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Optimization of Airfield Parking and Fuel Asset Dispersal to Maximize Survivability and Mission Capability Level

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OPTIMIZATION OF AIRFIELD PARKING AND FUEL ASSET DISPERSAL TO MAXIMIZE ATTACK SURVIVABILITY AND MISSION CAPABILITY LEVEL

THESIS

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Abstract

While the US focus for the majority of the past two decades has been on combatting insurgency and promoting stability in Southwest Asia, strategic focus is beginning to shift toward concerns of conflict with a near-peer state. Such conflict brings with it the risk of ballistic missile attack on air bases. With 26 conflicts worldwide in the past 100 years including attacks on air bases, new doctrine and modeling capacity are needed to enable the Department of Defense to continue use of vulnerable bases during conflict involving ballistic missiles. Several models have been developed to date for Air Force strategic planning use, but these models have limited use on a tactical level or for civil engineer use. This thesis presents the development of a novel model capable of identifying base layout characteristics for aprons and fuel depots to maximize dispersal and minimize impact on sortie generation times during normal operations. This model is implemented using multi-objective genetic algorithms to identify solutions that provide optimal tradeoffs between competing objectives and is assessed using an application example. These capabilities are expected to assist military engineers in the layout of parking plans and fuel depots that ensure maximum resilience while providing minimal impact to the user while enabling continued sortie generation in a contested region.

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Ryley RH. Paquette

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OPTIMIZATION OF AIRFIELD PARKING AND FUEL ASSET DISPERSAL TO MAXIMIZE ATTACK SURVIVABILITY AND MISSION CAPABILITY LEVEL

I. Introduction

Background

For the past 40 years, the United States has operated in combat theaters that have uncontested airspace [1]–[3]. Furthermore, most of the offensive operations conducted in that period have been against states and groups that do not possess standoff missiles such as theater ballistic missiles (TBMs) [3], [4]. As such, the United States has not had to focus on defense against ballistic missile attack in most bases and theaters. As the threat changes, however, this immunity to attack at non-forward airbases is beginning to diminish. The threat is shifting from non-state aggressor groups to near-peer and peer states whose policy or strategic aims put them at odds with the United States [5]. This results in a need to change the layouts and approaches of bases at risk for attack from munitions such as TBMs in order to minimize damage to valuable aircraft and strategic supplies. The primary threat from these attacks is anti-access/area denial (A2/AD) attacks using submunitions [6]–[8].

The origin of A2/AD attacks lies in Chinese strategy following the first Gulf War. While it had long been expected that the rise of fourth and soon to be fifth-generation fighters would result in an air war that was so lethal that alternative strategies would be needed, the shift in technique was not. After observing the Navy and Air Force domination of airspace over Iraq and Kuwait, the Chinese decided that, rather than competing with the United States directly for airspace domination in a future conflict, they would eliminate the ability of the

Air Force to generate sorties close to the theater, reducing the volume of airframes in the area and making control of the airspace in the theater untenable [6]. In order to enable this strategy, they developed standoff cluster warheads for their theater ballistic missiles. While this strategy was noted once discovered, the onset of the Global War on Terror (GWOT) after September 11, 2001, meant that the strategic policy shifted away from near-peer and peer conflict and toward suppressing insurgency. Now that GWOT has stabilized and is in decline, national policy is returning to a focus on peer conflicts, especially with Russian aggression in the Crimea and Chinese island construction, leading to concerns of increased risk of conflict in those areas [5], [8]. These concerns have resulted in a doctrine of increasing base resilience, especially in the Pacific theater.

Resilience, even in a military context, is a term without a standardized definition. As a word with a great deal of interest but without much structure, many seek to define it in such a way as to promote their service's or agency's needs. For the purposes of this thesis, however, resilience is the ability of a base to repel and weather attacks, especially in a near-peer or peer conflict, while maintaining an acceptable level of operations tempo [1]. While the implementation of this policy has not been finalized and varies by service, the Air Force has published a policy paper that outlines the desired objectives of the program and formalizes some of the language of resilient basing. A further paper was published by Conner that created a more formal view of resilience, with pillars of resilience organized by the role they play in either preventing attacking, mitigating damage, or speeding recovery efforts [9].

This thesis investigates the pillars of resilience for air bases and how civil engineer planning and layout efforts can lead to a more resilient air base. This investigation will culminate in an analysis of the efficacy of dispersal and the development of a novel model to enable planners to develop layouts of parking aprons and fuel depots in such a way as to maximize resilience while minimizing the impact on sortie generation rate.

Problem Statement

The Department of Defense updated its defense strategy in 2018 with the release of a new National Defense Strategy [10]. This plan distills the emphasizes the challenges posed by increased aggression of peer and near peer states. It also outlines several key objectives that the Department designates as its main priorities. Two of them rely heavily on the resilience of bases, especially bases with a close proximity to a contested region. These two are (1) Maintaining favorable regional balances of power in the Indo-Pacific, Europe, the Middle East, and the Western Hemisphere and (2) defending allies from military aggression and bolstering partners against coercion, and fairly sharing responsibilities for common defense [10]. In addition, the National Defense Strategy has placed an emphasis on improving ballistic missile defense and creating a lethal force. Both of these aims directly tie into base resilience. The civil engineer career field has several areas of responsibility in ensuring the success of the resilient basing concept. Many of the areas civil engineers focus on are the recovery aspects, as most recovery aspects are the responsibility of engineers. Several passive defensive capabilities, however, are also engineer responsibilities. These areas are (1) hardening, (2) redundancy, (3) dispersal, (4) mobility, and (5) concealment, camouflage, and deception (CCD) [9]. Mobility and CCD are excellent techniques to diminish the accuracy of targeting, but have been studied and are outside of the scope of this paper due to the complexity of implementation. Hardening is effective against targeted strikes with conventional munitions, but since the purpose of A2/AD attacks are to damage and destroy soft targets and pavements, hardening is not especially effective at preventing a loss in sortie generation rates in the specific case being considered [1], [6], [11]. Redundancy is an excellent technique for improving resilience to A2/AD attacks, and has the potential to be the single most effective method usable, but comes with significant drawbacks [9]. Built infrastructure is one of the most expensive parts of a base, and duplicating those assets is often infeasible with the availability of funds, materials, and manpower [8], [9]. Redundancy of aviation assets is even more expensive, and the current industrial complex in the United States would need time to scale to the demand of redundant airframes required for sustained combat in a peer or near-peer environment, even if unlimited funding was available [12]. This leaves dispersal as a happy medium of cost savings and maximized effectiveness at increasing resilience.

Dispersal is the strategic separation of assets, used in this case to minimize damage from indirect fire attacks. Dispersal is effective in two specific instances of indirect fire: (1) large warheads with significant potential for blast damage and (2) warheads with submunitions, since these warheads are designed specifically to prevent use of large areas of a base and the destruction of any soft targets contained within [2], [11], [13]. A primary consideration of a submunition attack is secondary damage or when the submunitions that were targeted at one asset damage or destroy an additional asset due to their proximity. Dispersal seeks to minimize this problem by spreading out assets as much as possible. This distance is limited by the practical need to access and service the assets, as daily sortie generation rates cannot be overly impeded by a desire to protect the assets, else the strategic value of the assets is compromised, and the enemy has succeeded without attacking.

Research Objectives

Given the intent of this thesis – to study and provide modeling support for resilient basing from an engineer perspective – the research objectives are as follows:

1. Review traditional basing techniques and existing research on resilient basing. Additionally, this thesis will review scholarly works on modeling, heuristics, nature-inspired metaheuristics, and other concepts relevant to the understanding of dispersal in a modeled environment.
2. Analyze the history of resilient basing, identify and discuss engineering challenges and opportunities in basing layouts, and identify a way forward in modeling resilient basing to provide an optimal solution for decision-makers and strategic planners.
3. Develop a novel model to analyze the tradeoffs between attack resilience and sortie generation for aircraft being staged at a forward base in a contested theater.

Thesis Organization

This thesis follows a scholarly format in which chapter 2 is a traditional literature review covering topics necessary for, but not covered by, the papers that follow. Chapters 3 and 4 each serve as stand-alone academic publications addressing the strategic thesis aims discussed above. Chapter 5 serves as a conclusion and discussion of future work. In chapter 2, the concept of a routing problem and a summary of existing literature on this topic is introduced. The types and solution techniques for the various vehicle routing problems are considered, as well as current academic advances and shortcomings in rich routing problems. This section is followed by a detailed discussion on problem solving techniques for complex problems with stochastic elements and large solution spaces. This chapter also introduces the various techniques scholars use to calculate distances in complex routing problems, discusses which routing problems are most germane to the discussion of base resilience, and introduces opportunities for further advances in resilience-related routing and problem-solving methods.

Chapter 3, titled “Defense of Military Installations from Ballistic Missile Attack,” is a study on the history of base defense and resilience, as well as the proposal of a staged modeling technique for base resilience that would form the basis for future work in the following chapter. The review section discusses previous academic and military research related to the fundamental principles engineers use to increase base resilience, with an analysis of 33 sources and discussion of current doctrine compared with the results of academic research. Furthermore, it synthesizes this current research and proposes a multi-objective genetic algorithm (MOGA) that could be used to determine an optimal base layout given space availability, resources, and funding. This paper was published in the proceedings of the International Conference on Military Technology, held in Brno, Czech Republic, on May 30-31, 2019.

Chapter 4, “Title TBD,” is a paper presenting the development and analysis of a novel model that optimizes (1) the airfield parking layout, (2) the fuel depot layout, and (3) their standoff distance from each other to determine a series of Pareto-optimal solutions for a base layout given information regarding the aircraft, aggressor missiles, and human performance factors relevant to sortie generation. This paper addresses the development of the model, its assumptions and attack models, and discusses an application example designed to validate model performance. It discusses the resulting Pareto frontier and shows the spread of solutions across the optimal solution space. The paper also identifies future opportunities for model enhancement and integration into the larger resilience model proposed in chapter 3. The target journal for this paper is Defense and Security Analysis. Finally, chapter 5 outlines conclusions, discusses potential future resilience research and the model introduced in chapter 3.

II. Literature Review

Introduction

Any effort to create an accurate model of the real world relies heavily on a body of experience and knowledge to produce viable results. Significant efforts have been made since the dawn of practical, automated modeling in the mid-twentieth century to create mathematical equations and representations that can create, optimize, and solve real-world problems for a variety of specific situations, such as the routing of vehicle traffic for parcel delivery. A similar effort has been placed into combining many of these smaller models into complex models that can provide Pareto-optimal solutions for situations previously considered too complicated for traditional efforts. Some of these models have been created with the goal of modeling the resilience of military bases to attacks from various vectors.

Routing Problems

Routing problems have been investigated in their modern convention for sixty years. This effort resulted in the first attempt to formalize an academic solution to improving delivery truck efficiency was first posited [14]. The core tenets of vehicle routing are the origin of vehicles from a hub and that a system of supply and demand must be satisfied [15]. These Vehicle Routing Problems (VRPs) are typically divided into four categories: (1) Capacitated VRPs (CVRPs), where all the vehicles are assumed to be identical in capacity and performance; (2) VRP with Time Windows (VRPTWs), which are CVRPs but where customers must be served during specific windows of time; (3) Split Delivery VRP (SDVRPs), a form of VRPs where a customer does not need to be serviced by a single-vehicle; and (4) Rich VRPs, a newer version of VRP that include multiple features of the earlier types, including heterogeneous fleets, loading constraints, or any other nonstandard parameters that need to be examined [16].

CVRPs are, by far, the most common and researched of the VRPs [16]. A combination of the Bin-Packing Problem and the traveling salesman problem, CVRPs represent a simplified but realistic view of many small delivery operations [17]–[19]. The fundamental requirement is the homogeneity of delivery vehicles, but other possible constraints must also be ignored, such as timing and compatibility issues. A routing problem involves a location with a supply, known as the hub, and locations requiring delivery, known as vertices. Each vertex has a demand associated with it. The vertex can, in simple cases, be unitless, or demand can be expressed in terms of several types of packages. In the most traditional form of the problem, a single delivery route is run by each vehicle, and the total demand of the vertices cannot exceed the total capacity of the delivery vehicles.

The traditional solution methods for VRPs are deterministic, using an algorithm to search for the ideal path [18]. The most common algorithms used to solve VRPs deterministically are branch-and-cut and Lagrangian relaxation [20], [21]. Branch-and-cut problems are the purest form of relaxation in programming, where some constraints are ignored in order to simplify the solution space. This simplified space is known as a branch. A solution for the simpler set of constraints is found and tested with the full set of constraints. If the test solution results in a valid solution for the entire problem, the program is complete. If not, the solution space in the branch is divided, and a new solution is attempted. This is known as a cut [22]. Lagrangian relaxation utilizes a Lagrangian duality and flips the order of solving, seeking a solution such that any changes in the variables of the problem produce minimal changes in the scoring function of that problem. This technique is useful since it allows for the conceptualization of highly complex problems, such as routing problems, in the form of a simple problem with complex limitations [23].

VRPs can also be solved using more unconventional techniques such as heuristics and metaheuristics [24]–[26]. While the intricacies of heuristics and metaheuristics will be discussed later in this chapter, several notable instances of heuristic and metaheuristic algorithms used in VRPs are worth noting. Heuristic algorithms are traditionally developed for specific solutions, and the most common heuristics used in VRPs are the savings method and a sweep search [24]. While heuristics are useful, they are limited to the specific forms of problems for which they have been developed. Metaheuristics provide greater flexibility in that they describe a specific way to find a solution, rather than prescribing the way to find a specific solution to a specific problem. Metaheuristics successfully applied to VRPs are Ant Colony Optimization, Particle Swarm Optimization, and Genetic Algorithms, among others [25]–[27].

VRPTW are an addition to the base VRP that provides increased success in modeling the needs of actual scenarios, since it is uncommon for a delivery service not to need to deliver within a certain window outside of very small or localized operations [28]. Traditionally, VRPTW algorithms assume unlimited vehicles and seek to minimize them. A variant of the VRPTW is the *n*-VRPTW, which limits the number of vehicles available to the hub for deliveries [29]. While bound-and-cut algorithms for this specific problem have traditionally utilized two cuts, as with CVRPs, a two-cut algorithm has been proposed that resulted in significantly faster solution times than traditional exact algorithm techniques [30]. Other variants have attempted to minimize route duration over the number of vehicles [31]. Tabu search heuristics have also been used to develop algorithms, including some that have utilized parallel computing to reduce solution time [32], [33]. The ease of use and popularity of metaheuristic algorithms results in a large number of specific models created for VRPTW, including Genetic Algorithms and other nature-inspired algorithms [34]–[38].

SDVRPs, while less common than the previous two types of routing problems, represent an important area of routing: variable levels of service [39]. This type of problem is perhaps best represented in the real world by parcel delivery. Many parcel delivery services utilize different vehicles for different levels of service. A vehicle may be designated exclusively for rapid delivery packages, while other vehicles service the same customer for lower priority packages. This is a relaxation of the CVRP. As such, many of the same techniques, including Tabu searches, optimization heuristics, mixed-integer programming, column generation, and branch-and-cut [39]–[44] may be employed. While metaheuristics have also been used for this problem, their frequency is significantly less than in other types of routing problems, perhaps due to the number of traditional heuristics already developed [45], [46].

Rich VRPs are more constrained in the methods that work to produce answers [47]. Due to their complexity, determinate solution techniques are computationally prohibitive or have too many variables to readily solve with current computing technology [48]. Rich vehicle routing problems are both more recent in their development and still an emerging area of research. Column generation algorithm has been developed to support some iterations of this problem; the column generation algorithm restricts the realism to a combination of time, vehicle restrictions, multiple vehicle types, and split delivery [49]. The most popular technique with RVRPs is metaheuristics [48], [50]. Nature-inspired metaheuristics, in particular, have been used several times to successfully generate solutions for RVRPs, with insect-based optimization being a favored model type [51]–[54].

Manhattan Distance

Many methods have been devised to measure the distance from one point to another. The most well-known is Euclidean, which is the straight-line distance between two points on a coordinate plane [55]. Many other techniques exist, however, including Chebyshev, Hamming, and Manhattan. Chebyshev distance is the distance expressed in straight lines capable of only ninety and forty-five-degree angles and only capable of making those changes at specific intervals.

Hamming distance is the distance of change required to make the two points the same; it is normally only found when needing to calculate distances in a non-geometric scenario. Manhattan distance is the distance expressed by straight lines and right angles. This is best visualized by comparing the distance between two points in a modern city. Euclidean distance would be the distance flown between the two points, Chebyshev distance would be the distance walked if cutting diagonally through each block were possible, which in many cases would equal Euclidean distance, though not in some cases. Manhattan distance would be the distance from driving between the two points [55]. While this technique may seem simplistic, it is used with success in a variety of subjects, from facial and mood recognition to spam email filtering [56], [57]. Manhattan distance is used with high frequency in VRPs, especially in the formulation of heuristics and metaheuristics [32], [58], [59].

Optimization and Heuristics

Optimization is a field of applied mathematics that seeks to find the best solution in a problem that cannot simply be maximized or minimized. Since the problem traditionally faces tradeoffs between multiple objectives, a balance between these objectives is sought. Optimization has four main categories of solution method: iterative methods, global convergence, optimization algorithms, and heuristics [60]. Iterative methods are a search technique that utilizes a series of possible solutions until the ideal solution is located. Hessian matrices are a common technique used and involve using eigenvalues to determine if a solution is close to an ideal value.

Global Convergence Optimization (GCO) offers a determinate solution technique that is similar to iterative methods, but that employs a form of simplification to find the answer. Global convergence is among the most traditional and simple forms of optimization technique, where a purely iterative algorithm tests solutions and analyzes if the solution is moving toward the desired maxima or minima of the objective function. Unlike purely iterative methods, however, GCOs utilize indicator variables to quickly test the solution space to determine which of the possible solutions are likely to be correct, then iterates among the likely solutions to find the optimal solutions. Due to this modified iterative technique, computational efficiency per calculation is acceptable, but the speed of convergence is sacrificed compared to other optimization algorithms. This technique is not efficient for complex objective functions since any function that has a series of near-optimal solutions will require a sufficient number of computations that convergence might take weeks to complete. In cases where the solution space has one clearly optimal solution, however, GCO can provide an easy way to attain a truly optimal solution without the development of a complex algorithm. GCOs are traditionally used in non-convex optimization problems, where a traditional search algorithm could fail to converge due to compatibility issues.

Optimization algorithms are another solution technique for IAM. They allow for slightly simpler problems to be solved to the mathematically perfect solution, as long as there are enough constraints. This system of processes is flexible, ranging from the use of algebra to calculus, depending on the difficulty of the problem. The most common form of optimization algorithm is linear programming. Linear programming is useful when the number of constraints on an objective function is small, and the solution space is also reasonably small. It is common to show the traveling salesman problem as a stereotypical example of simplex linear programming at work, but this is limited to reasonably small traveling salesman problems with no knapsack problem additions. Ultimately, linear programming is one of the best quick solution methods for simple problems that do not need the greater analysis of a more complex algorithm, or for problems with fewer constraints.

Heuristics are a toolset utilized when a determinate solution technique is not possible or practical due to system complexity. Heuristic models do not offer a guaranteed optimal solution, but instead, try to move to a solution that is as close as possible to the true optimal solution in a rapid or computationally efficient way. Heuristics fall into two categories: heuristics and metaheuristics.

Heuristics are the traditional technique and were favored for many years. They are traditionally developed for a specific problem or type of problem and will only work for that problem type. Heuristics will use a variety of guessing techniques to search for a local optimum. Heuristics are often ideal when: the number of possible solutions is sufficiently large as to render a search algorithm infeasible, the existence of some element of the objective function that is either stochastic or probabilistic and renders calculation difficult, or an element of the environment of the problem that changes over time, making a single solution a poor representation of the problem. Heuristics traditionally suffer in problems that have a large number of local optima, as they often do not have the ability to easily move past a local optimum to the global optimum. This has not limited their popularity, as a survey of papers from 1975-1986 alone returned 442 papers on heuristic models [61]. Their popularity can usually be explained by several factors. First, the non-technical nature of the senior leaders in many fields yields a desire to produce a decision-making model that can at least be generally understood by the senior leader. Leadership tends to resist relying on a model they cannot understand at all [62]. Additionally, many decisions in the real world would not benefit from the effort required to attain an exact solution. Much of the time, improvement is all that is desired [63]. Furthermore, heuristic solution techniques are generally able to get solutions rapidly and are agnostic to many changes or uncertainties in the data due to their ease of recalculation and partitioning of results [23], [64]. Typical heuristic problems include those of inventory, variable yield production, distribution network inventory, higher-order traveling salesmen, limited-resource project scheduling, vehicle routing, and network design [59], [65]–[68]. Solution techniques vary widely. Simple heuristics can utilize randomly generated solutions, as with the facility location problem explored by Mabert and Whybark [69].

Problem partitioning is another common technique, with a large variety of implementations. Many of those implementations pivot around the natural partitioning standard common in industrial engineering applications, such as scheduling with random yield [70]. Inductive methods are useful in many cases that involve complex solution spaces. These techniques rely on utilizing mathematical approximations of the problem to get close to an ideal solution, then iterating to find the optimal solution. This is seen in location and routing problems where partitioning would not be effective [71], [72]. Reducing the solution space, either by introducing new constraints or making existing constraints more restrictive, is also a possible solution method. This can be utilized in situations where managing assets or inventory is a key part of the problem but is also useful in situations where the combinatorial expansion of the problem makes conventional techniques impossible [73]. One of the most common techniques can be broadly referred to as approximating the solution. There are four techniques that can be utilized to solve the problem using this method: relaxation, approximating random or probabilistic variables, aggregation of the problem constraints, and simplification or approximation of the objective function. Relaxation is a solution method for problems that are difficult to solve due to the number or complexity of constraints. The technique involves ignoring or reducing the severity of some of the constraints, finding an intermediate solution, and testing it with the full constraints. Several techniques are utilized for this relaxation, ranging from turning nonlinear constraints into linear ones, allowing discrete constraints to function as continuous constraints, or using calculus to find extrema of constraints in order to aid in moving to a rapid solution. This is the most common technique used for VRPs but is also useful for predicting reordering needs [63], [74]. Approximating stochastic or probabilistic variables is useful for inventory problems and similar issues, where the exact amount of inventory is unknown at any given time. Intermediate solutions are found by assuming a single value, typically a mean value, and then tested using full constraints [63]. If full constraints cannot be predicted, probabilistic values can be approximated to give confidence intervals on the solution.

Aggregation is a solution technique often employed in logistics and related distributions problems, where the number of constraints rises to the point where a solution is computationally taxing [63], [75], [76]. This method is traditionally realized by combining multiple constraints into a single one, reducing the complexity or features of a constraint, or to increase the scale of a constraint to allow differences in the output to be more readily noticed. Another technique that bears a strong resemblance to clustering techniques is the constructive solution method. This method produces only a single, final solution that is based on the best possible value for each variable in the objective function. In the additive form, all variables are set equal to zero, and each variable is manipulated sequentially until the final variable has been manipulated. The dropping form of the solution process does the steps backward, with the final step having the fewest variables. This solution process is beginning to resemble something that might be used by a metaheuristic. However, because there are no generations or repetitions, it often produces inaccurate answers and is sensitive to the order of the variables in the function. Taking the constructive technique and adding iterations to it yields the Neighborhood Search method. Neighborhood search considers the best solution in a small range of possible input values, then moves on to the next range until the best solution is found. This is useful in guaranteeing a local optimum, but the search space may still be too small and is still too dependent on the order of initial values that are chosen for the search. In order to improve solving ability beyond Neighborhood Search, metaheuristics are needed [60], [63].

Metaheuristics

Metaheuristics are a newer technique rapidly increasing in popularity. They are usually implemented as a “black-box” solution, where they are simply used as a building block in a solution technique that is not specifically designed for the problem and little may be known about what is happening inside the algorithm to get a solution [63]. Metaheuristics have several significant strengths, one of which is a near immunity to becoming fixated on a local optimum [60]. Another is the ability to utilize parallel processing often to improve solution time, as the process can start from two points and converge. Five common types of metaheuristics are Beam Search, Tabu Search, Simulated Annealing, Adaptive Reasoning, and Evolutionary Algorithms.

Beam search is an excellent technique for solution spaces that are branching in nature [63]. Treating the space as a dendrogram allows for a simplification of the branch-and-bound heuristic discussed earlier. It calculates parameters called beam width that indicate the number of nodes at each level. The algorithm seeks to reduce the beam width as much as possible by removing branches that do not seem likely to contain an optimal solution. This is still time-consuming, and some Beam Searches utilize multiple passes with different levels of solution resolution to try and do an early cull before doing a detailed pass at each level of the dendrogram [77].

Tabu search is one of the most flexible and proven metaheuristic techniques available. It shares many similarities to constructive heuristics and neighborhood search, with the addition of the ability to move generationally to inferior intermediate solutions in an attempt to avoid becoming stuck in a local optimum. Possible uses range from classroom scheduling to vehicle routing with one survey identifying over 70 use cases [78]. The technique draws its name from the list of previous solutions, which the algorithm considers taboo and will not use for future generations of solutions until a certain number of generations have elapsed. This technique is effective but can be hampered by ineffective neighborhood sizes for generational searches. Too small and it will take a long time to gain an optimal solution, if one is found at all. Too large, and the algorithm can struggle to search the space effectively [63].

Simulated annealing is another technique common to routing problems. It is, in some ways, a nature-inspired metaheuristic, where the search process is based on the physio-chemical process of annealing [63]. It essentially takes the deterministic search patterns present in Tabu search and transforms them into a probabilistic search using a factor called temperature that evaluates the probability of an improved solution in a certain search space [79]. Temperature can be regulated by the programmer to allow changes to the level of diversity in the searches and intermediate solutions. Simulated annealing also randomly allows movement into an inferior solution temporarily, whereas Tabu search only allows inferior solutions during movement toward a perceived optimum. Aside from routing problems, network design and workforce utilization have successfully implemented this algorithm [63].

Evolutionary algorithms are an expansion on earlier concepts that utilize an array of solutions, referred to as a population. This population is allowed to combine, mutate, and transform, and each generation some of these solutions are carried forward while new ones are brought in. This replica of evolutionary theory allows for a robust solution process that is strongly resistant to local optimum entrapment and avoids issues of search area size created by previous metaheuristic techniques. A flaw in evolutionary algorithms is a tendency to lose solutions that are superior to others in the population due to this random process, a problem that can dramatically extend computation time. A technique developed to avoid this is known as elitism. Elitism ensures that a fixed number of the best solutions from each generation survive into the next generation. The number of solutions that can be carried forward is determined before running the algorithm. If too many are allowed to carry forward, the speed of computing the final value will be significantly reduced, as will the resistance to becoming stuck in a local optimum. This represents the greatest weakness of evolutionary algorithms, sensitivity to the numerous constraints that must be specified at the start of the computation. Elitism, along with the mutation rate, population size, crossover rate, number of generations, and occasionally other values must be selected, and an incorrect choice can hamper the quality of the results. Since evolutionary algorithms often run with large populations and generation counts, it can take significant time to come up with an ideal mix of settings to enable rapid, optimal results [63], [80]–[83].

While significant research has been conducted across many of these solution techniques in the area of network design and vehicle routing, facility siting for dispersion is a unique challenge that requires a flexible solution algorithm. This restricts the available techniques to metaheuristic algorithms, of which any would result in an adequate answer. While Tabu search is an excellent option that should be considered for future comparisons, it has shortcomings in the ability of the programmer to modify the algorithm. In order to provide a robust option to decision-makers to vary the results according to their installation defense emphasis and goals, evolutionary algorithms will be utilized.

Dispersal and Resilience

The subject of separation between similar assets has been the study for a variety of disciplines since the 1940s. Initially considered as a defense measure for cities against potential nuclear attack, early efforts for dispersal noted that breaking up large homogeneous areas would reduce the impact of an atomic blast, both on initial damage and radiation effects after [13]. The use of insular, self-contained city neighborhoods separated by unoccupied land was proposed, similar to modern concepts of standoff distance on a smaller scale. This concept has not entirely left the academic environment, as it was proposed as a potential response to the increased frequency of incidents of terror after the September 11, 2001 attack on New York [84]. While dispersal has been researched from a servicing perspective, that becomes more of a vehicle routing or coverage problem and less of a separation problem [85], [86].

Dispersal and modeling of facility resilience on a military level have primarily been a side-consideration of other, larger modeling efforts. RAND Corporation, a think tank primarily focused on military strategy and policy, has published several reports on base defense which cover resilience [2], [11], [87]. When the subject was first looked at in the early 1980s, the focus was on convincing the senior strategists then proposing conventional bases be made increasingly resistant to attack that their view was outdated. Think tank strategists reasoned that rather than a more pragmatic approach of trying to spread out the aircraft, in this case to many small bases, would be more effective than trying to turn existing airbases into fortresses. This wasn't given much credence in official doctrine until the later development of the adaptive basing concept proposed in 2017 and rapidly adopted by senior leadership, especially in the Pacific theater [88]. During the intervening years, however, two major models were proposed that attempted to model base resilience and provided groundbreaking aid to military strategists.

The first model developed for modern Air Force resilience concerns was the Theater Air Base Vulnerability Assessment Model (TAB-VAM), which strove to assess the overall resilience of current bases and their layouts and improvements [87]. It utilizes Monte-Carlo simulation to determine the overall threat level to an entire combat theater by simulating a large number of different attacks. This is not a purely stochastic model; the model was programmed with a limited amount of strategic thinking in order to allow a more realistic choice of targets across an entire theater [87]. This model does not directly output any data related to how the specific layout of a base did or did not improve its resistance to attack; instead it focuses on how the theater as a whole remained viable for the friendly forces. The primary output is percent sorties generated theater wide during a 3-day conflict relative to a baseline. In order to address a more base-specific optimization model, a second modeling module was built for TAB-VAM.

The Theater Air Base Resiliency Optimization Model (TAB-ROM) model was built as an extension to TAB-VAM that enables strategic planners to step through base layout changes and see the effect on overall resilience in the theater [87]. The model takes existing base layouts and attack strategies and iterates through incremental changes to the layout to see which layout is best resistant to an attack. In addition, the model has constraints provided by what is specified to be available during initialization. This model is also constrained by a maximum cost and seeks to minimize overall cost while maximizing the resilience. Like other RAND models, it is interdependent on other modules to be effective. For example, it relies on logistics availability being fed from START, RAND's logistics organization model. This model is fairly comprehensive and effective but is aimed at providing strategic planners with a high-level overview of base layout and resilience to inform war plans. It is not intended to help give civil engineers and other tactical-level planners the ability to help choose a base layout that provides the greatest overall resilience to the individual base being considered [87]. This gap in the literature provides an excellent opportunity to provide a contribution to improving the body of knowledge on base resilience.

III. Scholarly Article 1: Defense of Military Installations from Ballistic Missile Attack

Captain Ryley RH. Paquette and Major Steven J. Schuldt, Ph.D

Abstract

While NATO nations have long enjoyed relative security from air attack at military installations, recent developments in missile technology and doctrine have threatened that security. With 26 conflicts worldwide in the past 100 years featuring airbase attacks, doctrine and planning tools must be updated to allow continued use of air bases within missile range of enemy forces. Research conducted for the United States Air Force identifies the areas of base resilience and how they affect mission capability. Several models have been developed based on these principles, but there are gaps in model capability and usefulness for allied partners. This paper presents the proposal of a novel base planning model capable of directly quantifying missile attack consequences and generating optimal site layout plans and protection strategies. This model would be implemented using multi-objective genetic algorithms to identify solutions that provide optimal tradeoffs between the competing objectives of minimizing attack consequences, minimizing site construction costs, and minimizing mission impact. These capabilities are expected to assist military engineers in their critical task of analyzing and selecting the design strategy that minimizes operational impacts to a base located in a contested region.

Introduction

The armed forces of most North Atlantic Treaty Organization (NATO) member nations have enjoyed a period of relative freedom from attack by a peer or near-peer state since the advancement of anti-air defenses made bombing of bases difficult in the 1950s. Recent significant development of precision ballistic missiles and other standoff weapons, has resulted in a growing concern that base defense may not be sufficient to permit unrestricted mission generation from bases in theater in the face of conflict [89]–[91]. Given this increasing concern, senior defense officials have placed increasing emphasis on improving the body of knowledge regarding base resilience from the perspective of strategic planning, a field which has been given considerable study by professionals focusing on industrial planning, among other independent fields [92]. As military engineers, missile defense focuses primarily on minimizing the ability of enemy forces to inflict damage and enabling the fastest possible recovery to permit a return to mission effectiveness. Accordingly, there is a need for planning tools that utilize objective data to provide the best possible defense plan for an installation. The purpose of this research paper is to: (1) identify current doctrine and planning tools for base defense; (2) consider the challenges and shortcomings of the existing planning process; and (3) propose the creation of a novel model that provides the military engineer with an optimal base layout and protection strategies to minimize impact of attack.

Background

As early as World War Two (WW2), guided missiles have been used as a tool to deny use of an area to opposing forces. Airfields are one of the primary targets for this form of attack. Since 1919, there have been at least 26 conflicts worldwide where airfields have been attacked; these attacks were often made with rockets, ballistic missiles, and cruise missiles [11]. Until the advent of Global Positioning System (GPS), these missiles were sufficiently inaccurate, allowing all but the closest bases relative immunity to debilitating targeted attacks. While the ability to defend against missile attacks has become significantly better, as time has gone, the accuracy of Theater

Ballistic Missiles (TBM) and cruise missiles has increased dramatically. A report published by the nonprofit think tank RAND Corporation estimated that once the Circular Error Probable (CEP) reached 150m or less, total destruction of unprotected aircraft on a ramp would be easily accomplished [3]. CEP is the area around the point-of-aim where the missile is most likely to hit. Current missile technology allows for a CEP of 5m or less, far below the threshold established for air base destruction [11]. Since aircraft and airpower are far easier to destroy while still on the ground, the doctrine published by most nations, including the People's Republic of China and the Russian Federation, calls for missile strikes as the easiest way to disrupt air superiority in a region [11], [93]. As such, the United States (US) Department of Defense (DoD) considers missiles the most significant area-denial and anti-access threat [6]. Independent research has suggested that the threat to northeastern-NATO countries from Russian aggression is still significant, emphasizing the need for increasing cooperation and US assistance with preventing any further Russian expansion [94], [95]. The threat posed by China to allies in the Pacific are well documented, with extensive development of standoff missiles loaded with submunitions designed to destroy unprotected assets [8].

In 2017, the United States Air Force (USAF) published a report outlining its resilience principles for civil engineers. These principles are divided into three pillars: protection, response, and recovery [9]. Protection is the work done to minimize damage before the attack begins. Response is the effort that takes place once the attack has started and continues until the period immediately after attack. An action can be considered a response after the attack has concluded if completing it is necessary for the immediate safety of the base population or if completion is required before repairs to base assets can begin. This is especially important in the USAF, as civil engineers also control Chemical, Biological, Radiological, Nuclear (CBRN) response forces; Explosive Ordinance Disposal (EOD); and the base fire department. Ensuring these teams are working in sync with surveying teams and repair personnel, even as the attack is still underway, greatly shortens the time until mission effectiveness. Finally, recovery is the effort to repair damage after attack. The recovery period is generally the period most associated with the military engineer, as it is during this time that base assets and mission capability are restored to levels attained prior to the attack.

An Updated Model of Resilience

While the three-pillar model of resilience is an excellent look at how engineers broadly contribute to base missile defense, it does not consider the full joint capability of missile defense and is therefore incomplete. A recent report by J. Conner attempts to reconcile the role of an entire armed force in base defense with a more holistic approach. As shown in Fig. 1, this model considers three main tactics for defense: prevention, protection, and recovery, each with many defined areas of supporting doctrine [9]. This doctrine, unlike the one created by the USAF, focuses on layers of

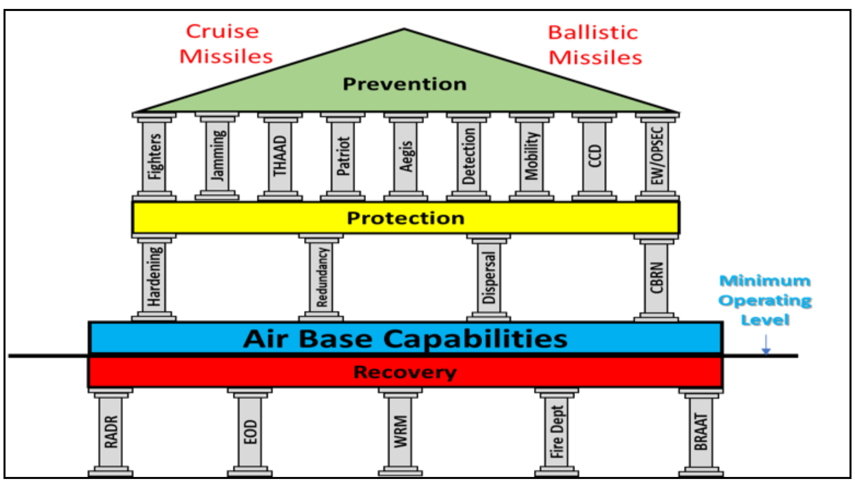

Figure 1: Holistic Missile Defense Model [9]

defense as a factor of mission effectiveness, rather than time. In this model, engineers have far more descriptive roles. When utilizing the prevention tactic, engineers are essential to camouflage, concealment, and deception (CCD) efforts and mobility. CCD tactics are both more significant and more elaborate in the age of satellites and high-quality surveillance images. Due to the rise in these technologies, it is safe to assume that no amount of distance between a base and its enemy protects it from observation. As missiles become more accurate, the targets being chosen by enemy combatants become more important. This stems from the trend of submunitions and other modern warheads relying on a correct target location rather than large yield to destroy their targets. Providing decoy targets and obscuring the correct targets could be the difference between no loss of operational capability and significant reduction of mission generation. Base mobility is also a primary concern of engineers, as the type of base layout and materials will be determined by engineers in coordination with base leaders. These choices can have an impact on the ability of the base to relocate as needed, especially in a forward operating environment.

Military engineer efforts reach their peak in the protection sector. Hardening is currently the preferred method of aircraft protection, though it is not without its difficulties. Making a hardened shelter for large aircraft, such as refueling tankers, is both difficult and prohibitively expensive in most scenarios, resulting in alternative solutions, such as keeping them outside of range of probable attack [1]. Hardened aircraft shelters also are very large and obvious targets, and peer states such as China and the Russian Federation have weapons capable of penetrating significant thicknesses of reinforced concrete.

Redundancy is another key aspect of base design. When possible, ensuring that the airfield has multiple runways, taxiways, and aprons is essential to minimize the effect of enemy attack.

This protective effort can be compounded by the creation of redundant fuel and maintenance facilities across base. Dispersal is a tactic that has been used as early as WW2, when the Polish Air Force and the Luftwaffe both dispersed their aircraft to minimize attack damage and maximize limited resources available for use [11]. This concept on a smaller scale ensures that base assets cannot be eliminated with a single strike and helps to render pre-attack reconnaissance useless, as complete dispersal is often only completed once warning of attack is given. True dispersal of assets over many airfields has its challenges, however, as modern aircraft have significant maintenance and runway requirements that limit the available airfields [2]. The preparation of a base against CBRN attacks is essential and part of a base engineer’s purview but is outside of the scope of this paper.

Recovery is the only sector of J. Conner’s defense doctrine that occurs below Minimum Operating Level (MOL). MOL is the minimum state of mission generation that leadership has defined to be acceptable and varies depending on the mission conducted at that base. Once recovery efforts begin, the attempts to prevent an effective strike have failed, and efforts must be shifted to restoration of a mission generation, either to enable retaliation and further defense, or to enable evacuation of the base.

The new doctrine provided by both J. Conner and the USAF both provide a groundwork resilience of a military base, but neither provide prescriptive methods by which a base may be made more resilient. Despite the significant contributions of the aforementioned research studies, there is no reported research that focused on optimizing the selection of physical infrastructure and passive defense capabilities to minimize the impact of anti-access/area denial weapons on mission generation

Analysis of Current Resilience Techniques

Hardening, while expensive, is currently the most effective method of asset protection on a military base. While techniques have existed since the Persian Gulf War to destroy aircraft protected in hardened facilities, all current methods to do so require Laser-Guided Bombs (LGB) and are not currently optimized for conveyance on a missile or rocket platform [2], [96]. Since base defense from aircraft is significantly more effective than current ballistic missile defense, most bases protected by NATO anti-air defenses can be considered to be comparatively safe from the effects of concrete-piercing LGB attacks.

Asset protection using concrete is not the only method of hardening. While ineffective at defending against a direct hit by unitary warhead or cluster munition attacks, earthen berms or other reinforced earth structures are effective at shielding from blast pressure. They are both cost effective and can be constructed rapidly, and acquisition of materials does not require outside contracts, so long as there is sufficient area to excavate fill on base.

Dispersal is an area that has been given considerably more attention in recent research [97]. Dispersal is the simplest method to create resilience in a military base layout, as most missiles have a relatively small area of effect, even with the rise of submunitions [2]. Despite this simplicity, many base infrastructure assets, such as fuel depots, are centralized for efficiency and are unhardened, making them an easy target for submunition-based attacks [6].

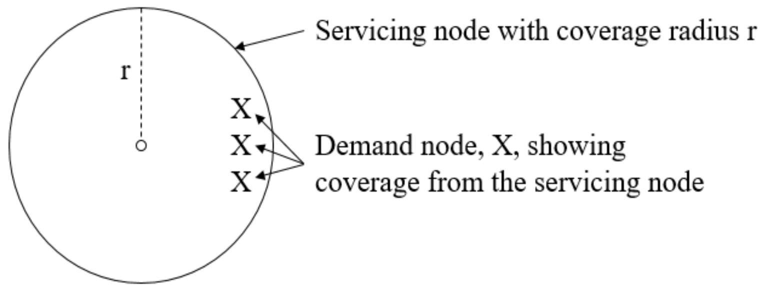

Figure 2: A Servicing Node Providing Coverage for 3 Demand Nodes [85]

As seen in Fig. 2, dispersal is traditionally modeled as a field of "demand nodes" that need a resource provided by a "service node" of some range in a radius. This subject has been studied at great length as a way to optimize industrial activity, with work beginning on it as early as 1909 and continuing to present day [85], [98], [99].

Dispersal can be of some value to air base defense, especially when hardened asset shelters are not available. When applied to fuel, however, it can be extremely costly at established bases, and is best used at smaller bases where resources are more easily relocated. Some dispersal at all bases is essential, but extended dispersal is either a component of the base planning phase or a feature of small, poorly hardened forward bases.

While not considered in this report, dispersal can also be considered from a macro scale, with assets being spread across a wide theater of operations. With current generation military assets having high levels of maintenance and stringent basing requirements, this is difficult [1]. Dynamic models of dispersal may be possible where units are moved from a base with low maintenance ability to bases with an established infrastructure as needed could be a subject of future research.

Redundancy is one of the techniques best able to secure use of area-based assets, such as airfields and fuel depots. Redundancy refers to the construction of distinct base assets that perform the same function and are completely independent in operation. Traditional airfield defense relied on active measures such as interception, and great progress has been made in active interception techniques. Despite these active defenses, it is safe to assume that airfields and fuel stores will be hit in the event of an attack. While specifics of active missile defenses remain classified, reports have stated that as few as 20 missiles fired in short interval at a relatively small target area, such as air bases on the Korean peninsula, could overwhelm current-generation fire control radar on ballistic missile defense systems such as the Terminal High Altitude Area Defense (THAAD) system used by the United States and her allies [2].

Redundancy is often coupled with dispersal, but dispersal is not required. While often expensive, the construction of redundant airfield components and fuel depots is often far less expensive than hardened defenses, and it is impossible to harden some large-area assets, such as an airfield, from attack. By having multiple taxiways and runways, it is possible to increase the chance that a Minimum Operating Strip (MOS) is available to generate sorties immediately, without time-consuming repairs. When coupled with dispersal, redundant fuel systems help mitigate losses of fuel due to attack damage and ensure the fuel system will function, even if one delivery system is damaged beyond repair.

While engineers often focus on solely the construction and maintenance of base assets during a conflict, logistics factors heavily in the feasibility of some methods to improve base resilience. While the impact of a base’s location relative to the home nation depends heavily on the nation’s logistic and industrial capacity, there are some universal considerations worthy of discussion. These issues can be divided into the number of fronts, the type of transportation needed, and the duration of the conflict [100].

The number of fronts in a conflict can drive the ability of an engineer to access resources, with an increase in the number of fronts inevitably driving a decrease in the overall resilience at each base, especially during base buildup. Rapid reinforcement of the base at the eve of a conflict requires significant logistic involvement that reduces the ability of an armed force to mobilize other assets [101].

Transportation types will vary by conflict location and strengths of the country’s logistical support. Many assets needed by the military engineer are too heavy for frequent airlift [102]. This leaves transport by sea, rail, or truck. Sea and rail are ideal for transportation of large quantities of needed construction materials to build redundant assets or harden a structure. The downside to sea and rail is that they are restricted to travel to and from distinct locations, and final transportation by truck is often required. They are also vulnerable to attack while in transit, though both can be protected. Sea travel is also often quite slow, with supplies often taking weeks, rather than days, to arrive. If rapid repairs are needed during a conflict, or hardening is needed in the buildup to a conflict, supplies that take a week or more to arrive may be too late [103]. Trucks are often quicker, provided the material is relatively close by, but trucks can be easily disabled by enemy combat or area denial tactics.

The duration of a conflict may have a significant role on the overall resilience of a base. Any modification made to a base will require periodic resupply materials, especially resource-intensive modifications such as hardening and CCD. The degree to which this affects overall resilience depends on the frequency and severity of damage sustained, as well as the overall availability of local resources and the amount of logistic support available to the base throughout the conflict if imported materials are needed.

All of the techniques discussed previously primarily focus on improving the resilience of bases that have already been constructed. For bases that are still in planning phases, or bases that are not built but are planned to be rapidly built in case of a new conflict, a more comprehensive approach is needed. Current approaches to base construction are primarily focused on three main tenets: mission accomplishment, safety, and quality of life. While guidance exists on base planning in a wartime environment, it offers few suggestions on actual layout, and primarily consists of committee member recommendations and site survey data [104]. Research has been completed on the layout of small installations based on other factors such as external attack, or civilian airfields not subject to indirect fire attack, but none have considered medium size bases with an airfield in a denial environment [105]–[108]. Layout optimization considers all of the tenets of resilience discussed above and produces the most effective base available given available funds or construction dollars. Nature-inspired metaheuristic algorithms, including genetic algorithms, ant colony optimization, and particle swarm optimization have been developed in the civilian sector for planning of industrial facilities that would be highly effective for defense planning, if adapted appropriately [109], [110].

Only two known groups of models have been developed for military base resilience. The Theater Air Base Vulnerability Assessment Model (TAB-VAM) was created by RAND for USAF Pacific Air Forces (PACAF) to enable advanced modeling of enemy attack. The model also considers how allocation of resources could alter sortie generation [87]. This Monte-Carlo simulation model is extensive, with dozens of input variables grouped into four main files, and a complete output of base condition after attack, as shown in Fig. 3. While a complementary RAND model utilizing metaheuristics was created, it does not consider effects of individual bases, and is intended to interface with the TAB-VAM model to produce data on base-level resilience effects [87]. This model, known as Theater Air Base Resiliency Optimization Model (TAB-ROM), was created to provide expanded planning support for theater doctrine staff, enabling increased consideration of multiple outcomes of the TAB-VAM model.

While this simulation is effective at generating the probable result of attack and recovery, it is not an optimization model and does not suggest how the result may be best improved. This results in a labor-intense iterative process to determine the best possible outcome. The simulation does not model cost; therefore, additional software must be used to determine cost of improvements made to a base model during the simulation [87]. Both TAB-VAM and TAB-ROM are proprietary models developed for a specific theater of operations by the USAF and are therefore unavailable to NATO allies or other theaters of operations. They are also primarily focused on established bases with fixed asset locations, not considering the possibility of dispersal or other resilience techniques. As theater models, they do not consider the scale of operations that a military engineer is traditionally focused on, with individual changes at a single base. As such, they do not meet the needs of a modern military engineer to plan for resilience against missile attacks. In their analysis, RAND partially solved these issues by incorporating one other program to simulate cost and provide optimization support, but this stop-gap measure is dependent on sufficient support and time for analysts to move the outputs of the TAB-VAM model into this software package.

Integration of these programs or a new program that combines optimization and cost with the Monte-Carlo simulation is needed to provide the best possible result.

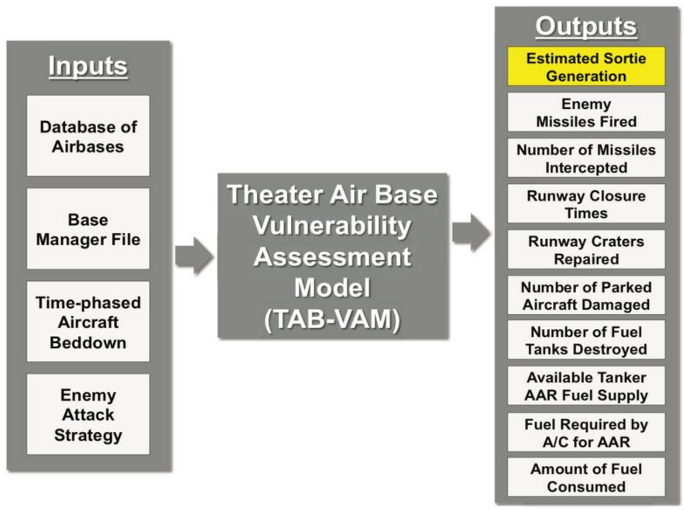

Figure 3: TAB-VAM Inputs and Outputs [87]

Another recently developed model is the Operational Resilience Analysis Model (ORAM). This model, also developed by RAND for the USAF, attempts to address some of the limitations in the previous models. The primary difference between this model and previous generations is the method of analysis. ORAM is a deliberate, iterative deterministic model, rather than a single run Monte-Carlo simulation as with the TAB-VAM or theater-level metaheuristic model like TAB-ROM. Variables considered for this model were: dispersal, distance from threat, hardening, increasing existing defenses or locations repair capability, and air defenses [1].

The advantages this model brings to a military engineer planning base defense are undeniable. Cost is considered, which is among the largest limiting factors in the modern, fiscally constrained environment. The model is not tied to any one nation, allowing for custom inputs for missile and aircraft details at the bases being considered, as well as for aggressor states. It places a heavy emphasis on fuel system attacks and targeted runway attacks using publicly available knowledge likely similar to the intelligence, surveillance, and reconnaissance (ISR) of the aggressor state, rather than random runway and parking apron attacks. Since the model runs in Microsoft Excel, it is easily run by anyone with a basic computer; no high-performance machines or specialized software is required.

While this model represents several advances in the simulation of base resilience during attack, there are several limiting factors to the construction of the model, as well as areas of future improvement. The model does not consider probabilities, as it deterministic, rather than heuristic. It does not automatically iterate to determine the best possible solution; multiple manual inputs are required. It also struggled to accurately represent existing base fuel supply. Like most models of this level, secondary effects like degradation of supply chain due to attack damage are not considered. As with the TAB-VAM model, optimization only considers existing established bases; the possibility of creating additional bases at the beginning of the conflict or as original bases are overcome is not considered. The model is independent of any land warfare that may occur simultaneously. Base evacuation may be necessary in many cases due to enemy forces pushing back defensive forces, so evacuation or other options for total base loss should be considered for future efforts.

Future Research

Genetic Algorithms (GA) have already been used to optimize small base design against outside explosive attack [111]. This technique is perhaps the best suited for the military engineer's role in base resilience and defense planning: consider many possible options and present a set of Pareto optimal solutions that represent nondominated tradeoffs between competing objectives and allow decision-makers to select a configuration base on available budget, acceptable risk level, or other factors. In addition, it allows for significantly quicker decision making, an essential consideration during a potential conflict. Any formulation of a GA for base defense would be heavily reliant on J. Conner's pillars of resilience. While an ideal model would consider all 18 pillars, many of these pillars remain comparatively static when considered over a short planning interval. Once an initial model is created, additional consideration for active defense could be added.

When optimizing a military installation to resist missile attacks and rapidly recover, three key objectives must be considered: (1) the improvements made to the base to reduce the impact of an attack; (2) the cost of any improvements, labor, and personnel required to maintain a higher level of resilience; and (3) Minimum Operating Level, which seeks to optimize the amount of personnel and equipment that is added to the standard base complement, as shown in Figure. 4. These objectives are quantified by several metrics that contribute to the impact on the base's ability to withstand attack.

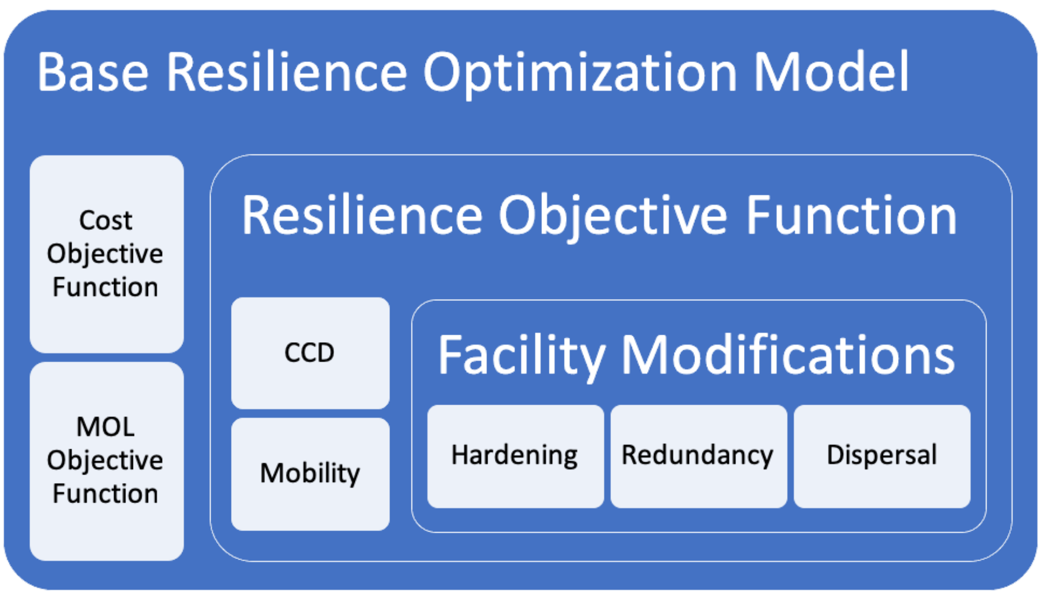

Figure 4: Proposed Genetic Algorithm Optimization Model

Resilience can be defined as a function of five metrics: hardening, dispersal, CCD, redundancy, and mobility. When considering hardening in an optimization model, three primary considerations emerge: the type of hardening used, the quantity used, and the type of asset it is being used on. When being added to an existing or temporary facility, hardening is generally only installed to the existing height of the facility. Comparisons across unlike buildings and hardening types, therefore, could use hardening effectiveness as the comparative metric. Percent destruction is calculated using a recently developed model for quantifying the blast effects on facilities behind blast walls [105]. Utilizing this model would allow for unique damage values for every configuration considered by the optimization equations.

Any consideration of dispersal of like assets across a base should utilize meters of separation between assets as a comparative unit. Type of dispersal being used could also be considered during optimization to determine which model of dispersal is most effective given available site and mission information.

During an analysis of redundancy, comparing numbers of duplicate structures by the type of structure would be an ideal method. While redundancy and dispersal are not connected directly, their use is complementary, and any model should consider their effectiveness raised when used in coordination.

CCD is a unique in this model due to the flexibility in its implementation. There are many possible options for concealing an asset or making a decoy. While further research into the science of modeling CCD is required, a factor that models percent chance of detection using conventional surveillance would be an ideal decision variable for cross-asset comparison of all types of CCD. This could be the most advantageous technique for many asset types.

Mobility is the most complex issue to be considered in a model of this type, as it has few benefits to the base being planned. Rather, the primary benefit of the mobility of base assets is to enable cost-effective and rapid movement of assets to a new location once a base has been compromised or is no longer serviceable. With that goal in mind, comparisons should be made by percent of facility or asset that is relocatable.

The equation governing resilience in the optimization algorithm will be a weighted sum of individual factors. Weights will be determined using utility curves, a technique well-established to promote a mathematically acceptable integration of human priority [112]. As shown in Equation 1, the Resilience Index (RI), a value ranging from 0 to 1, will be a factor of individual scores of the Hardness (H), Dispersal (D), Redundancy (R), CCD (C), and Mobility (M). A score of 1 would represent a base that has the optimal resilience level, with a score of 0 representing a base with no resilience at all. The sum of all weights assigned will be 1, as shown in Equation 2, and no weight will be negative, as seen in Equation 3. Weights will be assigned by decision makers for each base or combatant command and will reflect individual emphasis for the importance of each type of resilience activity in that theater and engagement. The use of importance weights provides leaders and planners with the ability to tailor the algorithm to meet the needs of their operation.

$$\max RI = w_1 \cdot H + w_2 \cdot D + w_3 \cdot R + w_4 \cdot C + w_5 \cdot M$$

Equation 1: Resilience Index Objective Function

$$\sum_{w=1}^{5} w_w = 1$$

Equation 2: Weight Constraints

$$w_w \geq 0$$

Equation 3: Nonnegativity of Weights

If resilience was not a concern, bases, like all industrial complexes, would simply be built in the most affordable method that met other existing performance requirements. This unadjusted minimum cost would be an ideal baseline to compare any added costs of defensive measures against. Considerations of cost should include cost of added resilience due to infrastructure modifications such as hardening and redundancy, CCD assets, cost of increased labor due to dispersal and other resilience efforts, and cost of staging personnel and equipment to accelerate repair after attack.

The equation to model cost, shown in Equation 4, is a sum of present-year dollars of Overall Cost (OC). This total is a function of the Resilience Cost (RC), or total cost of all activities associated with constructing increased physical resilience. Operating Costs (OC), the second term of the equation, reflects the increased cost of daily operation incurred by changes to increase resilience. Finally, the equation is also a function of Manpower Cost (MC), the cost of any additional manpower assigned to improve recovery rate.

$$\min \text{OC} = \text{RC} + \text{OC} + \text{MC}$$

Equation 4: Cost Objective Function

While some bases may be sufficiently protected that no single attack will limit mission capability, the current missile inventory of peer states limits the possibility of a truly immune base in the combat theater. If the enemy is successful in landing ordinance, the base’s operations will drop below the MOL, rendering the base temporarily out of action. It is at this time that human assets, such as EOD personnel and repair teams, will impact resilience as they return the base to operational status.

In order to model MOL in a way that is functional for both air and ground forces and is not dependent on a set of baseline values, personnel losses will be utilized as a surrogate. Personnel losses will be modeled by the ratio of personnel needed to those available and uninjured, as seen in Equation 5. The Recovery Rate (RR) takes the sum of the manpower ratio for all tasks from i=1 to I, where I is the total number of tasks for a given operation, and divides that by the total number of tasks to get an average manpower ratio. The number of personnel assigned to a task, P_h, is divided by the number of personnel needed, P_n, to obtain the manpower ratio. This equation will allow a planner to quickly see the effect of adding or removing personnel from an installation to balance the needs of the base with the needs of other bases across the theater.

$$\max RR = \frac{\sum_{i=1}^{I} \frac{p_h}{p_n}}{I}$$

Equation 5: Personnel Injury Objective Function

Conclusion

While the Cold War doctrine defensive doctrine currently used by many NATO engineers in planning cells is largely outdated, significant gains have been made in recent years in the pioneering of new models to try and create decision-making tools for war planners. The current focus on dispersal and permanent base design is limiting, however, and greater research is needed in how to create an optimization model for engineers to provide accurate timing and decision information to their commanding officers. The creation of a macro-level metaheuristic algorithm could provide the needed planning tool for military engineers, allowing for a detailed analysis of the best possible base given a set of limiting criteria.

IV. Scholarly Article 2: Optimizing the Dispersal of Aviation and Fuel Assets to Minimize the Effects of Ballistic Missile Attack

Ryley RH. Paquette, Noah W. Garfinkle, Steven J. Schuldt

Abstract

The US has long enjoyed a period of air dominance, with total air superiority as early as post-Vietnam. During its fight against counterinsurgency, this air superiority has remained. With a shift in concern from counterinsurgency to peer and near-peer conflict, the reality of continued air superiority and immunity to airbase attack can no long be relied upon. Dispersal is one of several techniques identified by research as a method to help limit the impact of attack on bases, especially attack by ballistic missiles and other high-risk vectors. This paper presents the development and testing of a novel base planning model capable of directly quantifying missile attack consequences and generating optimal dispersal plans for aviation and fuel assets. This model is be implemented using a multi-objective genetic algorithm to identify solutions that provide optimal tradeoffs between the competing objectives of minimizing attack consequences, and minimizing mission impact during a standard operations tempo pre-attack. These capabilities are expected to assist military engineers and base planners in their creation of a base layout that provides the correct level of resilience in a contested environment.

Introduction

Most critical military installations utilized by the United States were sited and designed before the era of ballistic missiles [113]. These bases were laid out with productivity as a primary motivation. This design choice stemmed from the current level of US air superiority and the nature of pre-ballistic missile attacks of air bases [11], [114]. The creation of long-range guided missiles changed that dynamic. The majority of bases in the Pacific and European theaters are within range of Theater Ballistic Missiles (TBMs) [6], [115], [116]. While traditional ballistic missiles were intended to carry unitary warheads, the Chinese pioneered a new strategy of anti-access/area denial (A2/AD) following its observation of the first Gulf War in 1990-1991 [6]. A2/AD is a technique focused on ensuring that assets cannot be utilized due to issues with logistics or support, rather than by outright destruction. A single missile might contain dozens or even hundreds of munitions, each small, only slightly larger than a hand grenade [117]. While each munition is unlikely to inflict a significant amount of damage and failure rates of cluster munitions are high, modern aircraft, fuel storage, and other military systems are vulnerable to even small impacts, and most aircraft cannot take off if even small pieces of runway have been removed.

Due to this failure rate, there have been significant efforts to ban cluster munitions, but no major power is willing to agree to discontinue their use. However, they are not used in regular peacekeeping operations [117]. While conventional hardening is an effective way to protect against such small-yield explosives, hardening of large assets such as an airfield or fuel depot is often prohibitively costly, either in time or resources. Chinese strategic aims, in particular, favor this A2/AD technique, as their goal is not to win a fight with the US, but rather to remove them from what they perceive as their own protectorate, similar to the Monroe Doctrine in the United States [6], [118]. Their immediate goal in any conflict involving the United States is to make a foothold in the Pacific Theater untenable. In response to this position and strategy, the United States is slowly changing its own Pacific Strategy. What has not changed rapidly enough, however, is the techniques for defense against A2/AD attacks [1], [9].

A base can use active and passive defensive measures to protect against to defend ballistic missile attack. Active defense is a direct action that attempts to prevent a missile targeting an asset from achieving its goal. Active defense is essential for base resilience, but relies on technology developed in advance and is outside of the realm of control for base planners. This is contrasted by passive defense, which attempts to mitigate the damage caused by a missile reaching its targeted location [3], [9], [11]. Excellent efforts have been made in the area of active missile defense, but the ability to create a passive defense effective against A2/AD ballistic missile attacks is still fairly nebulous [9], [119]. The United States Air Force (USAF) has outlined a strategic framework for base defense against ballistic missiles, emphasizing the need for improvements to passive defense [9].

The four key areas of passive defense are hardening, concealment/camouflage/deception (CCD), redundancy, and dispersal [9]. Hardening is an effective technique for resistance to both A2/AD attacks and point attacks, and can be done in a range of times from expedient hardening with indigenous materials to dedicated structures made with concrete [3], [11], [120], [121]. Hardening is not convenient or feasible for large structures due to the high cost per unit area and the need for ready access to facilities. Examples of structures for which opportunities for hardening are limited hardening are airfields, fuel depots in certain facilities, and some hangars for large aircraft. CCD is an excellent tactic to complicate enemy targeting and has a rich history dating back to ancient times [122]–[124]. It is more difficult in the age of satellite reconnaissance, but can still be used to limit the damage to actual targets by drawing potential targeting away from genuine assets. CCD should be considered for all air base operations in a permanent environment but is difficult to assess in a model of the modern world without actual wartime experience with a first-tier power in the 21st century. Redundancy is another excellent technique, although the purpose of redundancy pivots away from minimizing damage to existing assets and instead accepts the inevitability of a successful strike and attempts to minimize the total impact of the attack by having more throughput than needed [125], [126]. Redundancy, while the ultimate solution for enabling operations to continue unimpeded in a contested state, is a significant strain on the limited industrial capacity, a key limitation in wartime [12], [127]. This makes redundancy one of the most expensive ways to passively defend against attack.

Dispersal is the final passive defense option. It is uniquely suited to defending against A2/AD attacks, as it limits the compounding effects of a cluster munition. Dispersal can be counter-productive, as it has the potential to impede day-to-day operations due to increased time traveling between assets or moving assets to their designated location [2], [13]. Dispersal can occur at a base scale or theater scale, but base-scale dispersal is the sole consideration of this paper. Dispersal is ineffective for assets that require specific standoffs or are over a certain size, as the land must be available for their dispersal. Fuel depots are a primary candidate for dispersal, as they are difficult to harden in many scenarios, easy to find, and vulnerable to attack. Disruption of a fuel depot through a leak or fire would completely halt operations of any type at any military installation worldwide. Aircraft, especially light aircraft such as fighters, are another ideal candidate for dispersal, especially at expeditionary bases where hardened aircraft shelters are not available or feasible to construct. While dispersal does little to confound enemy attack, it successfully minimizes damage in a scenario where the enemy possesses limited missiles or is only willing to allocate a limited number of missiles, as it effectively reduces or eliminates "collateral damage" of cluster munitions striking one asset while targeting another asset or a centroid of assets. Dispersal is a technique with a non-infinite solution due to the limiting factors discussed above, and is an ideal candidate for optimization techniques to discover the ideal dispersal at any given installation to strike a balance between productivity and resilience.

Several efforts have been conducted to create models of base layouts and their impact on defensibility and theater combat effectiveness. The two key models created to date have both been by corporate think-tanks at the behest of the US Air Force. The first was the Theater Air Base Vulnerability Assessment Model (TAB-VAM), designed to assess the defensibility and combat strength of bases depending on the base layouts and attacks [87]. TAB-VAM utilizes Monte Carlo simulation to attack a given base a number of times using different techniques and determines the state of the base post-attack. It also allows a limited amount of iterative work, allowing a simulation of base counterattack and stepping forward to a further simulation given base parameters after initial attack [87]. This model does not, however, optimize base layout or defense, and is merely intended to provide war planners with a report on that state of base defenses against varying types and levels of attack.

In order to address some of the limitations of the TAB-VAM model, an additional model known as the Theater Air Base Resiliency Optimization Model (TAB-ROM) [87] was created. This model was designed to interface with TAB-VAM and provide an automated approach to changing base layout and defense features to allow a better simulation of the efficacy of various attack strategies and defense capabilities for theater planners. This was an excellent advancement, and greatly improves the usefulness of the TAB-ROM model for estimating defensibility of a theater, but some limitations can be seen in its use for planning of a single base layout [87]. Additionally, due to its stated purpose as a plugin to TAB-VAM, it does not provide optimal layout based on simulated attack without a theater-assessment from TAB-VAM. The model also is primarily designed for a total force attack from aviation and missile assets. This presents the opportunity for the development of an academically developed model designed to optimize base layout to improve resilience from ballistic missile attacks.

Objective

The objective of this paper is to present the development of a multi-objective model for optimizing the layout of airfield and fuel assets in order to maximize the resistance to sustained cluster munition barrage of a military installation while minimizing the impact of the layout during daily operations. This model is intended to equip civil engineers and war planners with a tool to enhance base resilience, especially in areas at high risk of missile attack such as the Pacific theater. The model is developed in three main stages: (1) formulation stage, which defines applicable decision variables, creates objective functions, and identifies practical model constraints; (2) implementation stage, which performs the optimization calculations using multi-objective genetic algorithm (MOGA); and (3) performance evaluation stage, which analyzes an example to assess and improve model performance. The following sections describe the three developmental stages of the present model.

Model Formation

This phase of development presents the formulation of a novel multi-objective optimization function for optimizing the location of aviation and fuel assets for military installations. This phase is accomplished in three steps: (1) defining the model decision variables, (2) formulating the daily sortie generation impact and attack resilience objective functions, and (3) identifying all practical model constraints.

Decision Variables

The decision variables of the presented optimization model are created in such a way as to represent the feasible choices a base commander or war planner would have when siting aircraft parking and fuel depot locations. The model's decision variables are x_i and y_i, representing the Euclidean positions for each aircraft and fuel asset on the base. These coordinates represent the centroid of each object, allowing for more computationally efficient modeling techniques. In an algorithm considering only locational data, this simple approach to decision variables allows for a more efficient approach to optimization of this geographic and routing problem.

Objective Functions

The present model is designed to accomplish two primary objectives: (1) minimize the impact of resilience efforts on daily operations, and (2) maximize attack resistance.

Minimizing Sortie Generation Time

As previously discussed, any effort to enhance base resilience to attack will result in adverse impacts on the efficiency of daily operations. In the case of aircraft at an airfield, increasing dispersion will impact almost every aspect of its time on the ground. The proposed model focuses on the following key aspects: (1) aircraft maintenance time, (2) refueling time, and (3) rearming time, as seen in Figure 5.

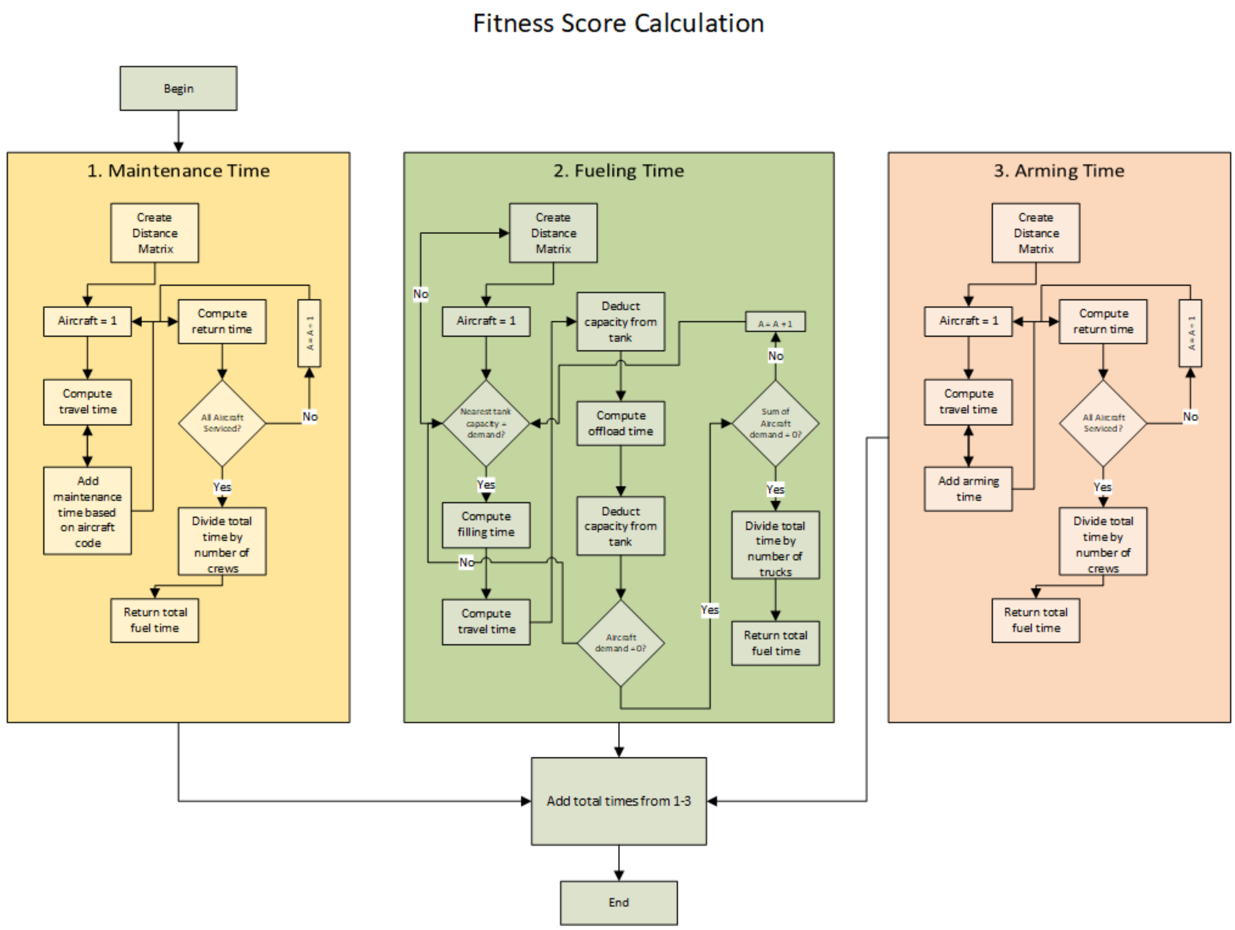

Figure 5: Sortie Time Generation Calculation

Maintenance

Aircraft maintenance time in the Department of Defense is based on a code system, which indicates the level of maintenance required based on an airframe self-diagnostic system. The codes run from one to three, with one being the lowest level of maintenance required and three being the highest. This does not represent corrective maintenance, which is difficult to predict without utilizing sensitive information and not considered for this model. The model assigns a random code value to each aircraft in a generation, and the time to perform maintenance is calculated by the Manhattan distance between a centrally located personnel staging area ($t_{tr,m}$) and the aircraft parking location plus the time for whatever code the aircraft has assigned (t_{code}). The total time is divided by the number of crews to get effective maintenance time (t_m). Equation 6 shows the formula utilized to calculate total maintenance time.

$$t_m = \frac{\sum_{i=1}^{n_a}\{2 * t_{tr,m} + t_{code}\}}{n_{c,m}}$$

Equation 6: Maintenance Time Calculation

Refueling

Refueling requirements and times for aircraft contain significant uncertainty when modeling. Because of this, the algorithm to model it represents one of the greatest computational requirements for the model. Bladders are assumed to be the standard bladders currently in use Air Force wide, which range in volume from 10,000 to 200,000-gallon fuel bladders common in current operations in Southwest Asia [128]. Bladder locations are assigned randomly, and then the model determines the distance from each bladder to all of the aircraft. The model attempts to fuel each aircraft from the closest bladder sequentially. If the remaining capacity in the closest bladder is insufficient for a complete fill, the model drains that tank, then recalculates the distance matrix and goes to the next closest bladder. The sum of the time required for all the airframes ($t_{f,i}$) is recorded and then divided by the total number of vehicles available ($n_{c,f}$) to calculate refueling time (t_f), as seen in Equation 7.

$$t_f = \frac{\sum_{i=1}^{n_a} t_{f,i}}{n_{c,f}}$$

Equation 7: Fueling Time Calculation

Arming

Rearming an aircraft is assumed to take place in a similar manner to maintenance, where personnel and munitions original from a specific location and the Manhattan distance between that point and each aircraft is calculated. An estimated average rearming time for the aircraft and mission being considered is utilized for the computation of arming time. The sum of the arming times for each aircraft ($t_{a,i}$) is computed and divided by the total number of arming crews ($n_{c,a}$) to quantify the total arming time (t_a) as seen in Equation 8.

$$t_a = \frac{\sum_{i=1}^{n_a} t_{a,i}}{n_{c,a}}$$

Equation 8: Arming Time Calculation

Maximizing Attack Resistance

Minimizing the impact of dispersion on daily operations tempo is futile if the dispersion does not provide measurable improvements in resisting attack. The current attack phase in the model assumes no successful CCD, with the adversary possessing accurate surveillance knowledge of the location of all dispersed assets. Each missile available to the adversary is assigned to one such asset at random. Once targeted, the algorithm shifts the actual burst location from the original targeting point to a random point near the targeted location to account for circular error probable (C_{ep}), the inherent inaccuracy of the given delivery platform [129]. Since the model is optimizing against air burst cluster munitions, it then scatters the cluster munitions randomly within a specified normal distribution of the burst location. Since launch azimuth is not known, assuming a circular, normally distributed landing pattern is the most conservative, as it represents the likely landing location for all of the azimuths combined. These cluster munitions have a Net Explosive Weight (NEW) of only 0.5-2 pounds of TNT, meaning that their blast effect radius is almost zero for anti-materiel purposes. Consequently, the model checks if each of the cluster munition points is within any of the aircraft or fuel assets and marks them if they are hit. The score is calculated by multiplying the number of hits by a predetermined alpha coefficient and dividing by the total number of cluster munitions directed at the assets. This alpha allows decision-makers to express their preferred level of risk aversion and brings the resulting value into a range that is more easily compared mentally. A shift of 0.1 in alpha represents the willingness of a commander to accept a 1-hour delay in sortie generation.

Model Constraints

The primary constraints of this model are geophysical in nature. Bounding variables restrict the placement of fuel and aircraft assets to within the bounds of the available depot and apron space, respectively. These constraints are limited to minimums and maximums for x and y coordinates in the current model. All aircraft and fuel assets must be placed such that their centroid falls within the minimum-maximum constraints. Due to the use of a centroid, the minimums and maximums should not be taken to mean the exact boundary of available spaces, but rather the bound of available centroid locations. In calculating the bounding box of the apron and fuel depot, a buffer is applied to the actual perimeter equal to the radius of the fuel bladders (r_{f1} and r_{f2}) and aircraft (r_a) as appropriate. While these constraints are applied to the locations of the fuel and aircraft assets, they are not applied to the attack section of the model. In order to maximize realism, submunitions from the missiles can exit the apron and depot areas, based on the missile's C_{ep} and the spread of the munitions once they leave the missile. All submunitions must land inside the area of the circle described by the spread. C_{ep} does not guarantee a burst within the radius; it is defined as the area in which 60% of the bursts occur. The Model current currently evenly allocates missiles between the fuel depot and apron, but more flexible targeting algorithms could be applied in subsequent simulations. The current layout and targeting algorithm is illustrated in Figure 6.

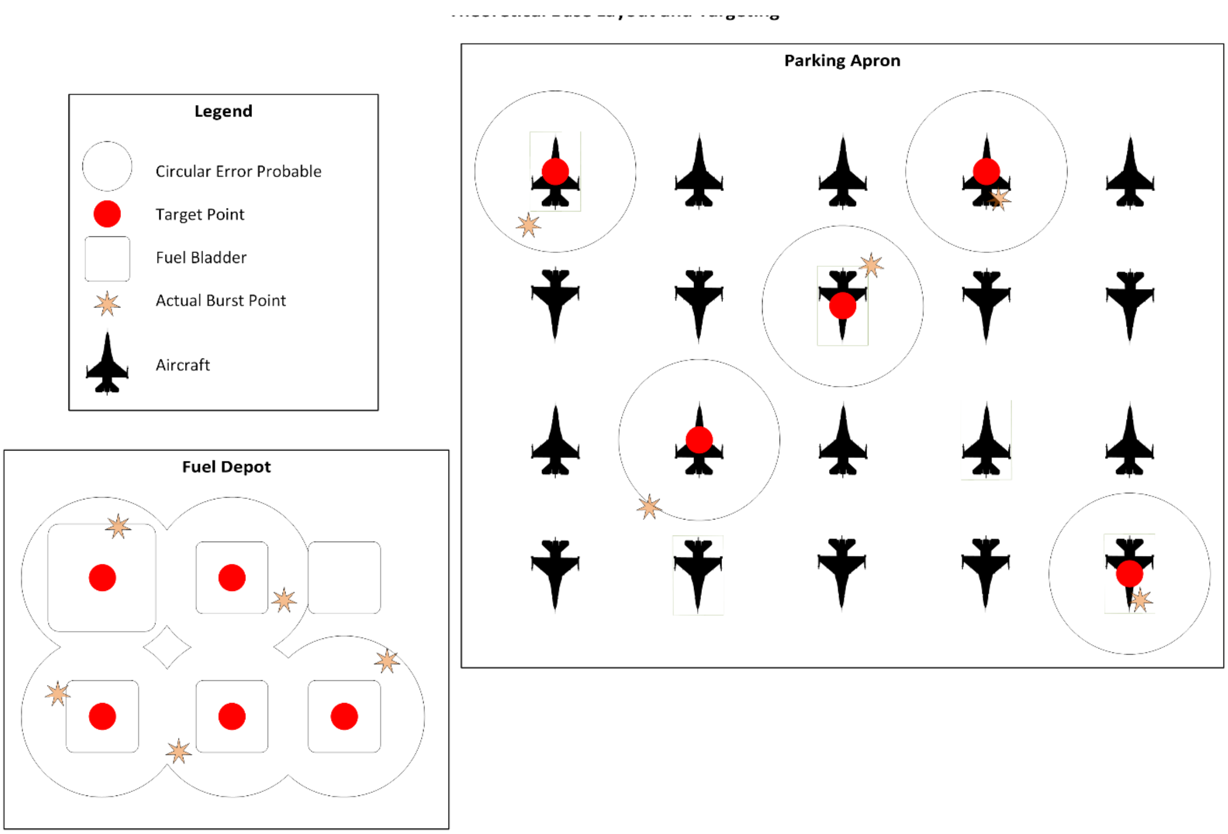

Figure 6: Theoretical Base Layout and Targeting

Model Implementation

While a variety of possible nature-inspired metaheuristic algorithms were tested, a multi-objective genetic algorithm (MOGA) was chosen to provide the greatest flexibility and ease of use. MOGAs have several strengths that lend themselves to this sort of problem: (1) a history of success modeling layouts problems [63], [105], [106], [111], [112], (2) the speed of convergence to an optimal solution on a variety of computing platforms, and (3) the ability of the MOGA to encompass the stochastic nature of a problem with multiple simulations of human behavior [63]. The present model was implemented and executed using a genetic algorithm developed specifically for R [130]. The model was implemented in five main phases: (1) data input, (2) initialization, (3) optimization, (4) Monte Carlo simulation, and (5) visualization and interpretation of the results, as shown in Figure 7.

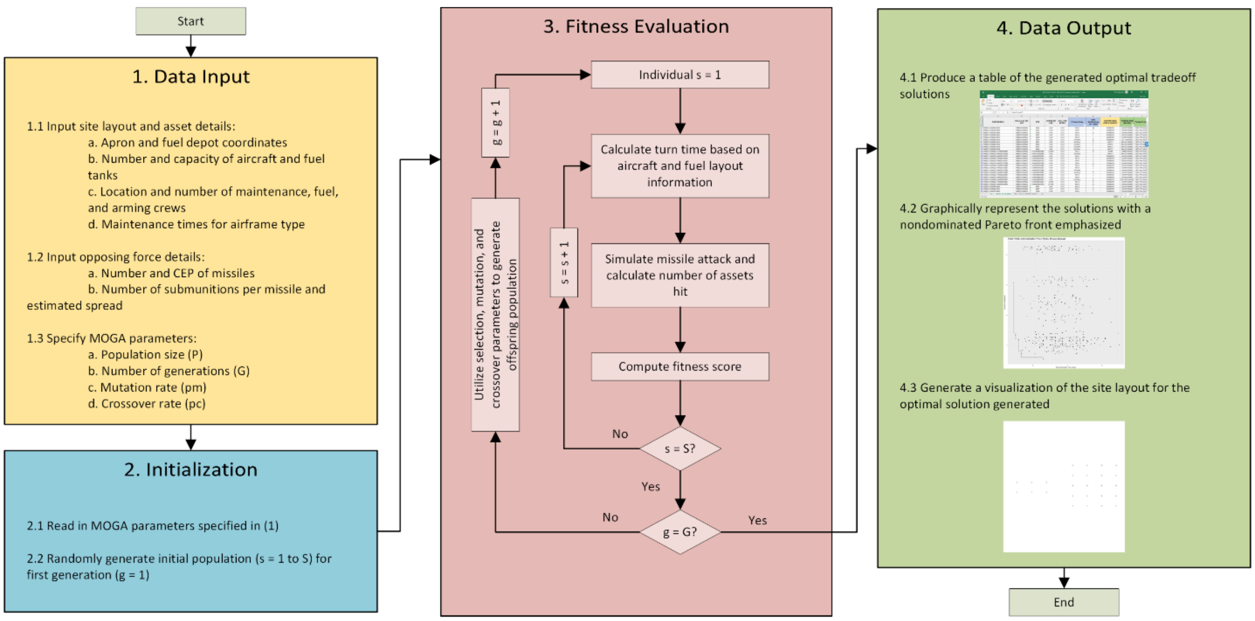

Figure 7: MOGA Implementation Stages

In order to accurately model the dispersal of assets, the first phase of implementation requires the input of 40 variables, broadly categorized as (1) asset performance characteristics, (2) base characteristics, (3) layout characteristics, and (4) attack characteristics. Many of these variables will remain constant for any given theater, reducing the number of variables required to be changed. Asset performance characteristics give information about the assets being considered. Once this initial set of data has been input, the parameters of the MOGA must be input. These include the mutation rate (p_m), the crossover rate (p_c), the population size (P), and the number of generations (G).

An objective function that utilized variables for rectilinear grids formation without directly varying the location of individual assets was developed for computational efficiency. For this system, the starting coordinates for the first row are varied, along with the number of assets per row. The algorithm then seeks to maximize the distance between the aircraft and rows given the amount of space available on the apron. This system drastically reduced the solution space while still providing functionally equivalent flexibility for the optimization model to vary the populations.

Variables that are considered by the user but not directly manipulated by the model are the number of aircraft (N_a), their fuel demand (F_a), and the number and capacity of fuel tanks (N_{fi} and T_{si}, respectively). In addition, bounding variables are predefined based on hypothetical or actual base layouts. These variables, noted as $x_{min,f}$, $x_{max,f}$, $y_{min,f}$, $y_{max,f}$, $x_{min,a}$, $x_{max,a}$, $y_{min,a}$, and $y_{max,a}$, can be representative of Euclidean or latitude/longitude coordinates. By default, the coordinates are Euclidean and represent distance in meters. The desired projection is the final input for location data and can represent any projection commonly available, with the default set to WGS84 Web Mercator (Auxiliary Sphere) (EPSG: 3857). Selection of proper coordinate system for the area under study is available to the user, based upon the location under consideration and any geospatial data utilized.

Other variables needed for the functioning of the model that are not actively manipulated by the optimization algorithm but remain essential to accurate modeling are: capacity and average speed of fuel trucks, number of trucks available for fueling, number of trucks available for arming, number of hours required to perform maintenance on a jet relative to its level of disrepair, location of the maintenance facility, location of the munitions yard, time required to arm the aircraft, speed of the munitions truck, number of missiles targeting the base, circular error probable of the missile, cluster munition spread, and number of cluster munitions per missile.

The initialization phase involves loading the variables and parameters above into the model, creating scorekeeping datasets and metrics, loading gridding functions, and initiating the genetic algorithm. The initial population for the model is randomly generated by the GA, although future work could consider variants of standard designs as an initial seed population

Once optimization has begun, the basic steps of model calculation are followed: (1) A layout is created by the algorithm based on the decision variables, (2) times for all the required steps to turn the aircraft are calculated, (3) attack sites are chosen, (4) an attack is initiated, (5) the damage is calculated, and (6) the fitness score is calculated based on times and damage. These steps are repeated across the population's generation (g), then crossover, mutation, and elitism factors are considered, and a new generation is created (g=g+1). These is repeated until the desired number of generations is reached (g=G).

Once a candidate solution is selected by the algorithm, the decision variable values of the optimal solution are assessed via a Monte Carlo simulation. This operation provides a sensitivity analysis of the optimal solution, as it is possible for a solution to be optimal due more to the stochastic nature of simulating a missile attack resulting in an overly generous score. The analysis is conducted by running the targeting and scoring section of the model a number of times (n_{runs}) with the parameters provided by the ideal solution. The results from these runs are analyzed using a histogram to ensure that the result does not exhibit an undesirable amount of sensitivity to the accuracy variability in the attack model. If a solution is deemed to have been chosen due to favorable attack characteristics rather than actual resilience, the MOGA is restarted.

The final step is to visualize and interpret the results. The performance of the MOGA is plotted and analyzed by score across generations to see the trends of the mean, median, and best scores. The physical layout of the airfield and fuel depot is constructed and visualized, with radii around each centroid to show approximate aircraft size and position. A Pareto Frontier is plotted to show the tradeoffs between resilience and daily sortie generation rate, allowing a senior leader to see the tradeoffs with each desired level of resilience or operations tempo. Finally, the parameters for the optimal solutions are exported as a table for further analysis. These visualizations of the model are analyzed and prepared for presentation to planners and decision-makers.

Performance Evaluation

This stage analyzes an application example to evaluate the performance of the model and demonstrate its distinctive capabilities in optimizing the dispersal of fuel and aviation assets at an airbase to protect against A2/AD attacks from ballistic missiles. The application example represents a military airfield in a forward location. Such locations are often commercial runways that are available for military use in a pre-arranged agreement when conflict arises. As such, substantially more space is available for fuel and parking than is required for the typical amount of deployed assets, providing room for assets to be dispersed. Due to these considerations, the example airfield is assumed to be (1) in an area outside of the United States but in a sufficiently developed area as to possess a commercial airfield, (2) an abandoned or otherwise cleared commercial airfield with 2000m by 1000m large apron and 1000m by 1000m fuel yard that can accommodate a wide variety of parking and fueling options, and (3) no HAS or other aircraft protection systems are available, and parking is not otherwise constrained.

The application example requires the siting of 20 F-16 fighter aircraft and 6 fuel bladders, with an analysis of the siting location impact on maintenance, refueling, and rearming times as well as damage resistance to an attack from 10 theater ballistic missiles, each with 100 bomblets. This application example utilizes five 10,000-gallon bladders and one 50,000-gallon bladder. In order to perform the optimization of the base layout, planners need to specify the number and capacity of refueling vehicles, their offload rate, a reasonable average speed given the vehicle and expected conditions, the number of maintenance crews, number of rearming vehicles and crews, and the expected turn time for each jet code level based on the maintenance facilities available. The values used for this assessment were based on best practice, unclassified data, or publicly available values and should be considered of test value only. A summary of applicable parameters can be seen in Table 1.

Table 1: Application Example Parameters

Parameter	Value	Units	Parameter	Value	Units
Fuel Tank Radius, 10k Gal	10	Meters	**Min X, Depot**	0	Meters
Fuel Tank Radius, 50k Gal	20	Meters	**Min Y, Depot**	0	Meters
Aircraft Radius, F16	15	Meters	**Max X, Depot**	1000	Meters
Fuel Load, F16	2500	US Gallons	**Max Y, Depot**	1000	Meters
Tank Capacity 1	10000	US Gallons	**Time to Ready, Code 1**	2	Hours

Tank Capacity 2	50000	US Gallons	**Time to Ready, Code 2**	8	Hours
Fuel Truck Capacity, R11a	6000	US Gallons	**Time to Ready, Code 3**	12	Hours
Fuel Truck Count	1	Each	**Time to Arm**	0.25	Hours
Arming Truck Count	4	Each	**Number of Maintenance Crews**	20	Each
Min X, Apron	1100	Meters	**Average Speed, Maintenance Trucks**	10	Miles per Hour
Min Y, Apron	0	Meters	**Circular Error Probable**	50	Meters
Max X, Apron	3000	Meters	**Spread**	100	Meters
Max Y, Apron	1000	Meters	**Projection**	3857	EPSG #

In addition to the human performance and equipment availability data, planners must also specify the preferred MOGA search parameters. The MOGA search parameters selected for this application example were identified based on recommended parameters for NSGA-II for practical computation times [131]. The best results for this application example were from a population size of 1000, 200 generations, a mutation rate of 0.01, elitism coefficient of 0.05, and crossover with a rate of 0.5.

The developed optimization model was used to analyze the aforementioned input data for this example in order to search for and identify optimal dispersal distances and patterns for this airfield. The model computations were implemented using the initial layout phase shown in Figure 6. After the initial layout phase, the model performed the calculations necessary for the objective function score. An attack was simulated, and the resulting values were used to compute an overall score. The model then selected the fittest individuals by identifying the nondominated Pareto-optimal solutions. Finally, a new offspring generation was created to replace the parent population by using the planner-defined parameters for MOGA selection, crossover, elitism, and mutation parameters. After each generation, the model logged the score and generation data. This application example was analyzed using a 3.2 GHz hex-core Intel (Santa Clara, California) Core i7 processor with 12 MB of cache memory and 16 GB of RAM, and the total computational time was 10 hours. This computational time was achieved using parallelization, with 6 physical and 6 virtual cores dedicated to the model.

The search space for this application example includes more than 240 trillion unique combinations of layout. The developed optimization model, executed using MOGA, was utilized to perform an efficient and effective search of this large and stochastic search space of feasible layout alternatives. The model generated a narrow spectrum of 6 Pareto-optimal solutions that represent unique and optimal tradeoffs between the two optimization objectives. The generated non-dominated solutions result in an expected number of assets damaged ranging from 0 to 17 and sortie generation times ranging from 3.4 to 5.39 hours.

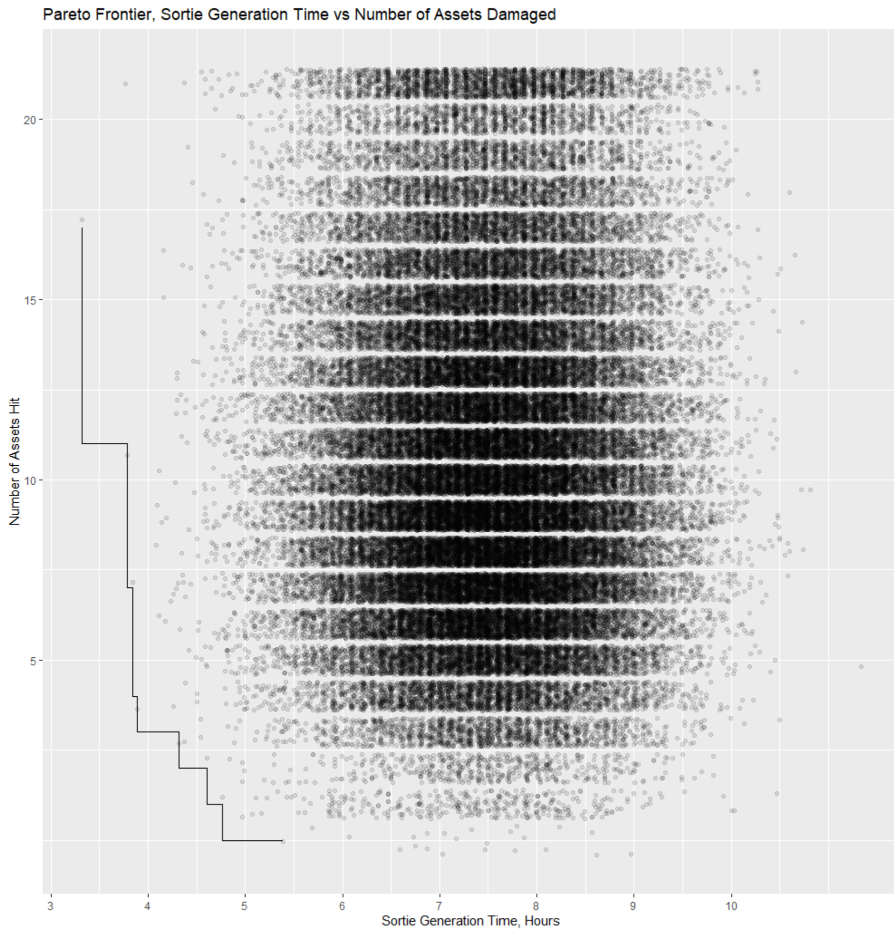

Figure 8: Partial Solution Space with Pareto Frontier

At one end of the solution space, solution S1 represents the generated Pareto-optimal solution that represents the fastest turnaround for sortie generation (3.4 hours). This result was generated by placing aircraft in a single column of aircraft. The starting point of the first column was 1760,990, which is roughly halfway down the apron and fairly close to the maximum height of 1000. This gave a minimum separation distance between aircraft of 62 meters. The fuel bladders were arranged in 2 rows of 3, and they were located on nearly the opposite end of the available space, with coordinates of 0,660. The fuel bladders in this configuration were spaced

330 meters apart. This layout can be seen in Figure 9, and exchanges this rapid sortie generation rate for a high attack damage probability, with 65% of assets damaged during an attack.

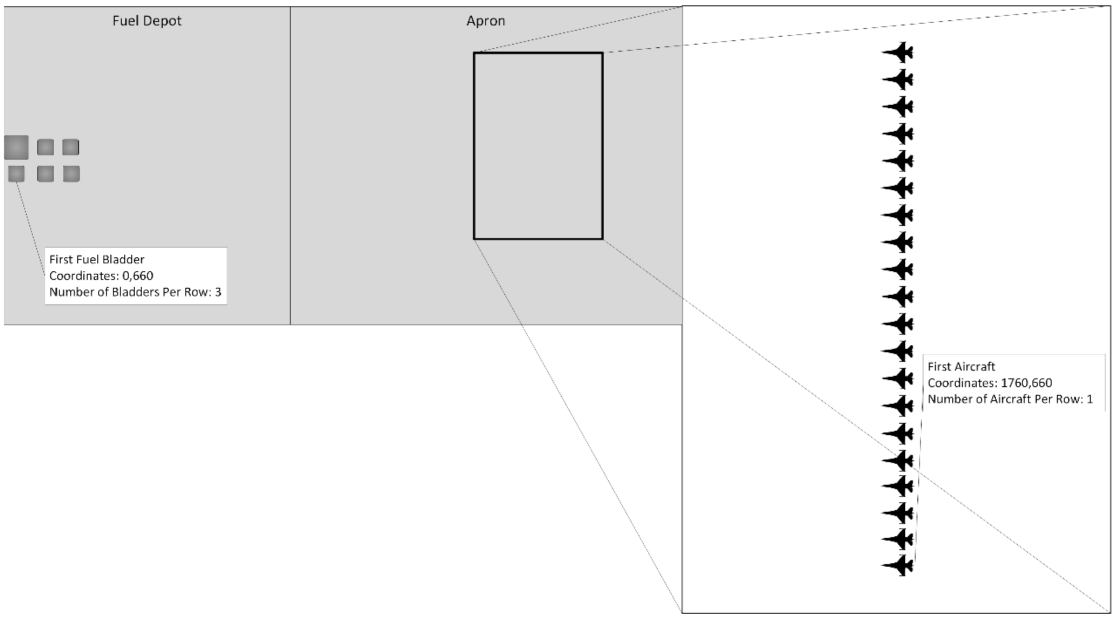

Figure 9: Base Layout, Solution S1

The opposite end of the solution space is represented by solution S8, which is extremely resilient, with no assets damaged during an attack. While the complete lack of hits is dependent on the accuracy of targeting and would not be the expected result of every attack, it shows the ability of this layout to completely eliminate collateral damage. It exchanges this favorable result in an attack for 2 hours (66%) of generation time, with a complete turn of the F16s in 5.38 hours. It leveraged an aircraft layout of 4 rows of 5 F16s and 6 fuel bladders in 1 row 1014 meters from the closest aircraft. The resulting separation distance was 314 meters for aircraft and 110 meters for fuel bladders. The large decrease in viability of A2/AD attack for a moderate increase in sortie generation time is indicative of the high value/cost ratio of dispersion in an airfield and fuel depot scenario.

Between the two ends of the solution space, the model generated 6 other Pareto-optimal solutions that enable planners to select the layout that best meets the unique conditions of the base and scenario they are operating in based on the (1) desired generation time, (2) acceptable level of damage, and (3) other specific considerations given a site such as standoff from a base perimeter. For example, solution S6 offers the planner a sortie generation time only 27% larger than that of S1 (4.32 hours) while only increasing the number assets damaged from S9 by 3 (3 assets damaged). Table 2 provides a comprehensive list of the optimal decision variable solutions for the solutions in the Pareto frontier.

Table 2: Pareto-Optimal Solutions

Solution	X Coordinate of First Aircraft	Y Coordinate of First Aircraft	Aircraft per Row	X Coordinate of First Bladder	Y Coordinate of First Bladder	Bladders Per Row	Sortie Generation Time (hours)	Number of Assets Damaged
S1	1760	660	1	0	660	3	3.32	17
S2	1100	330	19	660	660	1	3.79	11
S3	1760	0	15	0	330	5	3.84	7
S4	1100	330	15	990	990	1	3.89	4
S5	1430	0	11	330	330	2	4.32	3
S6	1430	330	13	0	660	4	4.61	2
S7	1100	990	3	0	330	6	4.77	1
S8	1430	990	5	660	330	6	5.38	0

Summary, Future Work, and Conclusion

A novel multi-objective optimization model was developed to identify optimal dispersion and siting considerations for airfields in a contested environment between the two main tradeoffs of maximizing resilience damage from A2/AD attack and minimization the sortie generation time. The model was developed in three main stages: (1) the formulation stage, which defined the relevant variables, created the objective functions, and identified feasible model constraints; (2) implementation stage, which performed the optimization calculations using a multi-objective genetic algorithm; and (3) the performance evaluation stage, which utilized an application example to assess model performance. The application example optimized the dispersal and layout of 20 F16s and 6 fuel bladders at an airfield to resist attack from 10 theater ballistic missiles with 100 cluster munitions each. The results from this model demonstrated the model's distinctive capabilities in optimizing dispersal layout by generating 6 Pareto-optimal solutions that represent unique optimal tradeoffs between minimizing sortie generation time and maximizing resilience to attack. The precise amount of hits would be expected to vary depending on the accuracy of attack

The primary contribution this research makes to the body of knowledge is the development of a novel model that is uniquely capable of (1) optimizing both the dispersal layout of the airfield and fuel depot yard and (2) siting them relative to each other with sortie time considerations. The developed model should prove beneficial to planners of airfields in contested environments, where air superiority and immunity to missile attack cannot be guaranteed, enabling them to rapidly calculate the optimal parking and fuel depot plan and efficiently evaluate all alternatives. While the application example utilized a gridded structure for individuals and specified targeting and routing algorithms, all components are written flexibly such that new or site/scenario adapted algorithms can be readily incorporated. The capability results in the use of airfields in a way that results in resilient, efficient operations that protect valuable and limited aviation assets from attack in a near-peer conflict.

V. Conclusions and Recommendations

Research Conclusions

In an effort to provide an increased empirical body of knowledge for airbase resilience in a contested environment, especially where there is a risk of anti-access/area denial (A2/AD) attack with submunitions, this thesis strove to address three primary research objectives:

1. Review traditional basing techniques and existing research on resilient basing. Additionally, this thesis will review scholarly works on modeling, heuristics, nature-inspired metaheuristics, and other concepts relevant to the understanding of dispersal in a modeled environment.

2. Analyze the history of resilient basing, identify and discuss engineering challenges and opportunities in basing layouts, and identify a way forward in modeling resilient basing to provide an optimal solution for decision-makers and strategic planners.

3. Develop a novel model to analyze the tradeoffs between attack resilience and sortie generation for aircraft being staged at a forward base in a contested theater.

The first objective was accomplished in Chapter 2, a traditional literature review that investigated the body of knowledge in the fields of (1) routing problems, (2) dispersal research, and (3) heuristic and metaheuristic solution techniques. The vehicle routing problem was revealed to be well suited in a simple implementation to modeling the refueling of aircraft using trucks filling from remote bladders [43]. This research also identified future improvement techniques for any initial model with the rich vehicle routing problem. Dispersal research summarized the previous academic work in dispersal and identified an opportunity to advance the body of knowledge in defense from modern ballistic missile attack [2]. The investigation into heuristic and metaheuristic techniques revealed many effective techniques to solve multi-objective problems such as dispersal enabled a comparison of the efficacy of each method for modeling airbase resilience.

The second objective was completed in Chapter 3, “Defense of Military Installations from Ballistic Missile Attack,” which reviewed existing base resilience research and doctrine and proposed the development of a novel model to optimize airbase resilience to an A2/AD attack delivered by ballistic missiles. This paper, published in the proceedings of the 2019 edition of the International Conference of Military Technology, identified the clear need for increased resilience based on official peer and near-peer doctrinal changes, especially those in China and Russia [6], [115]. From this need and the overview of historical doctrine, several key tenets of resilience that engineers have a significant amount of influence over (1) camouflage, concealment, and deception (CCD); (2) mobility; (3) redundancy; (4) hardening; and (5) dispersal. Mobility and CCD were identified as feasible options to prevent any damage in case of an attack, as they confused enemy targeting Due to the inherent challenges of holistic modeling of these varied subsystems, however, they were proposed to be separate models that fed into a complete objective function to be developed at a later date. Redundancy provided assurance that a base would still function despite damage but was limited by industrial and logistic capacity [12]. Hardening, a traditional method of airframe defense, was shown to be excellent at preventing damage during A2/AD attack but did not increase the ability of the aircraft to respond after an attack due to the scattering nature of submunitions resulting in a damaged airfield. Dispersal was identified as a cost-effective, simple technique to immediately improve resilience without any significant cost for airfields, and a worthy consideration for other assets.

The third objective was fulfilled by Chapter 4, “Title TBD,” which presented the development and assessment of a novel model to optimize parking apron layout, fuel depot layout, and the separation distance between the two to maximize resilience to A2/AD ballistic missile attack as well as minimize sortie generation time during daily operations. This model was developed as a first effort to begin the model proposed in Chapter 3. It was assessed using an application example of 20 F-16s, six fuel bladders in two sizes, and an aggressor force of 10 ballistic missiles, each containing 100 cluster munitions. It produced six Pareto-optimal solutions, allowing planners to utilize a variety of tradeoffs given a need for a certain sortie generation rate or need to preserve assets from damage.

Research Significance

Since the publication of the USAF Strategic Master Plan in 2015, there has been a renewed emphasis on resilience to peer and near-peer attacks due to a perceived loss of skills in the extended period of counterinsurgency operations. While some research has provided theoretical doctrine and theater-wide modeling, it has mostly focused on the development of modern doctrine, and there have not yet been significant efforts to model these doctrine in a way that is empirical, repeatable, and available to civil engineer planners and justifiable to senior leadership. Due to increasing tensions worldwide between major powers, it is imperative that research accelerates to provide useful options for planners in the case of an outbreak of conflict.

Research Contributions

This research produced one of the first peer-reviewed assessments of historical doctrine regarding airbase resilience and one of the first practical models on dispersal effects on both sortie generation rate and base resilience. The background paper on doctrine provided a unification of recent civil engineer resilience doctrine with professional and think-tank reports as well as historic, peer-reviewed literature. It identified the significant role that think-tank models have played in the planning of strategic doctrine in contested theaters as well as identified an area of research not yet implemented in engineer planning models.

The novel model provided senior leadership with a useful technique to identify parking plans that are both resilient and practical, as well as identifying the effects of fuel bladder standoff and dispersal while allowing computation that is possible in a reasonable amount of time on non-performance machines using publicly available software. This research culminated in a conference paper and journal paper.

Recommendations for Future Research

This field has many available opportunities for future research due to its recent resurgence and the increase in powers using A2/AD as an official doctrine to further strategic aims. These opportunities can be divided into (1) further expansion of the optimization model to add additional resilience techniques, (2) implementation of automated basemap module to increase usability at the base level, and (3) improvement of the routing problem logic to add realism.

The novel model currently only assesses the resilience of apron and fuel depot assets by manipulating dispersal. The ability to integrate hardening, redundancy, and other resilience concepts in a way that considers cost and the impact on industrial and logistic capacity would make this model eminently useful in the case of future conflict. This is the most pressing and useful future research vector, but it relies on the implantation of other goals to bring the model to its ideal usefulness.

While the grid-based system provided in the existing model is usable, the ability to implement a module to the model that would assess a raster of an existing base to identify available locations for dispersal and other modifications to increase resilience would make the model far more usable at the operational and tactical levels. It would also increase the user-friendliness of the model, allowing planners with less training at code implementation to still provide effective and accurate assistance to decision-makers on options for base modification and resilience improvement. This code would involve a fairly rigorous development process due to the machine learning involved, but once complete, would provide the most significant improvement in user experience and accuracy.

Finally, the implementation of a rich vehicle routing model for dispersal and other elements would provide a substantial improvement to the model [48]. Most importantly, it would dramatically increase the reliability and accuracy of the model, especially when implemented with the automated basemap module discussed above, which would allow the analysis of roadway conditions to provide dynamic routing speeds and alternative routes. Second, it would allow the implementation of post-attack sortie generation rate calculations, which would rely on the dynamic routing speed to create alternative routes to assess how quickly a base can generate sorties given various modifications to improve resilience. Ultimately, the confluence of these three improvements would result in a model that provides total base planning coverage in the case of conflict, dynamic basing, or the desire to improve base resilience at existing bases in high-threat zones.

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