A HYBRID LOCATION MODEL FOR MISSILE SECURITY TEAM POSITIONING

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ABSTRACT

This research provides solutions to the real-world problem of locating a limited number of security forces over a large geographic area in order to maintain security for the US Air Force's Intercontinental Ballistic Missile Systems. A combination of two widely accepted location modeling techniques, the p-median and p-center models is used to generate solutions which minimize the overall distances traveled by response teams while minimizing the maximum distance that any one missile site is from required security forces. Solutions for the problem are generated using heuristic and optimization techniques in a VBA enhanced Excel spreadsheet created for this purpose. The results indicate that a significant improvement in positioning can be achieved, and the techniques used in this research are currently being tested by the Air Force for possible implementation.

INTRODUCTION

The Minuteman Intercontinental Ballistic Missile system has been a pillar of the United States' military forces for more than forty years and will continue to be so for the foreseeable future. The current version of the weapon system, the Minuteman III, is deployed at three wings: Malmstrom AFB, Montana—200 ICBMs; Minot AFB, North Dakota—150 ICBMs; and F. E. Warren AFB, Wyoming—150 ICBMs. All wings are broken down into squadrons of 50 ICBMs each and flights of 10 ICBMs. A site containing an ICBM is known as a Launch facility (LF). A Missile Alert Facility (MAF) is also assigned to each flight. The MAF houses the launch control officers, flight security controller, and additional support personnel. LFs and MAFs at F. E. Warren AFB are alpha-numerically numbered with the letter identifying the flight and the number identifying the LF or MAF number. The Minuteman weapon system has earned credibility as a viable strategic deterrent through its ability to achieve high availability as measured by high alert rates on a consistent basis, normally exceeding 99% annually. Maintenance personnel performing priority, periodic, and weapon system upgrade maintenance are a key aspect of achieving these alert rates and traditionally security considerations have been linked to the goal of achieving high missile availability. A structured priority system serves as a guide to repair and upgrade the weapon system. The highest priority, Priority 1 discrepancies, are actions required to repair equipment critical to the safe operation of the weapon system and those actions required to prevent damage, or further damage, to the weapon system. The remaining priority levels have decreasing degrees of significance, and the lowest level, Priority 9, represents maintenance which is deferred. This hierarchy determines how and when to schedule maintenance actions and places periodic maintenance at the lower end of the priority spectrum. Protecting the weapon system from damage, destruction, and theft is crucial to the nation's security. Therefore, a specified number of security escorts are allocated to each maintenance team conducting maintenance on an LF. These security escorts are only required when the LF is to be penetrated, that is, when the maintenance team will enter into the silo itself. Additional requirements ensure that additional forces are close enough to respond if a hostile event occurs.

The events of September 11, 2001 have placed a much higher degree of emphasis on security for ICBMs. The nation cannot afford the dire consequences of damage or theft of even one of its nuclear assets. Over the course of the past several years, many physical security upgrades have been implemented. These physical security upgrades, along with the existing system, are designed to delay a hostile act long enough for a security force to respond to any threat and eliminate it. Great measures are taken to protect the system as it lies in its standby state, and great measures must also be taken to protect it when it is exposed for maintenance. Recent demands from the highest levels of government to reduce security forces response times place an increased strain on the already tenuous availability of limited security forces resources. Therefore, effectively deploying available security forces and exercising sound decision-making policies when completing all daily maintenance requirements is the only way to ensure system protection and effectiveness. These enhanced security requirements will require a balance between achieving maintenance goals and affording the proper level of protection to the weapon system. It is unlikely that both goals can be maximized on a consistent basis without some trade-offs occurring. Therefore, decision makers will be put in the tenuous position of having their maintenance schedule constrained by security requirements on a daily basis. Constant cancellation of maintenance actions will undoubtedly cause the system to degrade over time, while even more dire consequences are perceivable without adequate security for the weapon system. This research seeks to provide decision makers with a reliable method for balancing these competing objectives.

The overall research question for this research is: Can a user-friendly modeling technique be developed to minimize security force response times while providing decision makers with a tool for balancing trade-offs between maintenance requirements and optimal or near optimal security forces response times? This question addresses the current operating environment and acknowledges the possibility of requiring some trade-offs in alert rates to achieve heightened security.

BACKGROUND

Very little previous research has been conducted on this specific problem. An initial effort by Seaberg [10] introduced the umbrella concept. This concept was to create a security “umbrella” under which maintenance would be conducted, which attempted to limit maintenance operations that required an open hole or penetrated LF to remain within the umbrella. The proposal also had a goal of limiting below-grade maintenance operations to daylight hours. In related work, James [8] proposed the option of removing the Nuclear Reentry System and performing all annually required maintenance during a set period of time. His method would require extensive coordination between the various types of maintenance teams and would result in much overtime pay for civilian workers. His method purports to reduce the number of security escorts required per day, but comes at a high cost. Although several classified exercises and studies have analyzed the inherent vulnerabilities of the system and potential physical security preventative measures, no known studies have been conducted concerning the optimal placement of security forces personnel. Our study accomplishes such placement with the use of existing location modeling techniques found in [2] [3] and other texts.

METHODOLOGY

We use actual data on LF and MAF locations, interconnecting roads in the missile fields, and available security forces teams. This data is applied in three distinct location models to understand and study the

tradeoffs between maintenance and security requirements. Each of these models can be described as a discrete location model composed of different types of servicing locations and demand locations. The servicing facilities are the LFs, MAFs, and selected staging areas located at road intersections. Demand nodes are the penetrated LFs where maintenance is being accomplished. The models aspire to optimize the placement of security forces response teams based on daily scheduled maintenance requirements.
The remainder of this section provides, a description of the data, the formulation of the models, the method for generating solutions, and the necessary modeling assumptions.

Data

Data were collected on the 150 Minuteman III LFs at F. E. Warren AFB, Wyoming for calendar year 2003 and January through May of 2004. It includes:

- Security forces response times matrices from Missile Alert Facilities (MAFs) to LFs
- Daily maintenance status sheets from January through May of 2004
- Periodic maintenance due dates and locations; and Off-alert hours for missile systems
- Daily security escort availability and security teams requested by maintenance
- Daily LF maintenance performed

All data were collected from historical records maintained at F. E. Warren AFB and was obtained from the Headquarters of Twentieth Air Force [9]. Some data was missing on security escort availability and number of teams requested by maintenance; mostly weekend and holiday data. Data on LF and MAF latitude/longitude coordinates were collected from a public website, http://w3.uwyo.edu/~jimkirk/warren-mm.html, and coordinates for the additional staging areas were obtained by using the free trial version of *AccuGlobe*®. Road overlays for Colorado, Nebraska, and Wyoming were obtained at http://arcdata.esri.com/data/. The latitude and longitude coordinates of the staging areas were obtained by plotting the staging areas on these maps and viewing the displayed coordinates. Once generated, the coordinates were validated with personnel at F.E. Warren AFB.

Candidate locations for security team positioning included all existing Minuteman LFs and MAFs, and additional staging sites were selected at road intersections resulting in 233 candidate locations. Coordinates of candidate locations were represented in degrees, minutes, and seconds format and distances were calculated using the great circle method outlined in [1]. This distance data was then used to build a distance matrix detailing the mileage between each LF, MAF, and staging area as computed by an Excel® macro developed by Eberlan and Weir [1]. For this research, straight-line distances were used and it is acknowledged that using actual road route distances would improve the accuracy of the research, but would also add greatly to the complexity of the problems to be solved. Finally, distance calculations were converted to a response time in minutes by multiplying the distance by a factor of 60/40, to represent forty miles per hour average driving speeds.

Model Formulations

The problem of finding the optimal placement for security force teams is modeled as a facility location problem. Three of the many methods of locating facilities available in the literature are selected to solve this problem. This gives decision makers alternate methods to solve the problem based on their objectives. First, the p-center problem covers all demand and seeks to minimize the maximum distance between a demand point and a servicing facility. The p-median problem intends to minimize the demand-weighted total distance between demand sites and servicing facilities [7]. In addition, a third hybrid model is developed by first obtaining a p-center solution, and then reducing the total distance using a p-median approach.

The p-Median Problem

The formulation of Daskin [2] with four minor adjustments is utilized in this research. The first adjustment removes the demand weight multiplier from the objective function, because the demand in this model is assumed equal. The second adjustment allows for more than one security team to be capable of covering a particular LF of interest. The third adjustment allows fewer than the available number of security teams to be utilized. This is necessary when the number of available security teams exceeds the number of scheduled sites or when deploying additional security teams will not improve upon the objective function. The final adjustment allows each penetrated LF to be assigned to more than one security team. This is feasible because, theoretically, security teams may be placed in close enough proximity to one another to allow for an overlap of coverage. That is, one team could respond to an LF within another team's assigned coverage area, should that team be responding at another LF. The formulation is as follows:

MINIMIZE

$$\sum_{i}\sum_{j} d_{ij} Y_{ij} \qquad (1)$$

SUBJECT TO:

$$\sum_{j} Y_{ij} = 1 \qquad \forall i \qquad (2)$$

$$\sum_{j} X_{j} \le P \qquad (3)$$

$$Y_{ij} - X_{j} \le 0 \qquad \forall i, j \qquad (4)$$

$$X_{j} \in \{0,1\} \qquad \forall j \qquad (5)$$

$$Y_{ij} \in \{0,1\} \qquad \forall i, j \qquad (6)$$

where:
X_j = 1 if we locate a security team at candidate staging area j, 0 otherwise
Y_{ij} = 1 if penetrated LF i is served by candidate staging area j, 0 otherwise
d_{ij} = the distance between points or nodes i and j
P = number of security teams to be located.

The objective function (1) minimizes aggregate travel distance, thus minimizing response times, between all penetrated LFs and selected staging areas where security teams are placed. Constraint (2) requires that at least one team covers each penetrated LF. Constraint (3) states that no more than P teams are to be located. Constraint (4) links the location variables (X_j) and the allocation variables (Y_{ij}). Constraints (5) and (6) are binary constraints. The GRASP heuristic is used to generate solutions for the p-median problem [6]. The heuristic begins by checking all possible combinations of scheduled LFs as potential staging areas and also searches the areas around those points. The best solution found, which has the minimum total distance, is kept. The randomized portion of the heuristic is then performed, evaluating the neighborhoods around 100 randomly chosen points and comparing the solutions to the best original solution. If a better solution is found, it is kept as the very best solution. The solution identifies the locations of the staging areas, the allocations of penetrated LFs to staging areas, and the response distance/time. This model assumes all teams are available.

The p-Center Problem

The objective of the p-center model is to minimize the maximum response time or distance between a security team placed at a staging area and a penetrated LF. There are two different formulations of the p-center problem: the vertex p-center problem and the absolute p-center problem. The vertex p-center formulation is used in this model because staging areas can only be located on the candidate staging area nodes and not on the arcs (anywhere along the routes), as in the absolute p-center problem. The formulation used in this research is from [2] with minor adjustments. As in the previous modeling techniques used in this chapter, this modeling formulation again removes the demand-weighted multiplier. The same adjustments pertaining to security teams made in the p-median formulation are included in this model.

$$\text{MINIMIZE} \quad W \tag{7}$$

$$\text{SUBJECT TO:} \quad \sum_j Y_{ij} = 1 \quad \forall i \tag{8}$$

$$\sum_j X_j \le P \tag{9}$$

$$Y_{ij} - X_j \le 0 \quad \forall i, j \tag{10}$$

$$\sum_j d_{ij} Y_{ij} \le W \quad \forall i \tag{11}$$

$$X_j \in \{0,1\} \quad \forall j \tag{12}$$

$$Y_{ij} \in \{0,1\} \quad \forall i, j \tag{13}$$

where:
W = maximum distance between a penetrated LF and its assigned team
Y_{ij} = 1 if penetrated LF i is assigned to candidate staging area j, 0 otherwise
X_j = 1 if we locate a team at candidate staging area j, 0 otherwise
P = number of security teams to locate
d_{ij} = the distance between points or nodes i and j

The objective function (7) minimizes the maximum distance that any penetrated LF is from a deployed security team. Constraint (8) requires that each penetrated LF be assigned to at least one security team. Constraint (9) stipulates that no more than P teams are to be located. Constraint (10) states that a penetrated LF, i, cannot be assigned to a candidate staging area, j, unless a team is located at staging area j. Constraint (11) states that the maximum distance between a penetrated LF and a security team must be greater than or equal to the distance between any penetrated LF, i, and the team at staging area, j, to which it is assigned. Constraints (12) and (13) are the integrality and non-negativity constraints, respectively. This model is solved to optimality by using the Bisection method to achieve the lowest maximum distance any team is located from a penetrated LF. Because the maximum distance between any two points in the distance matrix is 93.29 miles, the method begins with a maximum value of forty-seven and a minimum value of zero. The maximum and minimum values are bisected until the lowest distance that covers all scheduled penetrated LFs, within one-tenth of a mile, is found. The Bisection method can be slow to converge to the optimal solution, but is guaranteed to obtain the optimal solution within the specified accuracy [5].

Hybrid Approach

The hybrid model utilizes the p-center and p-median formulations previously described. No model adjustments are required. This is the only model formulation that seeks to achieve multiple objectives, but only the objective of minimizing the maximum distance between a penetrated LF and its assigned security team can be solved to optimality. Again, the Bisection method is used to solve the p-center portion and then, sequentially after the p-center solution, the GRASP heuristic is employed to minimize the total distance given the p-center solution maximum distance constraint. Once all assumptions are made and incorporated into the models, distance calculations are accomplished so that the spreadsheet models can be constructed and solved

Modeling Assumptions

Several critical assumptions are also made in developing the models:

- No consideration is given to increased security procedures
- The collected data does not differ significantly from other years
- Response times are static—there is no allowance for increased speeds of responders. (NOTE: A speed of 40 mph is selected. This speed is a balance between speeds on a combination of gravel and paved roads)
- Data collected from F. E. Warren AFB is representative of the other wings
- No Peacekeeper LF maintenance requirements were considered
- The number of Security Teams, *P*, are always available for tasking
- A security team covering an open LF is unavailable to cover another penetrated LF

RESULTS

The current method of deploying security teams is based solely on experience and daily requirements in the missile fields. Since there is no established mathematical method associated with the current deployment scheme, the results of the three models are compared to each other for analysis. Each model is compared to the others based on several measures including security team utilization, average security team response time, average total distance to penetrated LFs, and the average maximum distance any security team is located from a penetrated LF. Additionally, the models are run with all potential staging areas and with a limited set of only the MAFs as potential sites for positioning security teams. These results are shown in Table 1.

		All Staging Areas		
	Usage	**Response time**	**Total Distance**	**Max Distance**
p-median	97.84%	4.92 mins.	28.83 miles	10.95 miles
p-center	97.84%	7.73 mins	43.94 miles	7.30 miles
Hybrid	97.84%	5.76 mins	33.75 miles	7.30 miles
		MAF Only Staging Areas		
p-median	97.84%	12.38 mins.	59.93 miles	12.98 miles
p-center	90.52%	13.44 mins	66.55 miles	12.53 miles
Hybrid	97.84%	12.71 mins	62.31 miles	12.53 miles

Table 1. COMPARISON OF MODEL RESULTS

The results are consistent with the objectives of the three models. For all staging areas, the smallest total distance from security team locations to penetrated missile sites is the smallest in the p-median model at

28.83 miles, and the maximum distance that any team is located from a penetrated site is minimized by the p-center model to 7.30 miles. The Hybrid model makes an additional contribution by fixing this distance at 7.30 miles and by adjusting the teams to accomplish a total distance of 33.75 miles. This model nicely balances the objectives of the two models and reduces the average response time to 5.76 minutes for all teams while ensuring that no single demand location it too far from a security team. Similar results are seen in the reduced MAF only data set. This time, the hybrid model is able to minimize the maximum security team distance to 12.53 miles using the p-center approach and then is able to reduce the overall response time to 12.71 minutes. Balance between the objectives is achieved.

CONCLUSION

The results of this research clearly indicate the need for a more analytical approach to positioning security teams to meet missile security requirements. Although, the Air Force goes to great lengths to determine and enforce security requirements, it is clear that efficiencies can still be realized by properly positioning the limited number of security teams available. In addition, the differences seen between the use of three different models appears to indicate that there are clear tradeoffs in time and distance based on which overall objectives are selected by military commanders. This research gives commanders a choice between three different models with different objectives and shows how security times and distances will differ depending on objectives. Additionally, it can be seen that the potential set of staging sites makes a significant difference in response times. If commanders limit staging areas to only secure MAF locations, they would do so at the expense of doubling average response times and distances in the example studied in this research. Overall, it is believed these results are generalizable to other missile fields in the US Air Force. Finally, continuing research on this subject is aimed at developing a model which simultaneously schedules maintenance jobs while positioning security teams in order to maximize the overall alert rate (availability) of a group of missiles over a defined time period. This effort will not only provide a tool for commanders in the field, but will also help them study the tradeoff between the amounts of maintenance which can be accomplished while meeting the hard constraint of security.

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