Application of Utility Theory in Ballistic Missile Defense Site Selection

Randy N. Brooks

Abstract — This paper presents a phased approach in selecting a single location for a land-based Ballistic Missile Defense (BMD) site in Romania. The study examines criteria governing the location problem that are a combination of well-known physical constraints associated with radar and missile systems, as well as uncertainties regarding public perception on the effects of electromagnetic radiation on health and welfare. This work differs from research published on the single site selection problem through the substantial use of derived quantitative measures based geography and population density, rather than on subjective intuition.

Phase one frames qualitative and quantitative measures about the BMD location problem using a value tree of the goals and criteria to form a hierarchy. The second phase examines quantitative measures such as absence or presences of a major airports and radar blockage zones. Additionally, an assumption regarding public reception is evaluated to ascertain an adversity profile; this is a major component of uncertainty within the model. Multi-Attribute Utility Theory (MAUT) and Simple Multi-Attribute Rating Technique (SMART) are used to model relative value and utility functions. The final phase provides a sensitivity analysis on criteria used in the model. Manageable boundaries consisting of 41 county regions are used to visually show an assigned utility for each geographical area. Furthermore, a thematic contour map is developed of the region to indicate optimal stationing of BMD assets.

Key Words — Location Theory, Value Tree, MAUT, SMART, Aegis Ashore, Romania, Ballistic Missile Defense

I. Introduction

In September 2009, President Obama proposed a Phased Adaptive Approach (PAA) to fielding land based BMD sites in Europe. During the same announcement, The President stated, “Iran's ballistic missile program poses a significant threat” (The White House, 2009). Reports to the United States (US) Congress indicate that the Obama administration is concerned about Iranian ballistic missile capability to strike targets within Europe. Iranian nuclear ambitions, whether used for peaceful domestic energy or for military purposes, have aggravated western concerns. To counter this threat, a BMD site is planned to be constructed to track, engage and intercept approaching missiles should the fear of North Atlantic Treaty Organization (NATO) member nations and the US be realized. Phase one capability is planned to be deployed in 2011 and will be provided by Aegis-equipped ships located in waters off southern Europe. Relying on the proven technology of the Aegis BMD system, the next phase will field a land-based system, referred to as ‘Aegis Ashore’.

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Iran’s undeterred nuclear ambitions and missile delivery capabilities remain a great concern to European as well as US interests (MacFarquhar, 2010) (United Nations, 2006). A Department of Defense (DoD) statement that quotes recent intelligence reports show Iran’s weapon capabilities advancing at a faster rate than anticipated for short to medium ballistic missiles, while long range intercontinental ballistic missile capabilities are lagging (Kauchak, 2009). To counter this threat, NATO countries and the US have joined together to place an ‘Aegis Ashore’ system in Europe. It has been reported that various agencies are negotiating with Romania to locate an Aegis Ashore site on its territory in 2015 (O’Reilly, 2010). Specific quantifiable measures relevant to the preferred location include: radar performance in terms of geographic blockage zones, infrastructure related to accessibility, and population density. Additionally, the model considers impact to the population and local sensibilities that could restrict locations and lead to sub-optimal performance of the Aegis Ashore system..

II. Literature Review

The spectrum of literature examined in preparation for this discussion includes: radar technology and BMD systems, single facility location theory, Romania’s unique characteristics, and MAUT. Additional literature concerning Iranian threat capability is explored.

A. Radar Technology

The Missile Defense Agency (MDA) is a research, development, and acquisition agency within the Department of Defense. The MDA maintains a web site that offers the following explanation of how BMD systems operate (Missile Defense Agency, 2010):

> The Ballistic Missile Defense System (BMDS) being developed and tested by the MDA consists primarily of “hit-to-kill” interceptors. These interceptors directly hit the incoming missile either inside the earth’s atmosphere or while the hostile missile is in space. The interceptors ram the warhead at a very high closing speed, destroying the target using only kinetic energy. It has been described as hitting a bullet with a bullet - a capability that has been successfully demonstrated in test after test.

BMD systems are composed of three major components: radar sensors, a launch system, in addition to command and decision systems (Global Security Org., 2010). The exact configuration of The Aegis Ashore System is unknown, however, a recently published article hypothesize how the Aegis Ashore component may be configured (Ellison, 2010):

> The Aegis Ashore system would be similar to a 03 level of the Aegis ship that would be contained in stacked levels approximately 60 feet high. The levels would include water coolers, power converters, processing computers, combat information center and radar processors with the S-Band radars and antennas on top. The communications, power source, cooling tower and the vertical launch containers, that would hold a mixture of interceptors, would be located outside of the main structure. The interceptors could be placed miles away if desired.

The term RADAR is an acronym for RAdio Detection And Ranging and defined as any device that emits electromagnetic radiation signal and detects their echo (Radar, 2000; Wagner, Mylander, & Sanders, 1999). The radar component has specific requirements for optimum detection and most affected by location problems due to blockage zone and beam scattering. Beam scattering reduces radar effectiveness.

B. Location Problem

In his thesis to determine the optimal radar location to detect space borne objects, Schick stated that limited research has been performed on solely military facility location problems (Schick, 1992). Schick suggests that analogies can be made between military facility location and general research on facility location models. In general, literature of facility location models concerns itself with problems of locating one or more new facilities in relation to a set of existing facilities. The objective is usually with regards to minimizing transportation costs or maximizing profit (ibid., p.2). This class of problem is referred to as a facility location problem. To solve the problem in this context, the factors affecting radar's resolution must be identified, and candidate locations evaluated on optimal radar performance.

The single facility location problem is a sub-class of the Fermat-Weber location problem (Chandrasekaran & Tamir, 1990). The objective of the Fermat-Weber location problem is to find a point that minimizes the sum of weighted Euclidean distances. Original work using a multi-phase approach to analyze this problem was performed by Canbolat, Chelst, and Garg (2005) in selecting a country for a manufacturing facility.

A logical association is made between weather forecasting radar sensors and BMD sensors as they would suffer the same physical problems with natural barriers. The radar location placement problem has its roots in early formal decision theory. While discussing the history and foundation of Operation Research (OR) Li & Soh made the following statement on the origins of formal decision theory.

> …formal decision theory can be said to start with the 1938 Battle of Britain during World War II (W.W.II). The English War Department banded together to a group of physicists, mathematicians, logic experts, crossword puzzle experts, and chess masters to solve the problem of locating positions for a new but limited technology called "radar." (2004)

Keeney & Raiffa have published an extensive amount of work on decision theory. They referenced an airport location problem concerning cost, capacity, noise, political objectives, access times and safety. They warned that, "…attributes are initially too vague to be operational, but in the analyst attempt to be more specific, care must be used not to inadvertently distort the sense of the whole" (Keeney & Raiffa, 1976, pp. 436-442). They also suggest that to have a complete set of decision measures the analyst needs to confirm that the measures are operational, decomposable, non-redundant and minimal. Clemen (1996) elaborates on Keeney and Raiffa, stating that a set of attributes should be complete (so that all important objectives are included), as small as possible (to facilitate analysis), not redundant (to avoid double-counting a common underlying characteristic), and decomposable (so that the decision maker can think about each attribute separately). An attempt will be made follow these guidelines in the course of model development and analysis.

C. Romania

Romania joined NATO in 2004 and the European Union (EU) in 2007. Its size is slightly smaller than the state of Oregon by comparison (The World Factbook, 2009). Figure 1 illustrates the location of Romania within the European Union. The dark green country is the outline of Romania. Light green countries belong to the European Union. The urban population represents a little over half of the country's total population according to a 2008 estimate. A curved mountain range intersects the country starting with The Carpathian Mountains in the North and joining The Transylvanian Alps in the South.

Figure 1: European Union (CIA Factbook, 2010)

A recent paper discussing optimum stationing of weather radar systems in Romania notes that the country has many environmental variations that affect radar wave propagation (Burcea, Antonescu, & Bell, 2010). Burcea, Antonescu & Bell report that Romania has substantial variation in its terrain, along with diverse weather conditions ranging from severe thunderstorms to heavy snow in winter (2010). Radar energy moving away from its origin is absorbed by obstacles causing decreased power as a result of scattering and beam shape loss. The beam is subject to ground clutter and may duct towards the ground causing anomalous propagation that result in loss of track and engageability of BMD targets (Wagner, et al., 1999, pp. 123-124). Locations with middle to high elevation reduce blockage zones and thereby improve radar performance. The mountain range intersecting the country is a factor the location model must consider to avoid radar blockage. Figure 2 is a topographical view of Romania and clearly shows mountain range.

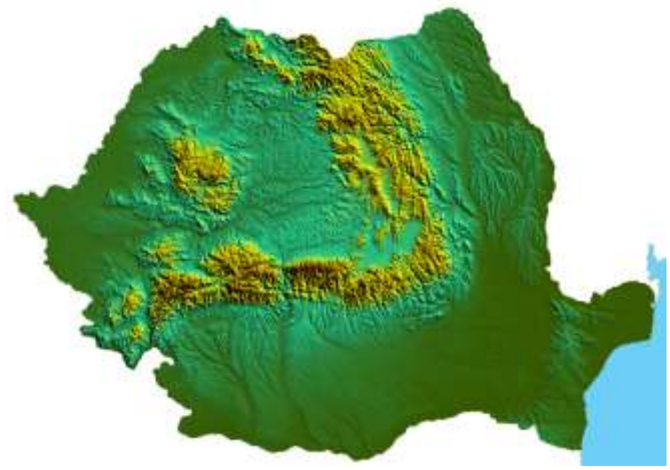

Figure 2: Romania (Adijapan, 2006)

S-Band radars have been emitting wavelength radiation safely since 1975 to develop, produce, integrate and test our nation's naval radars (Ellison, 2010). Research did not reveal Romanian public adversity of being located near radar sites. However, in the neighboring state of Hungary, there have been several failed attempts to install radar facilities, all resulting from public outcry for stopping the installation. The Hungarian NATO radar has been controversial since 2001. The main objection was due to environmental reasons and not fears of radiation (Xinhua News, 2010). As a result, environmental protection may need to be considered as a criterion for the site location. A lower population density in the selected location may alleviate environmental concern.

D. MAUT

In addition to MAUT, there are other methods discussed in literature that were briefly investigated. Fulop provides concise explanations of alternative decision methods. A summary of these methods are provided in the following table (Fulop, 2005, pp. 5-6):

Table 1: Decision Method Summary

Method	Concept
Pros and cons analysis	Simple list of good and bad attributes without mathematical formulation
Maximin and maximax methods	Strategy that tries to avoid worst possible performance and is best used on a common scale
Conjunctive and disjunctive methods	Strategy concerned with satisfactory rather than best performance in each criterion and alternative selection is based on screening rules
Lexicographic method	Strategy based on ranking the order of importance
MAUT	Strategy of weights associated with the criteria to properly reflect the relative importance of the criteria on a common scale

The approach of MAUT is based on weights being associated to criteria to reflect the relative importance of the criteria and based on the use of utility functions. The utility function can aggregate raw alternative values of unrelated criteria into a common scale (Fulop, 2005, p. 5). Utility theory is an analytical method for making a decision concerning an action to take, given a set of multiple criteria upon which the decision is to be based (Von Neumann & Morgenstern, 1947, pp. 15-17). In economics, utility is related to the expected ability to satisfy a human want (in terms of economic maximization). In decision theory, it is a measure of desirability of outcomes under uncertainty (Li & Soh, 2004, p. 8).

Simple Multi-Attribute Rating Technique (SMART) is a simple form of MAUT methods. SMART can provide decisions makers with greater understanding of decisions (Goodwin & Wright, 1999, pp. 33-36). An illustrative example using SMART to decide an office location is provided by Goodwin and Wright. They suggest the creation of a value tree to address attributes and general concerns. Since the value tree frames the problem, they warn that adjustment is frequently needed. Additional, to make this operational, the value tree may need to increase in size to capture important goals and criteria.

In preparation for this work, a trial edition of Logical Decisions for Windows (LDW) was downloaded and installed. The purpose was to gain better understanding of the software capabilities in creating SMART models (Logical Decisions, 2010) Two papers reviewed used LDW as the decision analysis tool of choice in location selection analysis (Canbolat, et al., 2005; Venable, 1998). LDW has the ability to present the decision information in a very professional manner. It produces graphical results for ease of understanding. One apparent problem was LDW's uncommon use of vocabulary words, making it difficult to compare the subject to discussions found in other literature. LDW uses 'measures' to express 'attributes' or 'criteria' that is commonly found in most decision analysis literature.

Microsoft Excel can be used to create the underlining SMART model and can provide suitable graphical presentation of the results. Middleton provides an implementation of SMART using Excel that will be leveraged to develop the model and display results (Middleton, 2003, pp. 1-10).

III. Model Formation

A. Value Tree

Value trees are hierarchal structures used to show an overview of the model. LDW software refers to the value tree as the goals hierarchy. A value tree frames the problem by helping to identify attributes used in the decision. A value tree is shown in figure 3 with one level of attributes. It defines a list of attributes used to satisfy the objective.

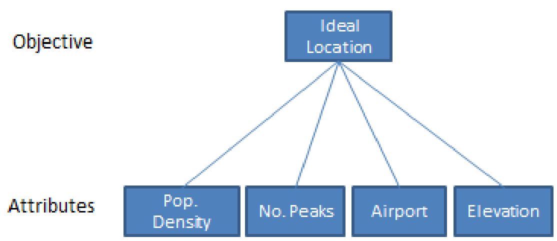

Figure 3: Value Tree

The overall utility function for a location has four attributes. They are population density, quantity of mountain peaks, inclusion of a major airport, and the average elevation above sea level.

Table 2 shows the attributes used in the model and the respective associations, along with preference assumptions.

Table 2: Attribute and Preference Association

Location Attribute	Preference
Population Density	Lower Preferred
Number of Mountain Peaks	Lower Preferred
Major Airport	Higher Preferred
Elevation	Higher Preferred

The territory of Romania is divided into 41 unique administrative districts or county. Each county is considered a candidate location for establishing an Aegis Ashore facility. The ideal location is based on the calculated utility function used in evaluation of each jurisdiction. Figure 4 shows the size and location of the counties.

Figure 4: Romania Regions (Spiridon, 2010)

B. Model

The multi-attributes model is based on information from a combination of course examples and reviewed literature (Hester, 2010). The model's output provides a utility score of the each candidate location. The low to high range identifies the location from less to most desirable. Location attribute data is linear with higher numerical values representing a better rating of the attribute. Our goal is to decide on the ideal location for an Aegis Ashore location, therefore, satisficing or accepting any candidate location that could meet minimum requirements was not taken into consideration.

The Romanian National Institute of Statistics provided the majority of model data (Romanian National Institute, 2007). It provided population data and the number of mountain peaks contained within a county boundary, along with major airport locations.

A location with lower population is considered a better candidate due to lowering the impact on Romanian society and less threat from disruption or terrorist attack. Additionally, it is believed that the desire to live in the proximity of an 'Aegis Ashore' location would be undesirable in the population.

Mountain peaks are very effective blockages to emitted radar and prevent full coverage. Therefore, to minimize the blockage would improve overall system performance.

The availability of a commercial airport for timely delivery of air transported supplies and personnel are essential since movement of equipment and personnel may be delayed in a crisis.

Radar is able to detect, track and engage BMD targets better at higher elevations. This lessens the effect of ground reflections and makes the radar system more effective. Generally, higher elevation provides better performance. Elevation data was derived by topographic map provided by The United Nations Environment Program (UNEP, 1997). The elevation data was provided in six ranges showing difference colors on a topological map shown in figure 5.

A county semi-transparent map of the counties was place on the topological map to provide estimated elevations for each county. Table 3 shows the assigned scores for each range.

Figure 5: Romania Topology (UNEP, 1997)

Table 3: Elevation and Score Association

Meters	Score
0 - 200	0
200 - 500	1
500 -1000	2
1000 - 1500	3
1500 - 2000	4
2000 -	5

A weighting scheme is implemented since attributes used in the model are not considered to have the same relative importance. Edwards & Newman state, "… some form of weighting is usually essential. Weights capture the essence of value judgments" (1982). The raw weighting values used in the model spans from one to one-hundred for all attributes. The attributes are normalized to effectively force trading-off one attribute for all other attributes in the model. The weights are subjective and could change from stakeholder to stakeholder. A means to easily manipulate the weights are provided in the implementation of the model.

There are two algebraic forms used to model the utility of an attribute. The form used to measure the relative importance when preferring a low value in the attribute set is shown in equation 1. Lower population density and minimum number of mountain peaks in a candidate location is preferred. These complementary attributes are included to lessen environmental concerns and lessen radar blockage zones respectively. The other form when preferring a high value is shown in equation 2. The algebraic forms of the additive utility functions are shown below:

When Lower Attribute Preferred

$$U_j = \sum_{i=1}^{n} \frac{Max(a_i) - a_{ij}}{Max(a_i) - Min(a_i)} (w_i) \qquad (1)$$

When Higher Attribute preferred

$$U_j = \sum_{i=1}^{n} \frac{a_{ij} - Min(a_i)}{Max(a_i) - Min(a_i)} (w_i) \qquad (2)$$

Where:

U_j = Utility value for a candidate location
j = Set of candidate locations {1, 2, 3 … 41}
a = Set of attributes {density, peaks, airport, elevation}
w = Set of normalized weights
$n = 4$

IV. Excel Implementation

The model is implemented in an Excel spreadsheet. Data was imported into Excel. The model was built using Visual Basic for Application (VBA). Code was inserted to view the data in a thematic map of each candidate county. This type of geographical visualization is called a thematic map, heat map or statistical map. The technique of creating thematic maps using Excel is derived from work explained by Robert Mundigl in his blog (Mundigl, 2008). Figure 6 shows the output of the MAUT model.

Sliders controls on the right hand side allow weight manipulation of attributes in the model. Changing the slider weight control provides insight into the sensitivity of the weight setting. Changes can be dynamically viewed in the thematic map. The model outputs the summation of the MAUT function and darkens the location on the thematic map from lower to higher in gradient scale from white to black. The darkest color represents the highest value and thus the more desirable location for the Aegis Ashore BMD system.

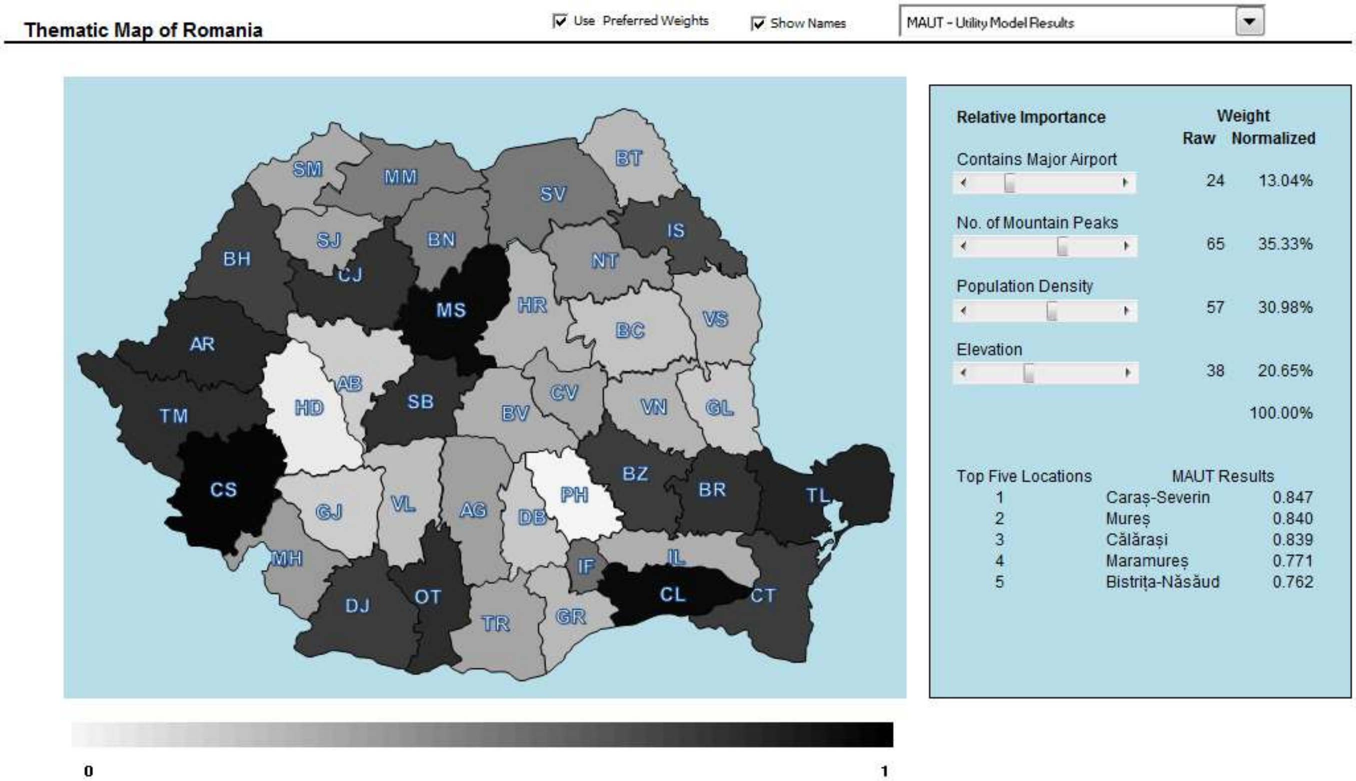

Figure 6: MAUT Results

The elevation utility function is an example of how higher values in the attribute data set are preferred since high elevation provides better radar coverage. This is contrasted to the population density function where a lower value or lower population density is preferred.

The elevation utility function with a higher preferred elevation is shown in figure 7. It shows a generally linear function with the elevation at several locations very low, thus providing sub-optimal performance.

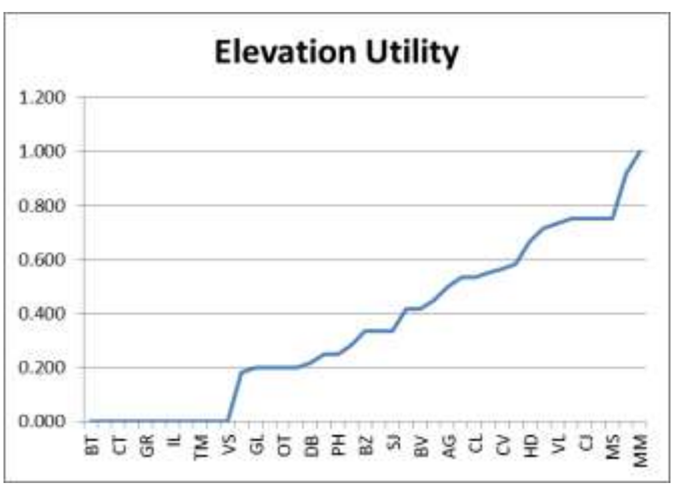

Figure 7: High Utility Preferred

The population density utility function with lower preferred population density is shown in figure 8. Notice the flatness of the function thus allowing most locations to be acceptable. The extreme right and left hand sides of the population density utility function shows very low density dropping down suddenly and very high density ramp up suddenly.

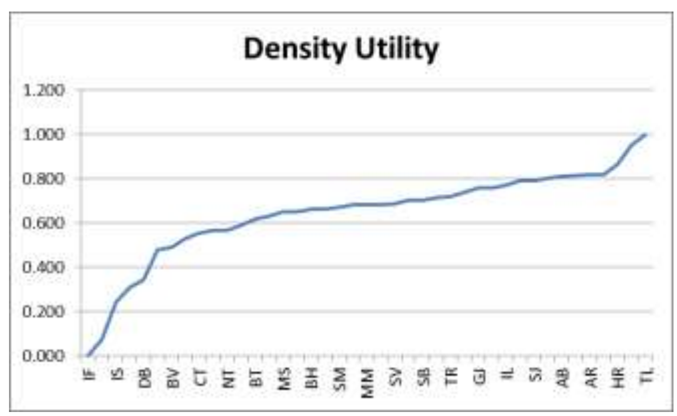

Figure 8: Low Utility Preferred

Trade-offs must be made due to conflicting preferences. In figure 7 the county of Maramureș signified by the abbreviation "MM" is shown on the right hand side to have the most preferential elevation. The county of Maramureș in figure 8 displays the relative utility in the middle of the data set. This is an example of where conflicting preferences must be made by accepting a location at a lower elevation to satisfy the need for lower population density.

V. Results Interpretation and Analysis

The weight of each attribute is set by adjusting the scrollbar on the Excel panel. Mountain peaks create blockage zones which lowers the radar system ability to provide search sectors is assigned the highest weight. A low number of peaks is most important. Low population density has the next highest rating followed by the location's elevation. Lower population density is thought to reduce the impact on the population and increase defensibility in case of an attack. Lastly, the attribute of containing or not containing an airport is important, since secure movement of technical personnel and supplies is required. Table 4 shows the assigned weights.

Table 4: Attribute Weights

Attribute	Weight
Airport in County	13.04%
Number of High Peaks	35.33%
Pop. Density	30.98%
Elevation	20.65%

The model output indicates that the county of Caraș-Severin (CS) is preference slightly over Mureș (MS) and Călărași (CL). Sliding the associated attribute's scrollbar permits the weight to be changed and the preferred weight checkbox disabled. Results of the change are viewed dynamically. Enabling the preferred weight checkbox returns the model to its original state.

VI. Conclusion and Future Work

While the utility model provides an adequate solution to the ideal location within Romania, further location specific refinement would enable higher granularity.

Additional sub-division of the forty-one county locations into smaller communes would enhance the models fidelity. There are 2686 communes in Romania (Romanian National Institute, 2007). To improve the decision, an increased number of local attributes could be used. Examples of improved local attributes are the proximity to manmade obstacles that create local blockage zones (e.g. radio antenna and bridges). There may be areas where microwave radiation is prohibited due to effecting equipment in hospitals or have an undesirable impact on wildlife. Figure 9 shows the smaller communes outlined in white. These smaller locations could be used to improve the model's fidelity.

Figure 9: Sub-Divisions within Counties (Rarelibra, 2007)

The current elevation data is fitted to a relativity large range of six discrete categories. Improved elevation data can be obtained by downloading Digital Terrain Elevation Data (DTED) formatted data that contains high resolution elevation information. This data is freely available on the internet (Geocomm, 2010). The mean elevation of small sections can be used as model input. Also, the data can be processed to eliminate locations with high slopes. To explore this concept in greater detail, data was downloaded and read using MATLAB software (Mathworks, 2009). MATLAB provides an engineering framework where large amounts of data can be easily manipulated. Figure 10 illustrates a map of Romania using downloaded DTED data using MATLAB.

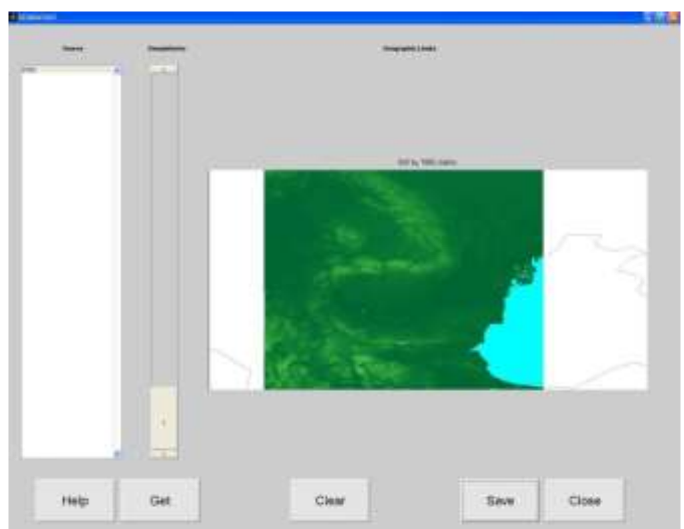

Figure 10: MATLAB with Imported DTED Data (Geocomm, 2010)

This model data could be refined by minimizing the Euclidean distance from major airports to a prospective location to facilitate movement of Standard Missiles (SM-3). Ragsdale (1998) provides a simple example to minimize the Euclidean distance using a combination of simple algebra and spreadsheet modeling. The objective function explained in his work is to minimize the distance between two or more points in a grid layout of candidate locations. This method could be employed to minimize the distance between a candidate location and major airport or roadway.

Other enhancements would be the inclusion of additional attributes to a candidate location. An example of an additional attribute is the closeness to existing Romania military facilities to provide security and local protection. Other examples include the abundance of electric power or the number of power sources to maintain the facility during an attack. More than seven attributes to weight may create confusion as the stakeholder attempts to evaluate each weight; however, a more ideal location may result.

VII. Appendix

A. Model Data

The companion Excel spreadsheet discussed in this paper contains data, formulas and VBA code. Contact the author to obtain a copy of the Excel 2007 or Excel 2010 file. The software is made available under the terms of the Creative Commons Attribution-ShareAlike 3.0 license. Copyright (c) 2010 by Randy Brooks.

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BIOGRAPHY

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