The State of Spatial Optimization in GIS: Review, Assessment, and Projections

THE UNIVERSITY OF ALABAMA

Kevin M. Curtin, PhD; Department of Geography and Laboratory for Location Science; University of Alabama; kmcurtin@ua.edu

Laboratory for Location Science

Introduction

The ongoing revolutions in high-performance computing and in the analysis of spatial data, combined with continued refinement of optimization solution procedures, are fundamentally changing the landscape for performing spatial optimization in the context of Geographic Information Systems (GIS). The number and types of optimization problems that are envisioned and formulated is continually growing. The demand for spatial optimization regularly extends to new application areas. The size of problems that can be approached with optimization grows as the bounds of tractability are pushed outward. Taken together these developments have altered the ways in which spatial optimization in GIS can be performed, and how the techniques are presented in an educational context. This session is dedicated to examining the changing practice of spatial optimization in the context of GIScience, identifying the current frontier of the possible in this field, and identifying challenges and opportunities for continued education and development in the future.

Spatial Optimization as an Integration of Disciplines

The notion of integration is foundational for the topic of Spatial Optimization. Fundamentally, Spatial Optimization requires the integration of the spatial analytic methods of Geography as instantiated in Geographic Information Systems (GIS), with the optimization techniques of Operations Research (OR). This integration is designed to solve problems that neither discipline could solve in isolation. Geographers are particularly well-suited to examine boundaries…we know that boundaries are the places where interaction is focused, where both conflict and cooperation are engendered, and therefore where the most dramatic changes occur. The boundaries between disciplines are similarly fruitful areas for change and advancement. This poster session embraces the boundary between GIScience and operations research as the space where integration will lead to mutual beneficial change.

$$\text{Maximize } Z = \sum_{i \in I} a_i y_i$$

Subject To:

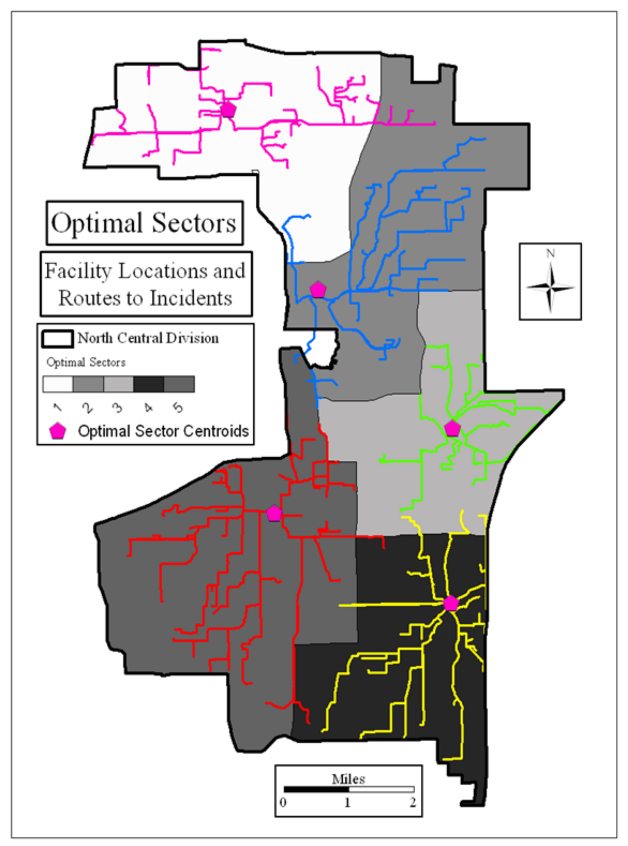
$$\sum_{j \in N_i} x_j \geq y_i \quad \text{for all } i \in I \qquad (1)$$

$$\sum_{j \in J} x_j = P \qquad (2)$$

$$x_j = (0,1) \quad \text{for all } j \in J \qquad (3)$$

$$y_i = (0,1) \quad \text{for all } i \in I \qquad (4)$$

Maximal Covering Formulation

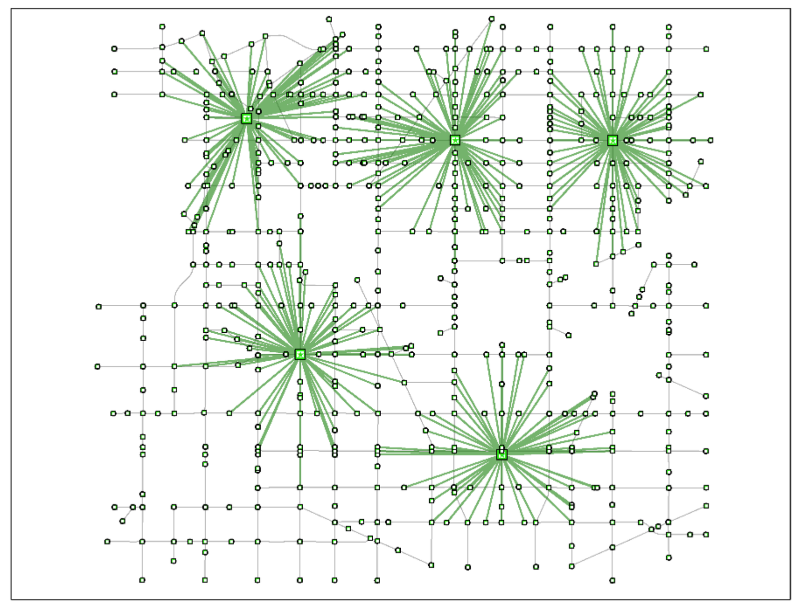


Spatial Outcome in the Context of Police Patrol [1]

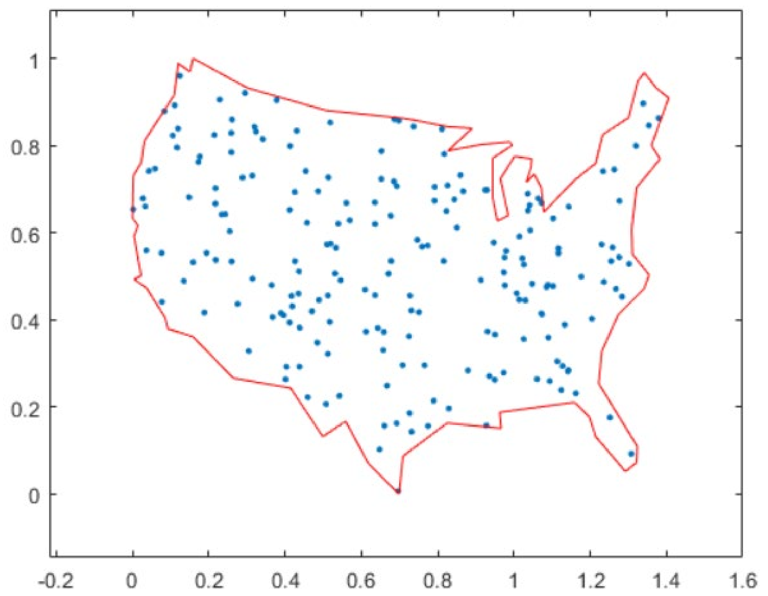
Current Practice

As GIS and OR integration has proceeded over four decades the two sets of techniques and tools have almost exclusively been loosely coupled. This generally takes two forms: either a standalone technique from one field is adopted into the other, or tools from both fields are used sequentially, but separately.

As an example of the first case, consider that heuristic solution procedures for a relatively small number of spatial optimization problems have been integrated into off-the-shelf GIS applications. True global optimization techniques and the ability to formulate and solve custom optimization problems have remained in the domain of OR and its associated solution software. Similarly, some OR software has adopted some display options that only touch on the cartographic capabilities of GIS, let alone the broad suite of spatial analytic tools that are available.

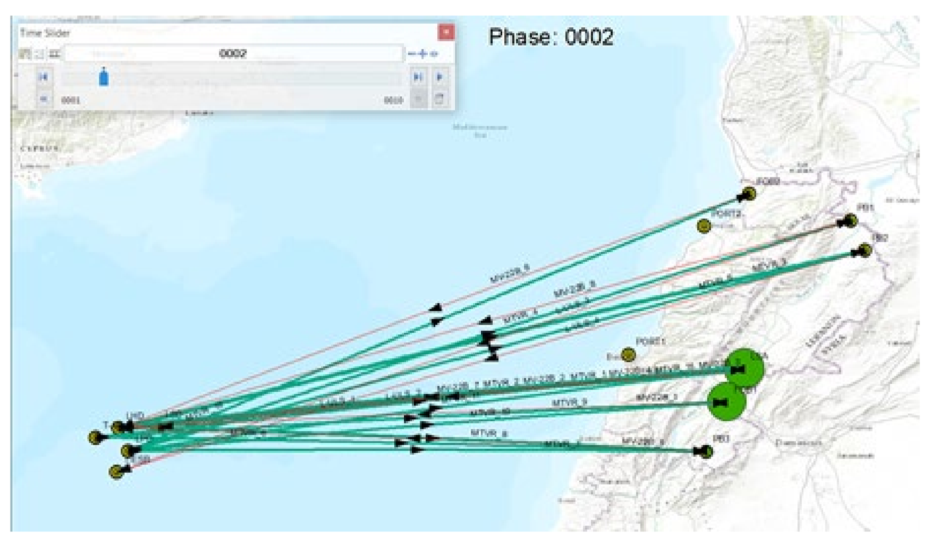


A P-Median solution generated heuristically in a GIS



A crude map generated from mathematical optimization software

In the second case the GIS and OR software essentially depend on each other to provide input data, or to post-process output data. An example is when the GIS is used to store spatial databases regarding supply and demand location, and compute origin-destination distance matrices. These are then transferred to populate the data files necessary to conduct the optimization. The optimization produces a rather unintuitive set of variable values that indicate the location of facilities or the movement of goods across the space under study. These variables can be transferred back to the GIS for display, or for further post-processing with spatial analytic tools. With the availability of general purpose programming languages these transfers of data between software domains can be automated to some extent, but the processing flow remains a sequential use of separate tools.



The output of a sequential process of creating and storing spatial data, transferring to linear programming solution software, and transferring back for display, query, and spatial analysis of the results in a logistics operation [2]

The Realm of the Possible

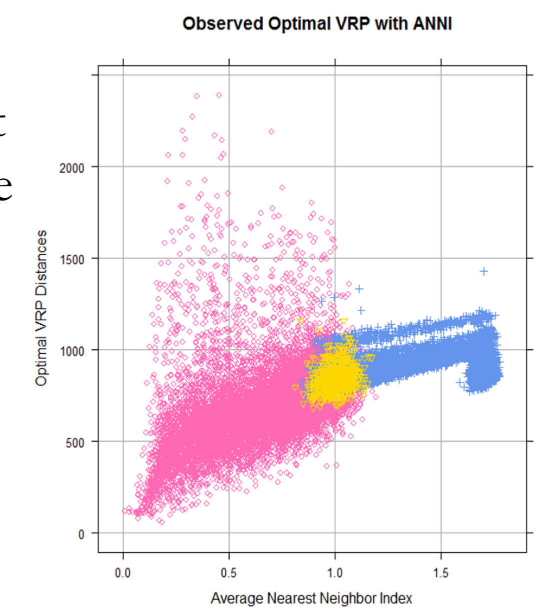
One can observe several key developments that are likely to change the landscape of Spatial Optimization in the foreseeable future. We consider here two of these, one applied and one theoretical. The former is the ongoing revolution in computing power. The latter is the direct introduction of spatial analytic techniques into the modelling processes in OR.

Many of the models addressed in spatial optimization are highly combinatorially complex. That is, the number of possible location combinations that need to be examined in order to determine the optimal solution is so large that solution procedures will exhaust their resources (generally computer memory or time) before the solution is reached. While a solution to overcome the fundamental nature of this class of problems in likely in the near future, the advent of high performance computing – including cloud computing – is pushing outward the bounds of tractability. With the ability to address larger problems it is likely that spatial optimization will be applicable in a larger set of domain areas.

Second and perhaps more importantly research advances are being made that are moving beyond sequential but separate integration of GIS and OR techniques toward fundamental integration of spatial analytic techniques in the modelling and solution processes of OR. By way of two examples, consider that the results of spatial statistics such as the identification of spatial clusters can be used to approximate the length of routing solutions, allowing the analyst to put bounds on the problem space and be more likely to generate the optimal solution quickly [2].

Similarly another poster in this session shows that identifying landform shapes that are more suitable es can dramatically reduce the size of the problem instance, bringing it within the bounds of tractability.

In summary, there are key ways in which the methods of GIS and OR can be more tightly integrated, allowing the solution of problems that could not be solved by either discipline in isolation.



Length of routes associated with different point patterns

Key References

[1] Curtin, K.M., K. Hayslett-McCall, and F. Qiu (2010) "Determining Optimal Police Patrol Areas with Maximal Covering and Backup Covering Location Models", Networks and Spatial Economics, 10 (1) 145-165.

[2] Mei, Xi (2015) "Approximating the Length of Vehicle Routing Problem Solutions using Complementary Spatial Information", Doctoral Dissertation, George Mason University.

[3] Heyns, A., W. du Plessis, K.M. Curtin, M. Kosch, G. Hough (In review) Analysis and exploitation of landforms for improved optimisation of camera-based wildfire detection systems.