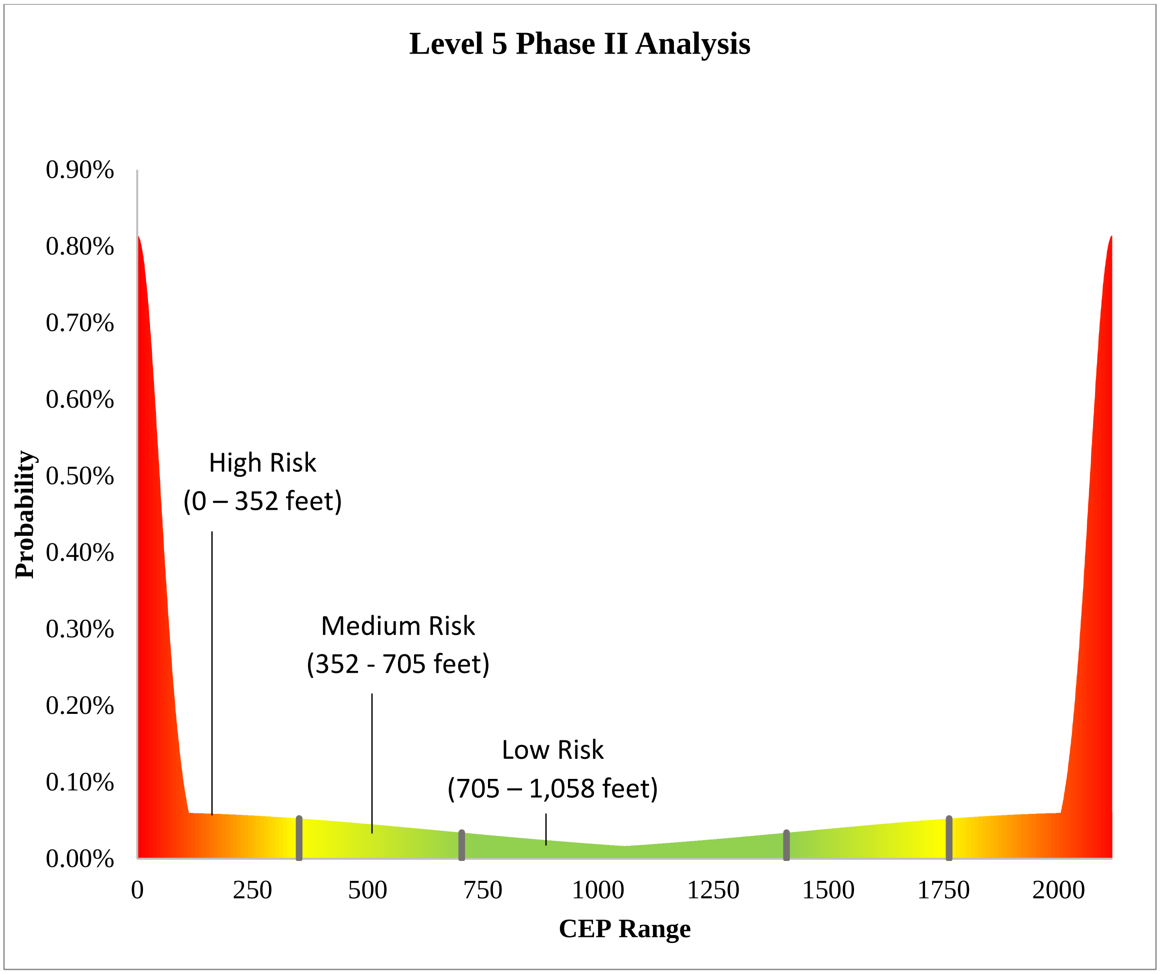

Figure 31: Level 5 Phase II Analysis - Probability distribution of one DF-15A and one DF-11 (M-11) SRBM over the CEP range

The output of the analysis categorizes the level of risk into three standard deviations over the maximum destruction distance within the geographically defined area: (1) the high risk of siting a facility while only considering both missiles will impact each target directly, or within 352 feet away, is equal to a 70.91% probability over any given number of missile impact iterations; (2) the medium risk in siting a facility while considering both missiles will impact within a range of 352-705 feet from the target coordinates, is equal to 16.73% probability over any given number of missile impact iterations; and (3) the low risk in siting a facility while considering both missiles will impact within a range of 705-1058 feet from the target coordinates, is equal to 12.60% probability over any given number of missile impact iterations.

In Phase II of the Level 5 analysis, the best location for a facility accounts for a 450-foot blast radius and a 1,058-foot weapon error potential, or 1,508 feet away from any facility, in any direction. This is because it cannot be determined which target the larger CEP weapon will impact, and therefore the location with the lowest P(D) for a facility is the intersection of the larger CEP risk profiles as analyzed from both directions.

Level 5 Combined Analysis

Phase I and II results are then combined to develop a combined risk profile for Level 5 analyses. Phase I shows the best location to disperse a facility is 1,434 feet away from any facility in any direction. Phase II analysis shows the best location to disperse a facility is 1508 feet away from any facility in any direction. As the methodology transforms from an anti-covering based model, to a covering based model, the risk reduces by over 15 percent. This is seen as the methodology transforms from anti-covering to covering and the dispersion distance is extended. The risk of P(D) for siting a facility within the Phase I analysis at 984 dispersion between facilities, the lowest probability of 3.946×10^{-4} is obtained. By transforming the methodology, the dispersion distance increases and when the maximum destruction scenario is used, the P(D) of a facility sited at 984 feet from any other facility changes to 3.350×10^{-4}.

Unfortunately, the DoD cannot guarantee its adversaries will employ a shot doctrine of maximum coverage for facility destruction. Therefore, the result of Level 5 analysis produces a dispersion risk profile that captures both the most amount of risk and the least amount of risk for the decision-maker and designer: (1) the high risk is categorized as dispersing a facility 450-778 feet away from any other facility in any direction; (2) the medium risk is categorized as dispersing a facility 778-1,106 feet away from any other facility in any direction; and (3) the low risk is categorized as dispersing a facility 1,106-1,508 feet away from any other facility in any direction. The risk profiles are for the combined Level 5 analysis is shown in Table 4.

Table 4: Level 5 Combined Analysis - Risk profile for DF-15A and DF-11 (M-11) SRBM impact locations

Risk Level	**Dispersion Distance Between Facilities (ft)**	**Probability of Destruction**
High Risk	450-778	69.96%
Medium Risk	778-1106	16.72%
Low Risk	1106-1508	13.32%

Results

The results of the study are that dispersion of facilities and risk tolerances can now be quantified. For evaluation of the model, a case study of a military installation in the Pacific region is used to show the dispersal of fuel assets and the resulting storage capacity within a constrained distance. A model that correlates risk with the optimized storage capacity of aircraft fuel is developed and implemented. The highest risk dispersion distance, the midpoint risk dispersion distance and the lowest risk dispersion distance were used to develop an overall risk profile based on weapon usage and weapon type. This risk profile is shown in Table 5.

Table 5: Risk profile for DF-15A and DF-11 (M-11) SRBM impact locations

Weapon Type	**Risk Level**	**Dispersion Distance Between Facilities (ft)**
DF-15A	High Risk	450
DF-15A	Medium Risk	524
DF-15A	Low Risk	597
DF-15A & DF-11 (M-11)	High Risk	450
DF-15A & DF-11 (M-11)	Medium Risk	1106
DF-15A & DF-11 (M-11)	Low Risk	1508

The results of this risk profile analysis are incorporated into design configurations that produce a model for each weapon type and risk profile. The efficiency of the model allows the designer to program facility dispersal according to the risk tolerance level of the decision-maker.

$$Q = \left(\frac{L_{ED}}{(L_{DD} + L_T)} + 1\right) SC$$

Where,

L_{ED} = Euclidean distance that bounds the geographical distance in one direction (ft);
L_{DD} = facility dispersion distance (ft);
L_T = length of the specified fuel bladder (ft);
SC = fuel bladder design storage capacity (gallons); and
Q = quantity of maximum allowable fuel to be dispersed within the bounds of the geographical distance per the risk level (gallons).

Case Study

The model performance was evaluated using a case study of Osan AB, Republic of South Korea. The output of the analysis is shown in Appendix 1. As reported in Chapter 3, the case study constrains the overall geographical bounds to a Euclidean distance of 7,000 feet. The case study applies the quantification equation to show the overall fuel storage capacity per risk and weapon type. The analysis of the model within the geographical bounds of the ramp space shows an overall storage efficiency gained by using the 210,000 gallon bladder in place of the 50,000 gallon bladder. This is shown in Figure 32.

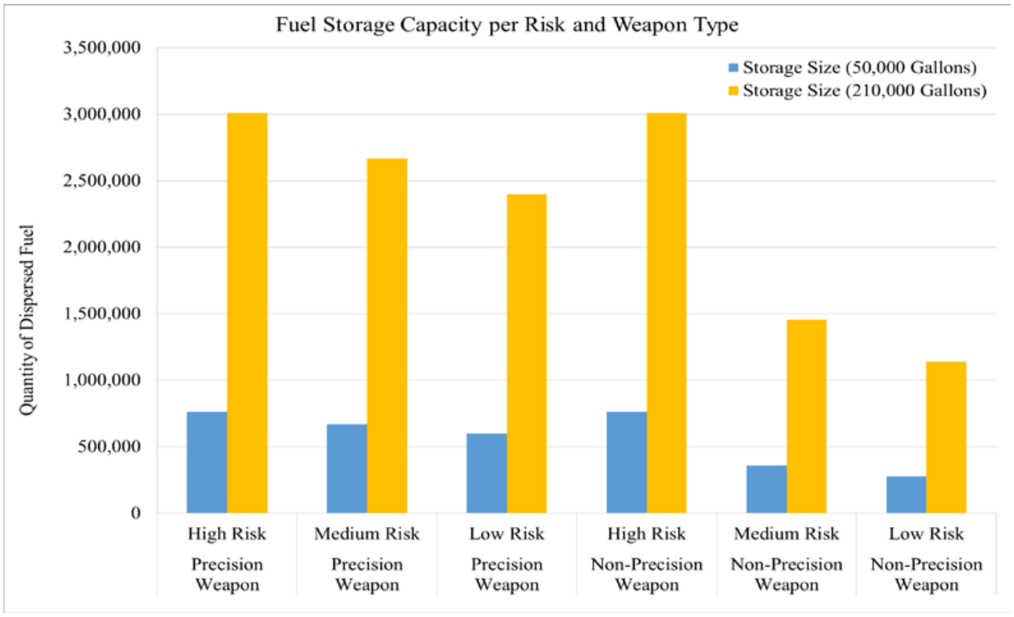

Figure 32: Case Study Analysis – The dispersed fuel storage capacity per weapon type and risk tolerance level

With an on-base storage capacity of 13,500,000 gallons of aircraft fuel, Osan AB would only be able to disperse up to 22% (3,010,000 gallons) of fuel within the geographical bounds set in this study. If further dispersal is needed, another area that meets the dispersal requirements must be analyzed.

The case study also allows for the analysis of the number of adversary weapons needed to destroy an asset within the dispersed environment. This information can be used, along with intelligence reports, to better assess the risk a decision-maker is willing to tolerance in a threatened area. Figure 33 shows that the higher the tolerated risk is, the more the adversary has to attack the asset to destroy it.

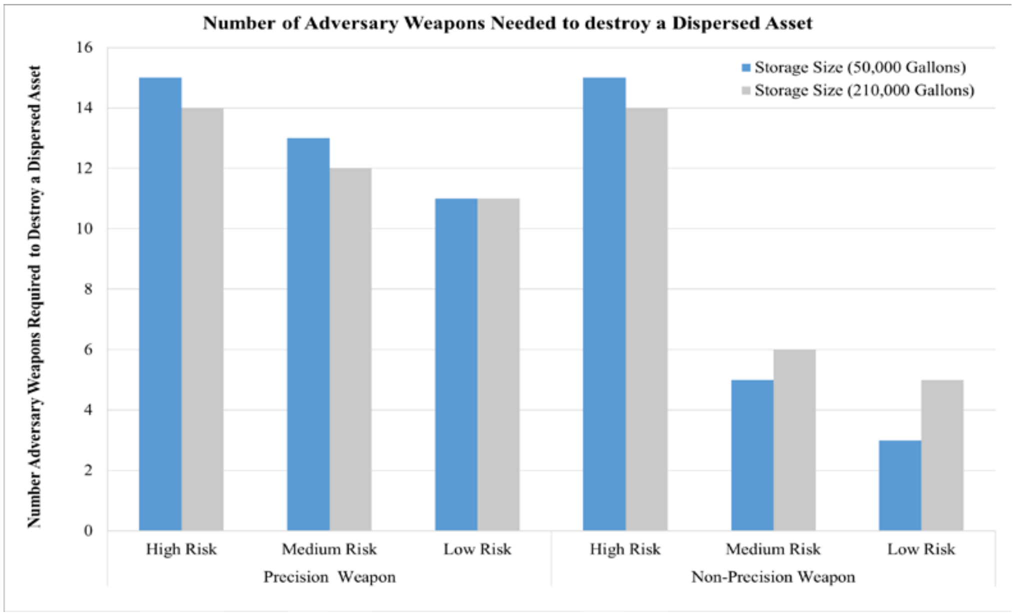

Figure 33: Case Study Analysis – The number of weapons required for complete adversary destruction of a dispersed asset per weapon type and risk tolerance level

Summary

Osan AB in the Republic of South Korea is oriented in a region roused with continuous threats from adversaries (Stillion & Orletsky, 1999). Therefore, Osan AB is used as the geographic area for a case study to illustrate the model capabilities and demonstrate its ability for risk analysis of dispersion. After applying the model to the quantities of Osan, the designer is assured that the use of 210,000 gallon fuel bladders allows for 16.7% more storage capacity in the bounds of the scenario. The analysis of the case study also allows the designer, within the bounds of the scenario, to see that 66% of the dispersion against precision weapons requires one additional weapon to destroy the asset over the dispersion against non-precision weapons. In a highly contested environment, the decision-maker now has the ability to choose between the risk tolerance associated with dispersal of facilities, and can quantify risk in: (1) dispersion of facilities; (2) quantity of fuel dispersed; (3) percentage of total fuel capacity dispersed; and (4) the number of missiles needed for the adversary to achieve asset destruction and associated mission failure.

V. Conclusions

Introduction

The purpose of this chapter is to highlight and discuss the conclusions and recommendations found from the results attained and identified in Chapter 4. The results from Chapter 4 will be put to use in the case study from Osan AB to demonstrate the effectiveness of the risk metric in a threat-contested environment. Specifically, the ramp space at Osan AB will be examined with the results from Chapter 4. Furthermore, this chapter will identify considerations for future research that will provide contributions to the field of knowledge and designers looking to disperse facilities.

Research Summary

This research identified a need to study airbase resiliency metrics contributing to the enduring presence of military operations in a contested environment. The development of the risk metric helps designers and decision-makers consider dispersal of critical infrastructure to reduce the risk of mission capability failure. By studying the risk profile of facility dispersion, the designer can correlate a risk tolerance to a dispersion distance.

In order to study the effects of short range ballistic missiles on a geographical area, the research was bounded by the characteristics of a high performance missile and a low performance missile. The associated circular error probable of each missile identified the bounds of missile impact locations associated with the desired mean point of impact coordinates, and developed the range of study in this research. The damage potential radii, which was developed by other research, was used to study the missile capability. It identified the full range of locations that had the potential for destruction based on the initial coordinates of the weapon.

After identifying the missile capabilities and developing the geographical bounds of the study, a distribution of potential locations provided the research to a distinct solution. This risk profile will provide the decision-maker with a probability of a facility being destroyed by either unintended damage or a direct missile impact, and is based on a distance calculation from other facilities.

To evaluate the risk profile metric, a case study was used to research how dispersal can be implemented based on different risk strategies taken. The research developed a high, medium and low risk profile for the decision-maker to consider when anticipating a high performance missile to show how facility dispersion can be effected when siting facilities closer together. The research also developed a high, medium and low risk profile for the decision-maker to consider when anticipating a low performance missile to show how facility dispersion can be effected when siting facilities farther apart.

Key Findings

By using covering-based models and anti-covering based models for the analysis of the dispersion within a geographically bounded area, the research was able to develop a risk profile that reduces the amount of risk a decision-maker will take when considering multiple attacks from multiple missile characteristics. The model is efficient in providing the designer with the ability to quantify risk in: (1) dispersion of facilities; (2) quantity of fuel dispersed; (3) percentage of total fuel capacity dispersed; and (4) the number of missiles needed for the adversary to achieve asset destruction and associated mission failure. This ability demonstrates that risk in airbase resiliency can be quantified and efficiently used for the analysis of asset dispersion in a contested environment.

Research Impacts

The impacts of this research can be seen through multiple lenses. One critical impact is in the military planning in which projects are advocated for, to receive funding for execution. A designer can now use risk profiles and the capacity models to quantitatively measure the resiliency of fuel storage in a forward location. The decision-maker can now statistically measure the successfulness of an operation based on the ability of that mission surviving a missile attack. The importance of this research is in the ability of the designer to assess resiliency by quantifying facility dispersal and risk tolerance levels. By being able to measure risk, a designer can maximize resiliency as mandated by the National Defense Strategy.

Recommendations for Future Research

Further research in the study of quantifying resiliency is bountiful. Other areas include how hardening a facility will affect the dispersion distance, and how ground attacks from outside the geographical bounds of dispersion analysis, such as a vehicle borne improvised explosive devices, can have on dispersion

The study of resiliency metrics is extensive due to the long list of potential considerations into what defines resiliency. The study of resiliency ultimately optimizes risk or recovery time associated with an adversary attack. The study of how risk can be perceived at multiple levels and at different times before, during and after an attack can generate research streams to determine resiliency at time intervals. Preparedness, versus respond, versus recover can be focus areas to further define resiliency. Further analysis within the paradigm model for data analytics can lead to continued advancement to the body of knowledge as descriptive analytics evolves into diagnostic, predictive and prescriptive analytics.

The impacts of the study on resiliency can help the DoD maintain mission capability levels in a threat constrained location. Further refinement of the risk metric can be seen by studying the effects of multiple target coordinates that are not facilities. The research can identify how dispersal will be affected when planning for the employment of more weapons by the adversary then what is needed to achieve maximum destruction of a geographical area.

Other work in base resiliency can study location based risk in which the facility is currently sited. This research can also develop risk profiles according to natural disasters. Resiliency is not only a forward location consideration, and should be studied holistically to reduce as much risk as possible. Ultimately, the use of genetic algorithms for optimization can lead to refinement in decision-maker risk tolerance levels and further quantify risk in resiliency.

Appendix A: Case Study Analysis

Weapon Type	Risk Level	Dispersion Distance Between Facilities (ft)	Quantity of Dispersal (Gallons)	Percentage of Total Base Capacity	Number of Adversary Missiles Used to Achieve Mission Failure
DF-15A	High Risk	450	761,382	5.6%	15.0
			3,010,000	22.3%	14.0
DF-15A	Medium Risk	597	597,731	4.4%	11.0
			2,397,500	17.8%	11.0
DF-15A	Low Risk	523.5	668,921	5.0%	13.0
			2,666,140	19.7%	12.0
DF-15A & DF-11 (M-11)	High Risk	450	761,382	5.6%	15.0
			3,010,000	22.3%	14.0
DF-15A & DF-11 (M-11)	Low Risk	1434.5	287,047	2.1%	5.0
			1,183,832	8.8%	5.0
DF-15A & DF-11 (M-11)	Medium Risk	2419	192,219	1.4%	3.0
			799,415	5.9%	3.0

Appendix B: Case Study Analysis (50,000 Gallons)

Storage Size (50,000 Gallons)					
Weapon Type	**Risk Level**	**Dispersion Distance Between Facilities (ft)**	**Quantity of Dispersal (Gallons)**	**Percentage of Total Base Capacity**	**Number of Adversary Missiles Used to Achieve Mission Failure**
Precision Weapon	High Risk	450	761,382	5.6%	15
Precision Weapon	Medium Risk	597	597,731	4.4%	11
Precision Weapon	Low Risk	523.5	668,921	5.0%	13
Non-Precision Weapon	High Risk	450	761,382	5.6%	15
Non-Precision Weapon	Medium Risk	1434.5	287,047	2.1%	5
Non-Precision Weapon	Low Risk	2419	192,219	1.4%	3

Appendix C: Case Study Analysis (210,000 Gallons)

Storage Size (210,000 Gallons)					
Weapon Type	**Risk Level**	**Dispersion Distance Between Facilities (ft)**	**Quantity of Dispersal (Gallons)**	**Percentage of Total Base Capacity**	**Number of Adversary Missiles Used to Achieve Mission Failure**
Precision Weapon	High Risk	450	3,010,000	22.3%	14.0
Precision Weapon	Medium Risk	597	2,397,500	17.8%	11.0
Precision Weapon	Low Risk	523.5	2,666,140	19.7%	12.0
Non-Precision Weapon	High Risk	450	3,010,000	22.3%	14.0
Non-Precision Weapon	Medium Risk	1434.5	1,183,832	8.8%	5.0
Non-Precision Weapon	Low Risk	2419	799,415	5.9%	3.0

Appendix D: Raw Data Used for Research

Methodology - Radii.xlsx

Analysis.xlsx

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)* 21-03-2019	**2. REPORT TYPE** Graduate Research Paper	**3. DATES COVERED** *(From – To)* |August 2017 - March 2019

TITLE AND SUBTITLE Quantifying Resiliency Risk Metrics Through Facility Dispersion	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) DeLong, Branden D., Major, USAF	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/ENV) 2950 Hobson Way Wright-Patterson AFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFIT-ENV-MS-19-M-170
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Intentionally Left Blank	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

During the last century, airbases were attacked at least 26 times in an effort to destroy the enemy at its base. Attacks on military airbases impose prohibitive losses to critical infrastructure, which in turn impacts the maintenance of air power projection. The primary enemy threat facing infrastructure today is the use of ballistic and cruise missiles to disrupt an airbase's ability to launch and recover aircraft. Over the last decade, ballistic and cruise missile technology has grown to allow the world's most powerful countries to achieve a nascent threat to forward operating bases used in security campaigns. Planners can reduce impacts from ballistic and cruise missile attacks on airfields by incorporating a number of resiliency measures, including dispersal of critical infrastructure assets, such as aircraft fuel containment and conveyance equipment. This research presents an airbase resiliency assessment capable of quantifying facility dispersal and risk tolerance levels in an environment threatened by missile attack. Model performance was evaluated using a case study from Osan AB, Republic of Korea. The model's distinctive capabilities are expected to support planners in the critical task of analyzing and selecting the design strategy that maximizes airbase resiliency against the threat of ballistic and cruise missile attack.

15. SUBJECT TERMS

Resiliency; facility dispersal; risk tolerance

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Steven J. Schuldt, Major, USAF, AFIT/ENV
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	UU	99	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-6565 x4645 steven.schuldt@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18