Geospatial Site Suitability Modeling for US Department of Defense Humanitarian Assistance Projects

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ABSTRACT

The purpose of this paper is to outline the requirement for data-driven methods for determining optimal geographic locations of United States Department of Defense (DOD) Humanitarian Assistance (HA) resources, including disaster mitigation and preparedness projects. HA project managers and tactical implementers charged with cost-efficient deployment of HA resources are challenged to produce measurable effects, in addition to contributing to broader Joint and Interagency-informed security assistance strategies. To address these issues, our ongoing research advocates geospatial multi-criteria site suitability decision support capabilities that leverage 1) existing geospatial resource location-allocation methodology as applied in government, retail, and commercial sectors; 2) user-generated criteria and objective preferences applied in widely-used decision frameworks; 3) assessments of the feasibility of obtaining data at a geographic scale where DOD tactical/operational level users can benefit from the model outputs; and 4) social science theory related to the HA domain criteria that form the foundation of potential decision models.

Keywords

Geospatial analysis, site suitability analysis, multicriteria decision modeling, disaster mitigation, disaster preparedness, analytic hierarchy process

INTRODUCTION

Within the range of military operations described in the Doctrine for Joint Operations (United States Joint Chiefs of Staff, 2001), Phase 0 (shape, prevent, prepare) operations are becoming increasingly important methods of engagement, as Department of Defense (DOD) support for non-kinetic operations has grown following recent guidance (United States Joint Chiefs of Staff, 2009). The Civilian-Military interface is critical for promoting the conditions for sustainable stability in nations with cooperative security relationships with the US DOD and other US Government entities. Humanitarian Assistance (HA) operations are an enabler of such stability, and are an integral component of DOD Civil-Military Operations (CMO). DOD personnel operating in the HA domain must be able to support Partner Nation governments and civilians with capacity-building programs and projects that will lead to best practice management of humanitarian situations and disasters. As a result, there exists a strong command requirement for DOD-sponsored and interagency-endorsed efforts (projects) that are likely to support reaching this functional end state.

Determining an effective and efficient strategy for deploying resources in these often complex operating environments requires evaluating multiple criteria and/or potential courses of action, many of which may represent competing interests or phenomena. Particular interest has been paid recently to multi-hazard Risk and Vulnerability Assessments (RVA), due to their ability to characterize areas of operation and aid in determining where resources can have significant impact on populations who might be highly affected by disasters and complex emergencies, as well as areas that may be at risk for instability. A lack of fine-resolution data (e.g. at the district or equivalent administrative boundary level) has resulted in limited success when applying data-driven approaches that are meant to impact partner nation stakeholders at these scales. Other command-driven criteria are subject to the same limitations, due in part to permissiveness or restrictions within the operating environment, or resource constraints leading to the inability to collect sufficiently sampled data on populations of interest.

One prominent example of DOD HA deployment is the Overseas Humanitarian, Disaster, and Civic Aid

(OHDACA) Congressional appropriation, administered by the Defense Security Cooperation Agency (DSCA). For Fiscal Year 2013, the OHDACA program saw 440 project proposals from five Geographic Combatant Commands (GCCs), with a total requested cost of roughly $108M (DSCA, 2012). OHDACA projects are currently characterized by a sector-subsector structure, and encompass a range of project types. Typical OHDACA projects include those in the Disaster Mitigation and Preparedness Training, Education, Infrastructure, and Health sectors. The projects can be structural (e.g. Emergency Operations Center construction, bridge repair, well drilling) or non-structural (e.g. disaster preparedness training). Projects are nominated and approval is managed through the Overseas Humanitarian Assistance Shared Information System (OHASIS), a Web-based capability built using a Geographic Information System (GIS) architecture. In 2012, DSCA introduced a new capability allowing users to submit an extended After Action Review (AAR) in order to provide a greater repository of success stories, lessons learned, and objective measures of performance.

Systems such as OHASIS have been critical for tracking and managing the life-cycle of DOD HA assets. The opportunity exists to extend these capabilities to create data-driven, repeatable approach to support decisions about resource allocation in geographic space. Many of the criteria used in OHDACA project placement decision process, such as the location and characteristics (e.g. sector, objectives, funding, time frame) of existing projects are known, and projects are geospatially-referenced. Further decision criteria, such as accessibility inferred through infrastructure availability (roads and public transportation data), physical land characteristics (e.g. slope, elevation), and land use classifications are widely available at certain geographic scales, and could be applied to the decision space, opening the door to adoption of widely-used multi-criteria decision models that have proven useful in several other domains.

Thanks in large part to the broad set of applications utilizing Multi-Criteria Decision Modeling (MCDM) and Site Suitability Analysis (SSA), DOD decision makers have many validated capabilities available to support them in determining optimal resource allocation strategies (Malczewski, 2006). The following sections will describe MCDM and related SSA concepts and an overview of requirements for applying these methods to the DOD HA decision space.

AN OVERVIEW OF MCDM AND SSA

At a basic level, evaluating where to commit HA resources involves answering questions that will inform decisions related to funding, level of effort, and the likelihood that the investment will produce appropriate returns (e.g. stability, partner nation well-being). Multiple (sometimes competing) criteria bound the decision space, requiring the decision-maker to assign relative importance to factors based on previous experience, scientific knowledge, or perhaps personal biases (Malczewski, 2004; Pereira and Duckstein, 1993). Application of a formal structure, such as those brought to bear in MCDMs, provides a necessary means of traceability to the decision space. In cases where multiple experts are consulted to provide preference data, traceability allows discrepancies to be identified, if not resolved. Decision-makers are asked to explicitly compare a set of criteria or objective statements, thus creating a weight matrix that is applicable to later stages in the hybrid MCDM-SSA process. Decision criteria are often described and measured as objective factors (e.g. numerical) or subjective factors and qualitative definitions (Liang and Wang, 1991). Objective factors can be normalized through mathematical transformation, whereas subjective factors must be assigned or ranked using another methodology. In many cases, these factors may be subject to preference reviews from multiple experts, requiring another process for determining a final weight matrix from the inputs.

It is important to distinguish various applications of MCDM-SSA based on a small but critical nuance. In some cases, the decision-maker may be presented a list of existing sites from which to select, requiring a short-list of prioritized sites to be generated. In other cases, the potential sites can be selected from a continuous area, requiring the prioritization to be done on the actual geographic space, rather than on a list of sites. The MCDM methods outlined in this paper are able to handle both cases, and support an eventual two-step process where geography is used to pare down a list of potential sites. However, the data requirements are significantly different for the two approaches.

A full literature review of MCDM science and methods is beyond the scope of this paper (a useful reference can be found in Malczewski, 2006). However, recent efforts to apply these techniques to criteria represented by geospatial data are directly applicable to the HA domain decisions we are evaluating in this paper. One such MCDM is the Analytic Hierarchy Process (AHP).

Analytic Hierarchy Process (AHP)

The strength of AHP (Saaty, 1980, 2008) lies in its ability to capture human preferences among the criteria and objectives in a complex decision space, and generally serves as a means for decomposition of the problem, comparative judgment, and synthesis of priorities (Estoque, 2012). The AHP evaluation provides the user a means to perform pairwise comparisons between the criteria, objectives, or alternatives relevant to the stated goal/question in order to build a preference matrix (Boroushaki and Malczewski, 2008). Once completed, the normalized principle eigenvectors of each matrix row are calculated, providing a relative weight value that can be taken as the relative importance of that factor in achieving the goal (Saaty, 2008). To manage consistency of judgments, a consistency ratio (CR) is calculated; when the threshold value exceeds 0.1, it is suggested that the pairwise comparison is inconsistent and needs to be redone (Boroushaki and Malczewski, 2008). The outcome of the AHP is a set of weights that can be applied to all values across a geospatially-referenced dataset.

Geospatial Site Suitability Analysis

Once the AHP has generated the weights matrix, the geospatial datasets (layers) that represent criteria in the decision space can be evaluated and assigned a suitability score. Many geospatial SSA processes use a Weighted Linear Combination (WLC) approach to determine a final suitability map. The WLC is a simple additive weighting method that applies the weights obtained from the matrix equally across all values in each dataset; once weighted, the values for each geographical location are added together to create a derived suitability layer (Malczewski, 2000, 2004). In the case of multiple objectives (e.g. a site should be accessible and in a perceived area of vulnerability), additional weights can be applied using the derived suitability layer for each objective, and the process is repeated.

While the geospatial MDCM provides a methodology for user-contributed preferences and geospatial layer generation, several factors must be considered before the models can produce valid and actionable results. There is a significant amount of effort required to standardize the geospatial data that form the foundation of the model (Jiang and Eastman, 2000; Malczewski, 2004). In many cases, the data are related at the domain level, but are collected using different methods (e.g. opinion survey vs. remotely sensed imagery) and are represented by incomparable measurement units (e.g. Likert Scale responses to surveys vs. reflectance values in imagery). Subject matter experts must be consulted to develop or identify existing reclassification or normalization methods that will result in applicable quantitative values. As with any index, the standardized values must be accompanied by the appropriate definitions and traceability to the raw data in order to ensure that users of the model will adequately understand how individual layers contribute to the model outputs. Adequate consideration must be given to linguistic (e.g. "Very Low," "Medium," "High") or fuzzy weighting sets that translate to an associated quantitative value (Banai, 1993).

Using the methods described above, it is possible to produce a static matrix and model output that adequately characterizes the HA suitability considerations in the decision space. However, this approach can be extended to provide users with the ability to dynamically generate model outputs on-demand. In the DOD case, a commander making a decision will have preferences that may be related to other operations (e.g. other Theater Security Campaign Plan objectives), or may be taking part in "what if" scenario modeling at finer geographic scales. Inputs to the preference matrix and the extent of the geographic study area can be elicited using various graphical user interfaces (GUIs). It is also possible to create a hybrid approach that takes into account previously-identified, social science- or expert-derived weights that can influence the on-demand preference matrix. The model structure and weighting scheme used by some of the indexes in existing RVA studies can guide the proposed HA SSA model criteria. For example, a Health Status Index (Pacific Disaster Center, 2012) uses a weighted average of life expectancy at birth, infant mortality rate, maternal mortal ratio, and undernourishment prevalence to calculate values 0 to 1, with 1 being the highest level of vulnerability. Other research into organic responses to mega-disaster events has shown the influence of evaluating social capital indicators such as the number of local non-profit organizations created or activated during humanitarian interventions (Aldrich, 2012). When evaluated in the context of dynamic command priorities, such as limiting exposure of military or civilian personnel to known non-permissive operating environments, expert-derived social science indexes and constructs can provide a better informed, data-driven justification for deciding to commit project resources to a given a geographic location over other options.

DATA REQUIREMENTS FOR GEOSPATIAL MDCM AND SSA

The site suitability methodologies identified in this paper have a common requirement for geospatially-referenced data sources. In many cases, the initial data source may reside in tables or spreadsheets that are not explicitly georeferenced (i.e. do not contain any sort of geographic coordinates that would allow them to be placed on a map representation of the world). These issues can be addressed with common operations such as joining the table to an existing geographic administrative boundaries dataset based on a unique key field.

Scale is one of the critical challenges to robust site suitability analysis. Many of the data applicable to HA projects SSA have been aggregated to the country boundary level of resolution. This is an example of geospatially continuous data, where a single variable (attribute) in the layer holds one value meant to be representative of all space within that geographic boundary. These values can be applied at finer resolutions, but are likely to obscure the natural geospatial variation that takes place at much finer scales of analysis (e.g. districts, villages may vary greatly in reality, but this is lost in the sampling). Conversely, discrete data are available at much finer geographic scales, and are often represented by point locations (i.e. a single coordinate pair). For SSA, discrete data points can be aggregated based on frequency or intensity of occurrence within a particular geographic boundary. The result of this aggregation, in the case of numerical data, can be mathematically-transformed values such as the mean, sum, or median of the records being aggregated; for other data types, a simple count can be the output used to describe the layer at the newly aggregated administrative boundary level. This manipulation is often a necessary step in normalizing the data to the desired geographic scale of analysis, and allows the layers to be compared in the MCDM. However, as with any analysis of this type, the coarsest resolution data represents the finest resolution to which the analysis can be carried out with any validity. This is particularly challenging for socio-cultural data. For example, the World Bank carries out surveys at the national level for many criteria relevant to HA project decisions, but these are not always applicable at the tactical or operational levels.

In response to the limitations imposed by scale and resource constraints, researchers are actively engaging in the development of innovative methods for increasing sample size without increasing the budget. Crowdsourced geospatial data (CGD) is an emerging trend within the geospatial industry and has become an accepted alternative data production method from the traditional authoritative data production methods employed by governments. CGD leverages the efforts of volunteers or other persons not formally trained in geospatial science to collect new and edit existing data. To initiate a CGD effort, a data call is put out and a data collection platform is put in place for users to generate new data. One perceived limitation to this approach is quality control, since multiple and sometimes unconfirmed sources are used in conjunction with more trusted contributions. Often the best quality control mechanism is the advantage of having numerous eyes looking at and, if necessary, correcting existing data. OpenStreetMap (OSM; http://www.openstreetmap.org/) is an example of a successful crowdsourcing application with the goal of mapping the entire world through user contributions. In the same line of operations, Ushahidi (http://www.ushahidi.com/) provides a deployable platform for users to submit both field-based and Web reports by anyone through structured SMS, mobile apps, or Twitter. Previous deployments of Ushahidi have supported knowledge of complex emergencies in Kenya, Libya, Japan, and Pakistan. The potential for meaningful contributions from “bounded crowdsourcing,” or receiving reports from a set of vetted and trusted users, is significant to the development of the geospatial datasets that might inform the MCDM-SSA structures in this paper.

Within the DOD and the individual Services, greater attention is being directed toward supporting CMO through Civil Affairs (CA) activity. An example of this can be found in Phase 0 priorities of US Marine Corps CMO, where Civil Information Management (CIM) is the predominant activity undertaken by CA personnel (United States Marine Corps, 2003). Recent efforts have led to the standardization of CIM into discrete categories and assessments forms that allow for data to be collected using smartphones and Web applications. CIM, in this form, is still in its infancy, but the demand signal for standardized, highly available structured data concerning the civil-military interface is driving significant research and development of capabilities that can feed data into MDCM-SSA capabilities. CA data collectors are performing assessments on infrastructure (e.g. buildings, schools, roads), government structures (key leader engagements), and humanitarian issues (dislocated civilians, district stability framework, health projects), among other activities. Since the systems supporting these efforts record the time and location of each assessment, they provide ground-truthed data representing the criteria important to HA project resource allocations, and can reasonably be incorporated into MCDM-SSA.

SUMMARY

Several opportunities exist for DOD HA managers and decision-makers to improve the likelihood that their resource allocation strategies will result in an optimal return on investment. In the HA domain, these returns are sometimes difficult to quantify. A robust structure for providing support to assertions regarding the best placement of limited HA resources should include widely-applied decision models and suitability assessments. Many such technologies and frameworks exist and can readily be applied to the DOD HA decision space. The MCDM and SSA approaches outlined in this paper represent a first step in ongoing research toward addressing data and information gaps. Advances in geospatial technology, Web-based user interfaces, mobile data collection capabilities, and crowd-generated data have the potential to greatly improve the business processes in a rapidly expanding approach toward defense, diplomacy, and development.

REFERENCES

1. Aldrich, D. P. (2012) Building Resilience: Social Capital in Post-Disaster Recovery. University of Chicago Press, Chicago.
2. Banai, R. (1993) Fuzziness in Geographical Information Systems: contributions from the analytic hierarchy process. *International Journal of Geographical Information Science*, *7*(4), 315–329.
3. Boroushaki, S. and Malczewski, J. (2008) Implementing an extension of the analytical hierarchy process using ordered weighted averaging operators with fuzzy quantifiers in ArcGIS. *Computers & Geosciences*, *34*(4), 399–410.
4. Defense Security Cooperation Agency (2012) Fiscal Year 2013 Budget Estimates, Overseas Humanitarian, Disaster and Civic Aid. Retrieved January 11, 2013, from http://comptroller.defense.gov/defbudget/ fy2013/budget_justification/pdfs/01_Operation_and_Maintenance/O_M_VOL_1_PARTS/O_M_VOL_1_BASE_PARTS/OHDACA_OP-5.pdf.
5. Estoque, R. C. (2012) Analytic Hierarchy Process in Geospatial Analysis, *Progress in Geospatial Analysis*, ed. Y. Murayama, Springer Japan.
6. Jiang, H. and Eastman, J. R. (2000) Application of fuzzy measures in multi-criteria evaluation in GIS. *International Journal of Geographical Information Science*, *14*(2), 173–184.
7. Liang, G.-S. and Wang, M.-J. J. (1991) A Fuzzy Multi-criteria Decision-making Method for Facility Site Selection, *International Journal of Production Research* 29, 11, 2313–2330.
8. Malczewski, J. (1996) A GIS-based approach to multiple criteria group decision-making. *International Journal of Geographical Information Systems*, *10*(8), 955–971.
9. Malczewski, J. (2000) On the use of weighted linear combination method in GIS: common and best practice approaches. *Transactions in GIS*, *4*(1), 5–22.
10. Malczewski, J. (2004) GIS-based land-use suitability analysis: a critical overview. *Progress in Planning*, *62*(1), 3–65.
11. Malczewski, J. (2006) GIS-based Multicriteria Decision Analysis: a Survey of the Literature, *International Journal of Geographical Information Science* 20, 7, 703–726.
12. Pacific Disaster Center (2012) Global Hazards Information Network (GHIN) Health Status Index. Pacific Disaster Center, Kihei, HI. Retrieved January 11, 2013, from http://www.pdc.org/mde/full_metadata.jsp?docId={BA5E53D4-02FB-4AE7-A2D1-D94EC4C046E3}.
13. Pereira, J. M. C. and Duckstein, L. (1993) A multiple criteria decision-making approach to GIS-based land suitability evaluation. *International Journal of Geographical Information Science*, *7*(5), 407–424.
14. Saaty, T. L. (1980) The analytic hierarchy process. McGraw-Hill, New York.
15. Saaty, T. L. (2008) Decision Making with the Analytic Hierarchy Process, *International Journal of Services Sciences* 1, 1, 83–98.
16. United States Joint Chiefs of Staff (2001) Doctrine for Joint Operations (Joint Publication 3-0), Washington, DC. Retrieved September 20, 2012, from http://www.dtic.mil/doctrine/new_pubs/jp3_0.pdf.
17. United States Joint Chiefs of Staff (2009) Stability Operations (Department of Defense Directive 3000.05), Washington, DC. Retrieved September 20, 2012, from http://www.dtic.mil/whs/directives/corres/ pdf/300005p.pdf.
18. United States Marine Corps (2003) Marine Air-Ground Task Force Civil-Military Operations (MCWP 3-33.1), Quantico, VA. Retrieved September 20, 2012, from http://www.marines.mil/Portals/ 59/Publications/MCWP 3-33.1 Marine Air-Ground Task Force Civil_Military Operations.pdf.