PUBLIC BIKE SHARE STATIONS IN INDIANAPOLIS:

A LOCATION ALLOCATION STUDY

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Samuel D. Cooper

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A LOCATION ALLOCATION STUDY

Location Allocation, rooted in Operations Research and Mathematical programming, allows real world problems to be solved using optimization (based on mathematics and science) and equity principles (based on ethics). Finding nearest facilities for everyone simultaneously is a task solved by numerical and algebraic solutions. Bikeshare as a public good requires equitable allocation of bikeshare resources. Distance, as an impediment, can be minimized using location allocation algorithms. Since location allocation of this kind involves large numbers, sophisticated algorithms are needed to solve them due to their combinatorically explosive nature (i.e. as 'n' rises, solution time rises at least exponentially – sometimes called 'Non Polynomial Time-Hard' problems). Every day, researchers are working to improve such algorithms, since faster and better solutions can improve such algorithms and in turn help improve our daily lives.

Aniruddha Banerjee, Ph.D., Chair

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Introduction

Public bike sharing programs offer an alternative method of transportation in urban environments that can not only help to lower the emission levels of greenhouse gases, but can also increase public health while offering cost savings to users who choose to bike instead of drive (Fishman, 2014). The concept of public bike sharing is quite simple—there are a set number of bicycles dispersed through docking stations within a given area as small as a college campus or as large as a city metro. Riders pay to check out a bike from one docking station and then return it to the same or another once they are done. The docking stations for a public bike sharing program along with the streets and bike paths of a city make up its geographic network, and help to bind the range of service the program can provide. In the current age of bike sharing riders pay using either credit or debit cards or a subscription card that can be sold to more frequent users (DeMaio, 2009, p.42). Some bike share programs offer subsidized memberships for those with lower incomes.

Public bike sharing has gone through three different generations throughout the years, beginning with the launch of "Witte Fietsen," or "White Bikes," started in Amsterdam in June of 1965. In this program, ordinary bikes were painted white and "[o]ne could find a bike, ride it to his or her destination, and leave it for the next user." The lack of docking stations and a proper tracking system led to thefts and vandalism of bikes, ultimately leading to the program's collapse within a few days. This would later lead to the second generation of the early-1990s based on a coin deposit system and eventually in the mid-1990s the third generation of magnetic

swipe card recognition (DeMaio, 2009, p.42). By using magnetic swipe cards such as credit and debit cards an extra layer of security is established in which those that do not return bikes are traceable.

One of the most useful innovations of third generation bike share systems is the ability to track the usage of bikes using data collected by each bike share station such as location checked in, location checked out, time of check in, time of check out, and billing zip code. In some cases data can be obtained from GPS units in each bike that generate a point every few seconds during a bike's trip, providing a way to map and visualize individual paths of users (Fishman, 2013, p. 148-149). This is especially useful in determining where demand for additional bike trails or docking stations may be needed within a bike share's network.

Figure 1 and Table 2 depict US cities with public bike share programs, when they began, and how many stations they each include.

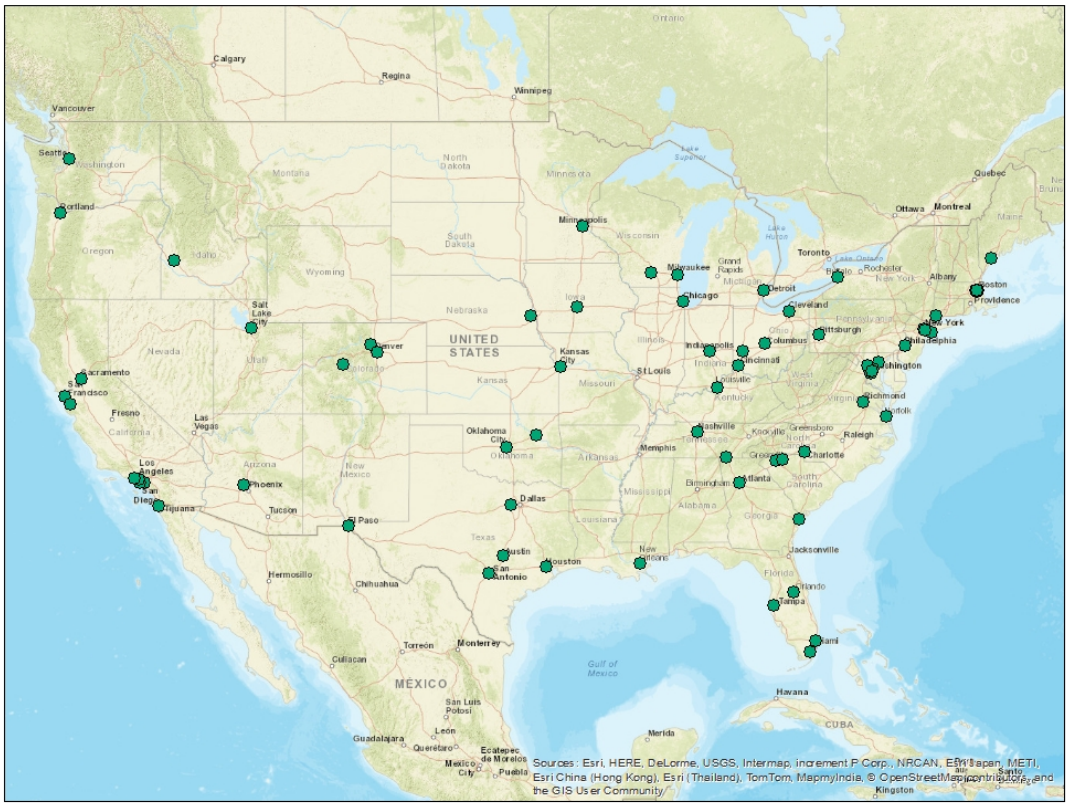

Figure 1: Contiguous US Cities with Public Bikeshare Programs (Bikeshare, March 2017)

This study focused on the Indiana Pacers Bikeshare system, launched in Indianapolis, Indiana on April 22nd, 2014 with twenty-five docking stations and two hundred and fifty bikes (Benbow. 2014). The Pacers Bikeshare is interconnected with the Indianapolis Cultural Trail, an 8-mile long bike and pedestrian path that connects multiple downtown neighborhoods and cultural districts, through its strategic placement of stations along or near the trail. The trail was originally dedicated to its largest sponsors, Eugene and Marilyn Glick, and has become a major artery for non-motorized-traffic in parts of downtown Indianapolis. Since its

inception, four new docking stations have been added to the Pacer Bikeshare system bringing the total to twenty-nine.

The Pacers Bikeshare program falls into the third generation of bikeshare programs. Customers either use their credit card to purchase a twenty-four hour pass or a previously purchased membership card to take unlimited thirty-minute trips. Customers incur progressive fees for trips longer than thirty minutes, but are allowed to check a bike back in and then immediately back out to reset the timer.

The costs associated with a bike sharing program can be staggering. According to a U.S. News report on the Capital Bikeshare in Washington D.C., docking stations "can cost well over $50,000 each" (Kurtzleben, 2012). The margins on operating a bike share program are slim, meaning that systematic inefficiency through suboptimal docking station placement can potentially cause a program to go under. GIS and location allocation algorithms can help to build a better network and thus improve efficiency.

Location allocation problems were first posed by S. L. Hakimi in 1965 when he put forth the P-Median problem, a model used to locate facilities so that the distance between customers (demand nodes) and facilities (supply nodes) were minimized across the whole of the network (Hakimi, 1965). Through geographic analysis the level of efficiency of a given program can be quantified and potential changes to increase the efficiency and coverage of its network can be provided.

The maximal covering algorithm was employed in order to solve the location allocation problem in the current study and determine optimal station location placement while achieving full coverage over the study area. P-median algorithms

were originally considered but were not incorporated since they require a set number of stations to allocate across the network. This would require a set number of stations to be determined before running the model and prioritizes efficient placement over full coverage. The difference with maximal covering algorithms is that they continue to add stations until full coverage is achieved. The emphasis on full coverage in this study was based on developing a model that would improve equality to access the bikeshare system throughout the study area. Since the P-Median problem only looks to minimize the average cost of service to all users, a solution set may not adequately service the entire population. The strength in the maximal covering problem is that it looks to minimize the highest cost of service throughout the network so that each demand source is serviced to a minimum of the chosen degree.

Design

The aim of this study was to determine the current coverage of docking station locations for the Pacers Bikeshare throughout Indianapolis and to explore how to best expand and locate stations using location allocation algorithms so that the central portion of the Indianapolis metropolitan area, bounded by Center Township, would have full coverage. Full coverage was considered using three different measures: locating docking stations within a half mile, one mile, and two miles of every location within Center Township.

These definitions of full coverage are presented to shape the study while examining the feasibility and number of docking stations that would be required to cover Center Township within a reasonable walking distance. A finite set of locations within Center Township was defined as the centroid of each 4219 census block. Census block centroids were chosen because they offered a reasonable balance between coverage and algorithmic efficiency so that the algorithms weren't overloaded with potential locations.

In total there were three levels of efficiency generated and considered during this study:

1. Coverage efficiency using the maximal covering location problem to generate full coverage within half a mile
2. Coverage efficiency using the maximal covering location problem to generate full coverage within one mile
3. Coverage efficiency using the maximal covering location problem to generate full coverage within two miles

Part of the aim of this study was also to determine whether or not this problem can be solved using different mainstream GIS programs. The primary program utilized in this study was TransCAD™ 7.0. TransCAD™ was chosen for its renowned ability to handle network problems with built-in network, routing, and logistics capabilities. The secondary program, ArcMap™10.4.1, was chosen to determine if the market leading program in GIS provided the functionality to handle and solve large NP-hard problems like the ones discussed in the previous paragraph.

By employing the maximal covering model using TransCAD™, optimum locations for docking stations were identified. Network partitioning was also used on the original docking stations and the outputs from the maximal coverage model in order to determine the levels of efficiency for each modeling approach.

To contrast the TransCAD™ solutions, the same problem was attempted using ArcMap™ and its Location Allocation functions. After executing the half mile problem with the same parameters that were run in TransCAD™ and letting the program run for a week straight it was determined that ArcMap™ was not sufficiently capable of handling this problem.

In order to come out with some semblance of ArcMap™'s capabilities 10% of the census block centroids were randomly selected and chosen as the new set of potential sites. This was to further limit the scope of the problem in order to determine if ArcMap™ could provide a relative answer to this problem. Even this limited problem proved too much for ArcMap™, running for more than a week without an answer, and so no answer is provided.

Two pieces of hardware were utilized in this study. While running ArcMap™ 10.4.1 and Microsoft Excel™ 2010 a PC with the following specifications was used: 1.60 GHz Intel™ Core i5-4200U Quad Core Processor and 8.00 GB of RAM (Random Access Memory). While running TransCAD™ the IU Online vPC was used. This is essentially a virtually streamed desktop using the Citrix XenApp™ application used to stream an instance of an IU PC to a home computer. This is useful for utilizing software that is licensed to the university but not the individual students.

Data

Existing Bike Share Docking Stations

At the time of writing this study there were 29 docking stations located throughout downtown Indianapolis and its surrounding communities. Existing station locations were selected by Indianapolis Cultural Trail, Inc. and its stakeholders after multiple public meetings and were based on both areas of heavy pedestrian traffic and integration with the Indianapolis Cultural Trail. Stations range from 7 to 23 docks, but for the purpose of this study all docking stations are weighted equally and redistribution of bicycles throughout the network was not considered.

Shapefile of U.S. Census Blocks (2010)

A Census block shapefile for the state of Indiana was downloaded from the U.S. Census Bureau's TIGER/Line Shapefile website (U.S. Census Bureau, 2010). The shapefile contained basic demographic information joined from the 2010 U.S. Census including total population and housing units per block. The area examined in the study was limited to the 4219 census blocks located in Center Township.

U.S. Census Block Demographic Data

Total residential population for each census block was acquired from the American FactFinder, an extension of the U.S. Census Bureau's website (American FactFinder, 2010).

Standard Geographical File of Street Centerlines and Intersections

Street centerline data from a 2012 version of TransCAD™ was utilized in this study. Street centerlines and corresponding intersections were limited to that of the

Center Township study area. In total there were 11,950 road segments with 8,238 intersection nodes. The advantage of using street centerline data provided in TransCAD™ over publically available shapefiles is that the compact geographic files (CDF) are preloaded and allow for the creation of network layers which can then be used to solve location allocation problems. Figure 2 depicts the boundary of Center Township and current bike share station locations while Figure 8 includes the network partition of each current station.

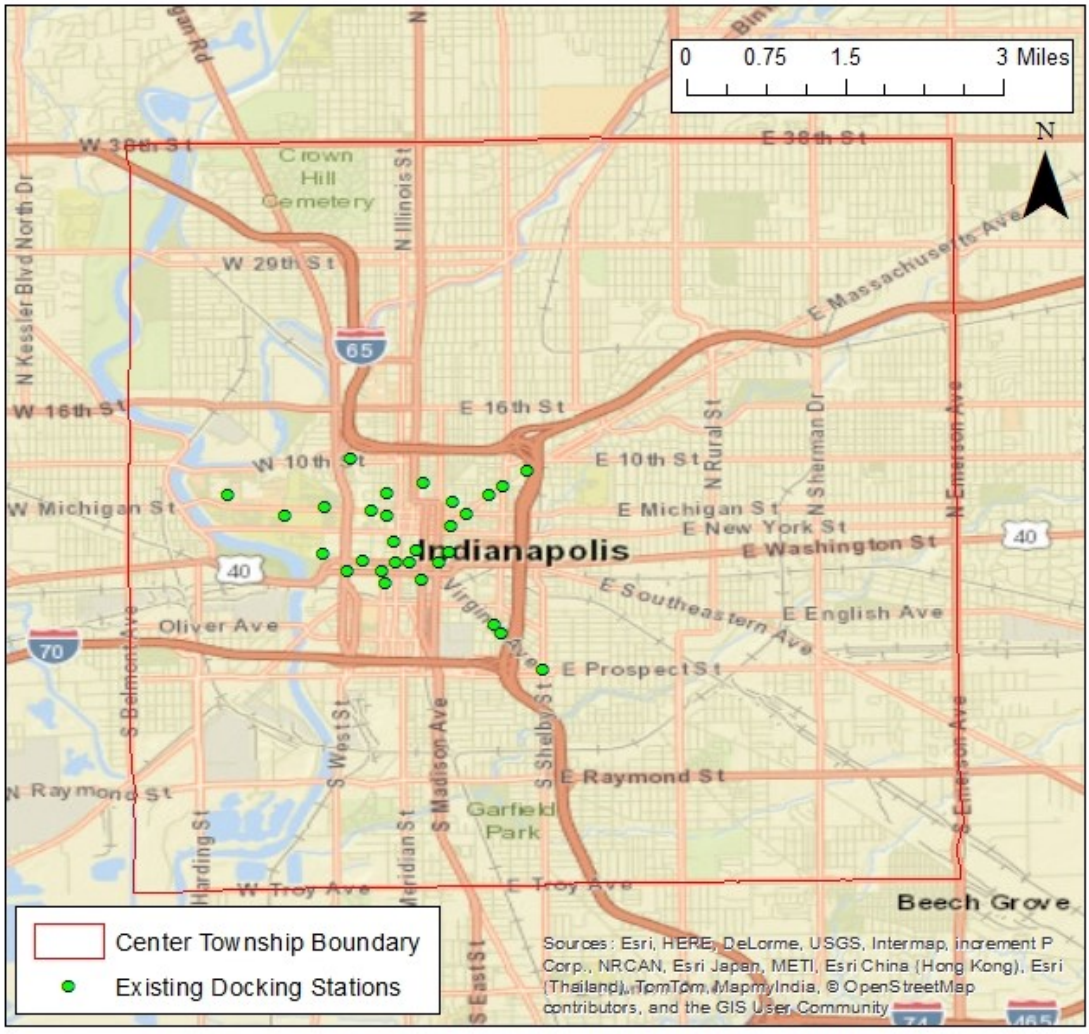

Figure 2: Center Township, Indianapolis with Existing Docking Stations

Methods

Data Preparation

There were preliminary steps required for the study once the data was acquired. The first task was to incorporate demographic data for total population from the American FactFinder into the Tiger/Line census block group file from the US Census Bureau so that statistics for the number of people serviced by each station in each solution set could be determined. This was accomplished through a series of joins based on the "GEOID" column in the Tiger/Line census block group file and the "GEO.id2" column from the .csv files acquired from the American FactFinder.

Once population data was added to the census blocks the file was converted from a polygon file to a point file by generating centroids for each block. This allowed for each record to retain its attributes, including total population, but the geometry was simplified to point features. This was necessary in order to use the census blocks as potential locations for docking stations in a network analysis context.

The analysis was restricted to the boundary of Center Township, which is bounded by 38th Street to the north, Emerson Avenue to the east, Troy Avenue to the south, and Belmont Avenue to the west. This boundary was then used to extract the Census block groups within, whose outer boundary perfectly lined up. Center Township is made up of 156 census block groups containing 4219 census blocks and encompassing 42.684 miles. The total population within the study area reported in 2010 was 142,679.

Latitude and longitude coordinates were obtained for the 29 existing docking stations around downtown Indianapolis. This was done by cross referencing stations listed on the Pacers Bikeshare website with aerial imagery of Indianapolis and identifying where each station was located. Coordinates were compiled into an Excel file and geocoded using ArcMap™ 10.4.1. Coordinates for all 29 stations were accurately obtained. Though station capacity was not used in this study station capacity was added as an attribute in the associated database table.

Street centerline data within TransCAD™ was used to generate a network upon which potential locations could be determined and location allocation problems could be solved. Interstates are shown in figures for context but were removed from processing since they are restricted to motorized vehicle traffic. Census block centroids were used to create a cost matrix determining the cost to travel in miles from one census block centroid to another over the network.

In order to run the location allocation problem in TransCAD™ both a street network file and a cost matrix file had to be created. Cost Matrix here is an 'n' by 'n' matrix based on the shortest paths between each node in the network where 'shortest path' is the cost. The street network file was created using the street and intersection data included in TransCAD™ without specifying turn penalties or incorporating speed limits. This decision was made since it is only walking distance that is considered in this study. It assumes people will walk along the side of the roads to get to and from docking stations. The cost matrix file was then created using the network previously mentioned and the census block centroids as both the origin and destination of the matrix.

Network Partitioning of Current System Configuration

The current locations of bikeshare docking stations were utilized to partition the street network of Center Township in order to compare the current levels of efficiency to those generated by an optimized model. The partitions were created based on street segments' proximity to the existing docking stations, creating both a classified selection of the road network assigning each segment to a docking station and a coverage polygon bounding the roads within each of these selections. With the classified selection of the road network created it was then possible to calculate the length of roads associated with each docking station. The map generated as the output of this function (Figure 7) reveals what happens when a coverage area is expanded without adjusting the supplying facilities. Since the current coverage range of the Pacers Bikeshare program is about a sixth of the size of Center Township the majority of the docking stations service a very small area while those furthest out service the vast majority of the study area.

P-Median Problem

While the P-Median problem was not used in this study, it had previously been considered and it is still important to understand seeing as it is the basis behind the Maximal Covering model. In order to better understand these problems it is important to consider that they are both classified as NP-hard problems and what that actually means. In complexity theory, P is the set of decision problems that can be solved in polynomial time, NP is the set of decision problems where if the answer is yes then there is proof of this fact and that proof can be checked in polynomial time, and NP-hard problems are those where a polynomial time

algorithm for the problem would imply there is a polynomial time algorithm for every problem in NP (Erickson, 2015, pg. 3). NP-hard problems are considered to be outside of NP. Simply put, if a problem is NP-hard then any problem within NP can be reduced down to it, making NP-hard problems harder than any within NP.

The travelling salesman problem, like the P-Median problem is considered to be NP-hard and serves as a good example of how increasing n in an NP-hard problem can drastically increase the time it can take to find its solution. In a 2013 Wired article, it is explained that:

> The traveling salesman problem is easy to state, and — in theory at least — it can be easily solved by checking every round-trip route to find the shortest one. The trouble with this brute force approach is that as the number of cities grows, the corresponding number of round-trips to check quickly outstrips the capabilities of the fastest computers. With 10 cities, there are more than 300,000 different round-trips__.__ With 15 cities, the number of possibilities balloons to more than 87 billion. (Klarreich, 2013)

It is this explosive growth in the size of the problem that makes it NP-hard and highlights the importance of being able to automate these problems.

As previously stated, the P-Median problem was formulated by S. L. Hakimi (1965) in order to place 'n' facilities on a network so that the distance between customers and facilities was minimized throughout the network as a whole. The strength in this location allocation algorithm lies in its ability to rebalance, expand, or contract a network given its desired size. Because the P-Median Problem does not build up to a desired coverage level but instead maximizes efficiency given a set number of facilities it is applicable under real world constraints.

The following represents Owen and Daskin's formulation of the P-Median problem:

Inputs:
i = index of demand node
j = index of potential facility site
h_i = demand at node i
d_{ij} = distance between demand node i and potential facility site j
P = number of facilities to be located

Decision variables:

$$X_j = \begin{cases} 1 & \text{if we locate at potential facility site } j, \\ 0 & \text{if not.} \end{cases}$$

$$Y_{ij} = \begin{cases} 1 & \text{if demands at node } i \text{ are served by a facility at node } j, \\ 0 & \text{if not.} \end{cases}$$

Using these definitions, the P-median problem can be written as the following integer linear program:

$$\text{Minimize} \quad \sum_i \sum_j h_i d_{ij} Y_{ij} \tag{1}$$

$$\text{subject to:} \quad \sum_j X_j = P, \tag{2}$$

$$\sum_j Y_{ij} = 1 \quad \forall i, \tag{3}$$

$$Y_{ij} - X_j \leqslant 0, \quad \forall i, j, \tag{4}$$

$$X_j \in \{0, 1\} \quad \forall j, \tag{5}$$

$$Y_{ij} \in \{0, 1\} \quad \forall i, j. \tag{6}$$

Figure 3: The P-Median Problem as stated by Owen and Daskin (1998, pg. 426)

Figure 3 explains that the objective (1) is to minimize the total demand-weighted distance between customers and their allocated facilities. Constraint (2) restricts the equation so that exactly P facilities are located. Constraint (3) establishes that every demand is assigned to a facility, while constraint (4) permits assignment only to locations where a facility has been placed. Constraints (5) and (6) serve the purpose of binary requirements for the problem variables so that demands will be assigned only to the nearest facility. Constraint (6) can also be relaxed to a simple non-negativity constraint $Y_{ij} \geq 0$ (Owen and Daskin, 1998, pg. 426).

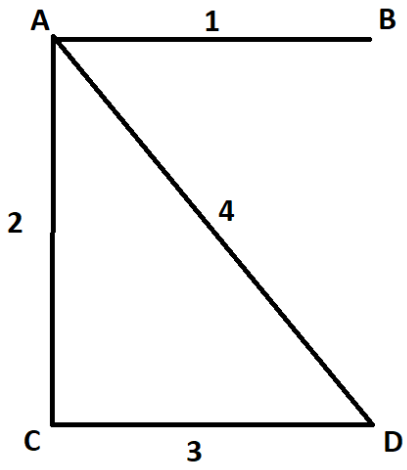

Figure 4: An Example P-Median Problem

1-Median Cost Matrix					
	dA	dB	dC	dD	Sum
A	0	1	2	4	7
B	1	0	3	5	9
C	2	3	0	3	8
D	4	5	3	0	12

2-Median Cost Matrix					
	dA	dB	dC	dD	Sum
AB	0	0	2	4	6
AC	0	1	0	3	4
AD	0	1	2	0	3
BC	1	0	0	3	4
BD	1	0	3	0	4
CD	2	5	0	0	7

Table 1: Example Cost Matrices for P-Median Problem with Solutions

In Figure 4 above an example network has been created to illustrate a simple P-median problem. In the example there are four nodes that serve as both demand sources and potential facility placements. When solving for 1-median, the cost matrix must be generated with the shortest distance from each node to each potential solution set. In this example the solution is to place the facility at Node A

because the sum of distances (cost) of all demand sources is lowest. When solving for 2-medians only the shortest distance from the demand node to either of the potential facilities is entered into the cost matrix. In this example, the solution is to place one facility at Node A and the other at Node D. Table 1 depicts the cost matrices for these simple P-Median problems.

Maximal Covering Model

Though location allocation questions were first posed by Leon Cooper in 1963, location allocation as used in this study is similar to the application by Richard Church and his colleague Charles ReVelle in 1974 with their piece "The Maximal Covering Location Problem," a paper that depicted location allocation algorithms in their earliest forms but that still holds weight today. This paper put forth a few different models including the basic maximal covering location problem which is at the root of applications in GIS software today as well as the Greedy Adding method, the Greedy Adding with Substitution method, and the Maximal Covering Model with Mandatory Closeness Constraints.

I. Maximize $z = \sum_{i \in I} a_i y_i$

S.T.

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

$$\sum_{j \in J} x_j = P \tag{2}$$

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

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

where

I = denotes the set of demand nodes;
J = denotes the set of facility sites;
S = the distance beyond which a demand point is considered "uncovered" (the value of S can be chosen differently for each demand point if desired);
d_{ij} = the shortest distance from node i to node j;
$x_j = \begin{cases} 1 \text{ if a facility is allocated to site } j \\ 0 \text{ otherwise;} \end{cases}$
$N_i = \{j \in J | d_{ij} \leq S\}$;
a_i = population to be served at demand node i;
p = the number of facilities to be located.

Figure 5: The Maximal Covering Location Problem as stated by Richard Church and Charles ReVelle (1974, pg. 103-104)

II. Minimize $z = \sum_{i \in I} a_i \bar{y}_i$

S.T.

$$\sum_{j \in N_i} x_j + \bar{y}_i \geq 1 \quad \text{for all } i \in I \tag{5}$$

$$\sum_{j \in J} x_j = p \tag{6}$$

$$x_j = (0, 1) \quad \text{for all } j \in J \tag{7}$$

$$\bar{y}_i = (0, 1) \quad \text{for all } i \in I\,. \tag{8}$$

Figure 6: The Maximal Covering Location Problem adjusted to minimize the population not covered by service stations (Church and ReVelle 1974, pg. 105)

The purpose of the maximal covering location problem is to maximize the population served in a given geography within a stated network-distance or time-distance of a number of service stations that is determined as the model executes. This is shown in Figure 5 above. Using substitution on the model, it can be rewritten

to minimize the population not served by the determined facilities in the model as depicted by Figure 6.

$$\text{Minimize} \quad \sum_j c_j X_j \tag{7}$$

$$\text{subject to:} \quad \sum_{j \in N_i} X_j \geqslant 1 \quad \forall i, \tag{8}$$

$$X_j \in \{0,1\} \quad \forall j. \tag{9}$$

Figure 7: The Maximal Covering Problem simplified (Owen and Daskin, 1998, p.427)

The model is stated even clearer by Owen and Daskin in their paper "Strategic facility location: A review" shown in Figure 7. Here they explain that "[t]he objective function (7) minimizes the cost of facility location." Constraint 8 is present so that every demand *I* is serviced by at least one facility. Constraint 9 simply requires integrality for decision variables (Owen and Daskin, 1998, p. 427).

Network Partitioning of Docking Stations

In order to determine the current coverage level of each docking station network partitioning was employed using TransCAD™. According to Caliper's website, network partitioning is "the process of creating zones or territories from a street network, such that each link is assigned to the closest or least cost service location, based on a service value, such as driving distance or time." This creates a new network file that associates each line segment with the docking station that is closest to, based on network distance rather than Euclidean distance. It also creates a polygon file that bounds the coverage of each docking station. Using these newly created files the area covered by each docking station can be determined using both

square miles (boundary file) and linear mileage of road as well as the population serviced.

Results

2 Mile Solution

The Maximal Coverage problem was set up using the "Minimize maximum cost of service" option so that no person traveling from a census block centroid was more than 2 miles from the nearest facility, generating 18 docking station facilities. It took TransCAD™ a runtime of 23 minutes and 17 seconds to arrive at this answer. The minimum cost of service for this solution was 0 miles, the maximum was 1.94 miles, and the average was 1.08 miles. The total population allocated to each station ranged from 0 to 22,577. Amongst the 18 facilities the average number of people served per station was 7927. The minimum number of census blocks serviced by a placed facility was 1 while the maximum was 674. The average number of census blocks allocated to each station was 234. Of the eighteen placed stations five of them only serviced the census block where they were located. The minimum population of these blocks was 0, the maximum was 243, and the average was 71. Figure 9 depicts the 2 mile solution's sites and network partition while Table 3 depicts the census blocks and population serviced.

1 Mile Solution

When running the Maximal Coverage problem with a required 1-mile maximum cost of service 50 facilities were placed within the network. This operation took 2 hours, 5 minutes, and 28 seconds to run. The minimum cost of service for this solution was 0 miles, the maximum was 0.99 miles, and the average was 0.54 miles. The total population allocated to these facilities ranged from 0 to 7545 with the average facility servicing 2854 people. Of the 50 facilities in the

solution only 5 serviced only the census block that they were placed within. These 5 facilities are the same as the 5 facilities from the previously described 2-mile solution and therefore have the same statistics behind them. Figure 10 depicts the 1 mile solution's sites and network partition while Table 4 depicts the census blocks and population serviced.

Half Mile Solution

When running the maximal Coverage problem with a required 0.5-mile maximum cost of service, 220 facilities were placed within the network. This operation took 21 hours, 30 minutes, and 51 seconds to successfully run. The minimum cost of service for this solution was 0 miles, the maximum was 0.46 miles, and the average was 0.23 miles. The total population allocated to each of these facilities ranged from 0 to 3294 while the average facility serviced 649 people. Of the 220 facilities located only 8 serviced only the census block in which they were located. Of these 8, 5 were the ones found in the previous two solutions. With the 3 new self-serving blocks considered, the minimum population served by one of these facilities was 0, the maximum was 243, and the average was 44. Figure 11 depicts the half mile solution's sites and network partition while Table 5 depicts the census blocks and population serviced.

Discussion

While one of the original aims of this study was to determine if both TransCAD™ and ArcMap™ would generate the same solution sets given the same inputs, that was deemed impossible after ArcMap™ was unable to solve even the two mile problem using the same street network, census blocks, and problem parameters. The two mile problem was allowed to run for more than a week's time before ending it without an answer. After discussing this issue with Professor Banerjee it was determined that in order for ArcMap™ to be able to handle the problem 90% of the census blocks would be dropped randomly from the set of potential facility placements. Even this proved too much and so no solution using ArcMap™ was provided.

In regards to the problem of five stations that only service the census blocks they were placed in appearing in each of the three TransCAD™ solutions it was determined that there was an error placing them on the network due to the centroids being located on topological islands. These census block points were unable to be connected to the network because the street network did not reach them. There is a pattern found in three of the five being located near the White River, two of those being located within the Indianapolis Zoo. Of these blocks the two located within the zoo grounds have a population of zero while the other located near the White River only has a population of five. The two remaining have populations of 106 and 243 respectively.

As for comparing the results of the Maximal Coverage problem using TransCAD™ it was apparent that as the maximum distance to a kiosk was reduced,

the number of docking stations required to solve the model drastically increased. Decreasing the maximum cost of service from 2 miles to 1 mile and from 1 mile to 0.5 miles increases the number of docking stations required from 18 to 50 to 220 compared with the 29 current stations. Going off the previously mentioned estimate from Kurtzleben -- of docking stations costing "over $50,000 each" and adjusting the estimate to a flat $50,000 it is possible to estimate costs for each solution generated.

Given the network's 29 current facilities it can be estimated that the network of docking stations is worth $1,450,000. Using the 2 mile solution and reducing the network's docking stations to 18 could generate a cost savings of $550,000 by selling off deactivated docking stations, bringing the value of the network down to $900,000. When accounting for the 1 mile solution an additional 21 docking stations costing $1,050,000 would be required, bringing the total value of the network to $2,500,000. Finally, when implementing the half mile solution an additional 191 docking stations costing $9,550,000 would be required, bringing the total value up to $11,000,000. These calculations are purely based on the costs associated with purchasing and disposing of docking stations and do account for station maintenance, redistributing bikes throughout the system, or any other variable cost associated with the program. However, this does not include economies of scale.

Conclusion

This study has introduced the concept of location allocation problems to the Indiana Pacers Bikeshare program and has provided a few different solutions to consider in restructuring and expanding the network of docking stations and their current coverage capacities. The Maximal Covering problem was utilized to look at feasible varying levels of coverage given how capital-intensive new docking stations can be.

In reviewing the three solutions TransCAD™ provided the half mile solution can be discarded from a feasibility standpoint given that it would involve adding more than seven times the number of stations currently in use. This leaves the one and two mile solutions to consider. While feasible from an economic perspective, the two mile solution would not provide an adequate level of coverage to be considered accessible to all. Two miles are simply too far to be considered convenient enough to use on a regular basis. The one mile solution seems both possible and relatively feasible as it adds fewer stations than are currently deployed and given a maximum cost of one mile to access, it would take a maximum of twenty minutes to access a bike at a three mile an hour walking speed.

In future iterations of this study it would benefit to fix the network of potential sites for the census blocks that were not able to be reached by the road network. It is likely that if these blocks would have been connected to the road network they would have been covered by a properly placed station. This could potentially eliminate these stations or at least shift the allocation of stations.

Tables and Figures

Name	Location	Began	Stations	Website
Capital Bikeshare	Alexandria, VA	2012	31	https://www.alexandriava.gov/Bikesharing
Capital Bikeshare	Arlington, VA	2011	85	http://www.bikearlington.com/capital-bikeshare/
WE-cycle	Aspen, CO	2010	43	https://www.we-cycle.org/
Relay	Atlanta, GA	2016	76	http://relaybikeshare.com/
Austin B-cycle	Austin, TX	2013	50	https://austinbcycle.com/
Boise GreenBike	Boise, ID	2015	60	https://boise.greenbike.com/
Hubway	Boston, MA	2007	185	https://www.thehubway.com/about
Boulder B-cycle	Boulder, CO	2011	43	https://boulder.bcycle.com/
Hubway	Brookline, MA	2012	4	https://www.thehubway.com/about
Broward B-cycle	Broward County, FL	2011	23	https://broward.bcycle.com/
Reddy Bikeshare	Buffalo, NY	2016	70	https://reddybikeshare.socialbicycles.com/
Hubway	Cambridge, MA	2011	44	https://www.thehubway.com/about
Bike Chattanooga	Chattanooga, TN	2012	33	http://www.bikechattanooga.com/
Charlotte B-cycle	Charlotte, NC	2012	25	https://charlotte.bcycle.com/
Divvy	Chicago, IL	2013	580	https://www.divvybikes.com/
Red Bike	Cincinatti, OH	2014	57	http://www.cincyredbike.org/
UH Bikes	Cleveland, OH	2016	29	http://uhbikes.com/
Zagster	College Park, MD	2016	23	http://bike.zagster.com/mbike/
COGO Bike Share	Columbus, OH	2013	46	https://www.cogobikeshare.com/
Link Dayton	Dayton, OH	2015	26	https://www.linkdayton.org/
Denver B-cycle	Denver, CO	2010	89	https://denver.bcycle.com/
Des Moines B-cycle	Des Moines, IA	2010	21	https://desmoines.bcycle.com/
El Paso B-cycle	El Paso, TX	2015	15	https://elpaso.bcycle.com/
Fort Worth B-cycle	Ft. Worth, TX	2013	46	https://fortworth.bcycle.com/
Greenville B-cycle	Greenville, SC	2014	10	https://greenville.bcycle.com/

Hudson Bike Share	Hoboken, NJ	2015	65	https://hudsonbikeshare.com/
Houston B-cycle	Houston, TX	2012	46	https://houston.bcycle.com/
Indiana Pacers Bikeshare	Indianapolis, IN	2014	29	https://www.pacersbikeshare.org/
Biki	Kailua, Oahu, HI	2017	100	http://www.bikesharehawaii.org/
Kansas City B-cycle	Kansas City, MO	2012	41	https://kansascity.bcycle.com/
LimeBike	King County, WA	2017	Dockless	http://www.limebike.com/
LouVelo	Louisville, KY	2017	27	https://louvelo.com/
Long Beach Bike Share	Long Beach, CA	2016	60	https://www.longbeachbikeshare.com/
SoBi	Long Beach, NY	2017	11	https://sobilongbeach.com/
Metro Bike Share	Los Angeles, CA	2016	61	https://bikeshare.metro.net/about/
Madison B-cycle	Madison, WI	2011	43	https://madison.bcycle.com/
CitiBike Miami	Miami, FL	2014	75	http://citibikemiami.com/
Bublr Bikes	Milwaukee, WI	2014	76	http://bublrbikes.org/
Nice Ride Minnesota	Minneapolis, MN	2010	200+	https://www.niceridemn.org/
BIXI Montreal	Montreal, Canada	2009	540	https://montreal.bixi.com/en
Nashville B-cycle	Nashville, TN	2012	36	https://nashville.bcycle.com/
CitiBike NYC	New York City, NY	2013	706	https://www.citibikenyc.com/
Spokies	Oklahoma City, OK	2012	8	http://spokiesokc.com/
Heartland B-cycle	Omaha, NE	2011	34	https://heartland.bcycle.com/
Juice Bike Share	Orlando, FL	2015	37	https://juicebikeshare.com/
VeloGo	Ottawa, Canada	2014	25	https://velogo.ca/
Indego	Philadelphia, PA	2015	100	https://www.rideindego.com/
Grid Bike Share	Phoenix, AZ	2014	110	http://gridbikes.com/
PGH Share	Pittsburgh, PA	2015	50	http://pghbikeshare.org/
Portland Bike Share	Portland, ME	2018	15	http://www.portlandbikeshare.org/
Biketown	Portland, OR	2016	100	https://www.biketownpdx.com/
Capital Bikeshare	Rockville, MD	2014	8	https://www.capitalbikeshare.com/
San Antonio B-cycle	San Antonio, TX	2011	60	https://sanantonio.bcycle.com/

DecoBike	San Diego, CA	2015	180	http://www.decobike.com/sandiego/
Ford GoBike	San Francisco, CA	2013	104	https://www.fordgobike.com/
Green Bike SLC	Salt Lake City, UT	2013	32	https://greenbikeslc.org/
Ford GoBike	Santa Clara County, CA	2013	43	https://www.fordgobike.com/
Breeze Bike Share	Santa Monica, CA	2015	80	https://santamonicabikeshare.com/
CAT Bike	Savannah, GA	2014	2	https://catbike.bcycle.com/
Spartanburg B-cycle	Spartanburg, SC	2012	5	https://spartanburg.bcycle.com/
Coast Bike Share	Tampa Bay, FL	2014	36	http://coastbikeshare.com/tampa/
Tulsa Bike Share	Tulsa, OK	2018	23	http://tulsatrc.org/bike/bike-share-2/
Capital Bikeshare	Washington, DC	2010	480	https://www.capitalbikeshare.com/

Table 2: North American cities with public bikeshare programs

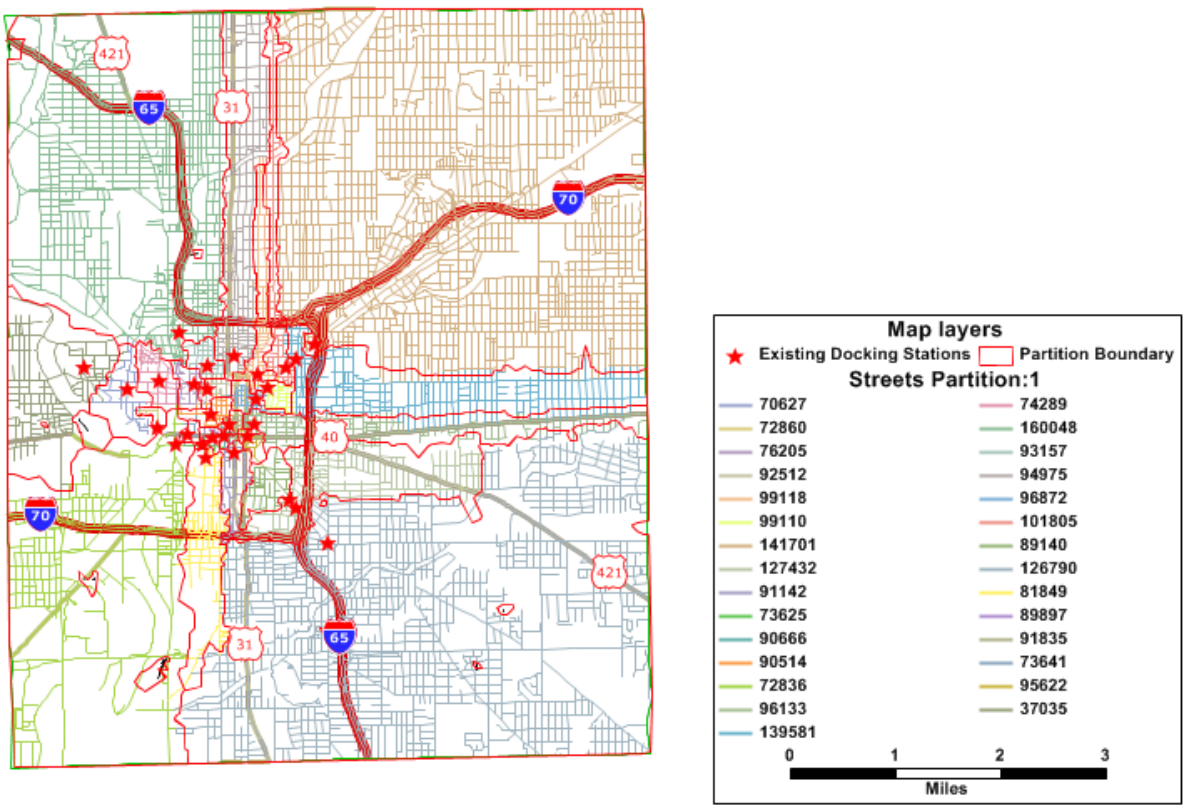

Figure 8: Current Docking Station Locations with Partition of Center Township

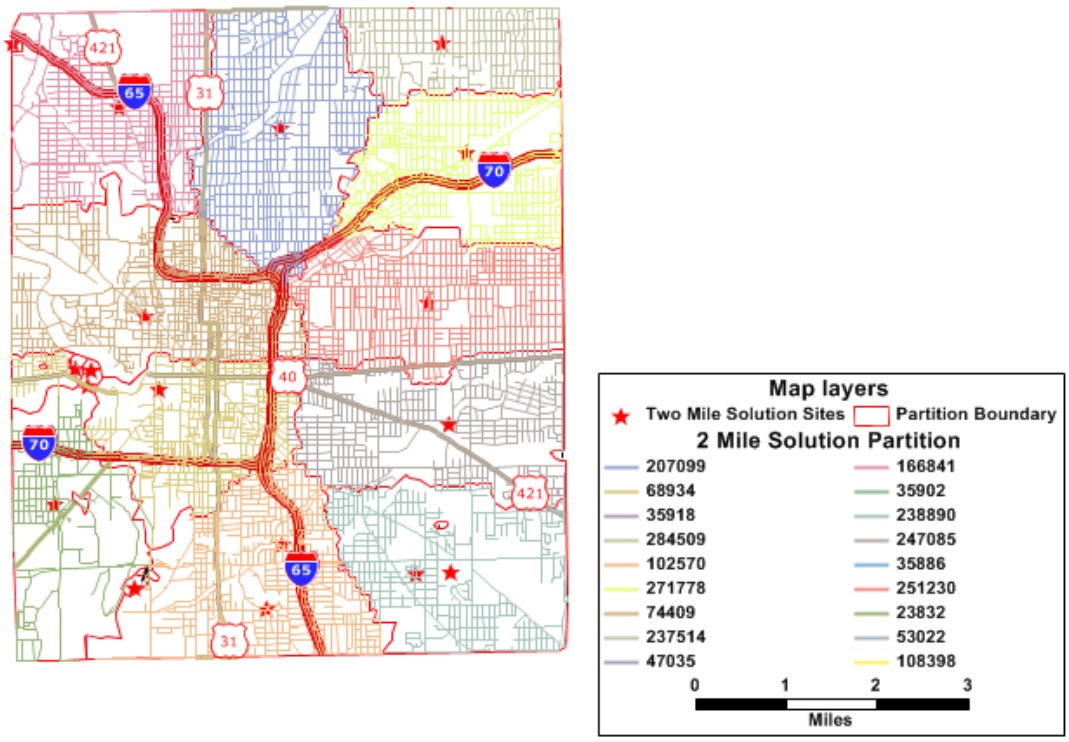

Figure 9: Two Mile Maximal Covering Solution Sites and Network Partitioning

ID	Census Blocks Serviced	Only Services Self
2	485	0
58	414	0
71	492	0
145	3	0
148	1	1
303	271	0
339	177	0
413	375	0
461	390	0
684	1	1
887	314	0
1006	466	0
1194	674	0
1218	151	0
1372	1	1
1553	1	1
2101	2	0
2877	1	1

Table 3: Census blocks and population serviced by two mile maximal covering solution

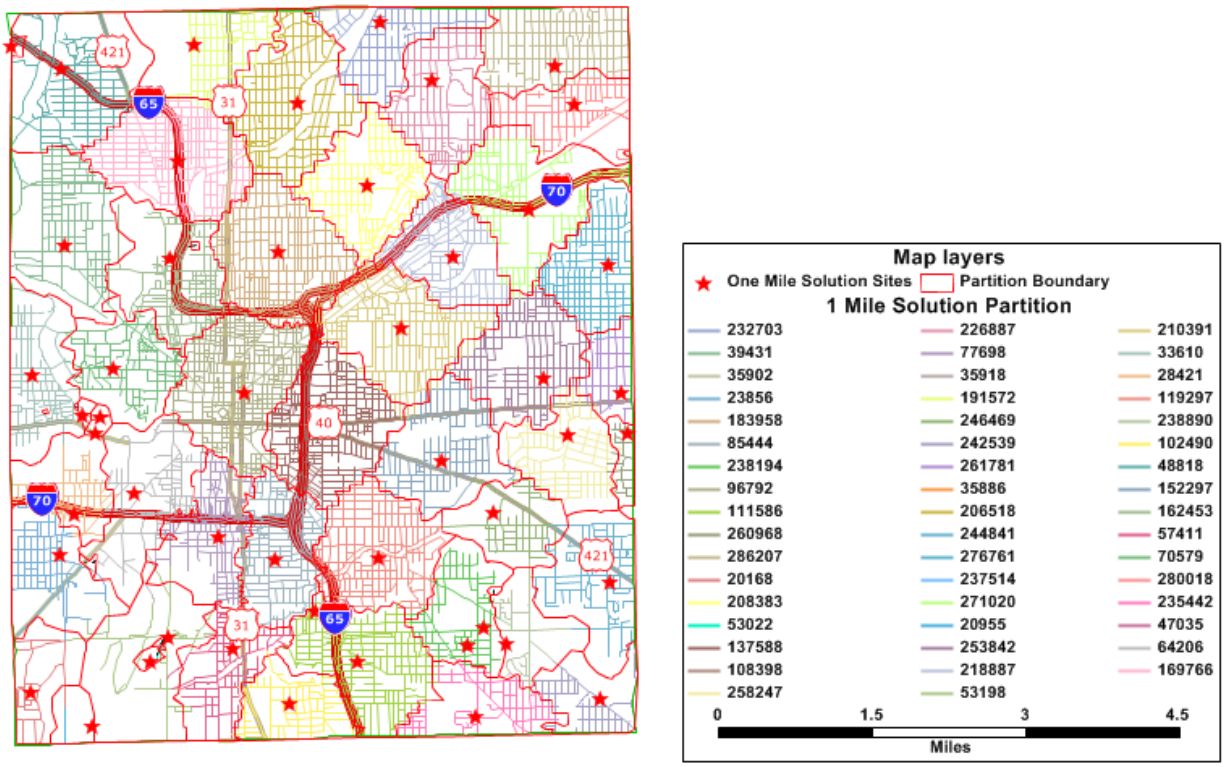

Figure 10: One Mile Maximal Covering Solution Sites and Network Partitioning

ID	Census Blocks Serviced	Only Services Self
6	71	0
12	88	0
40	163	0
78	114	0
133	100	0
142	95	0
145	3	0
148	1	1
159	48	0
185	65	0
208	59	0
254	163	0
290	213	0
302	37	0
303	18	0
308	129	0
315	49	0
405	57	0
437	51	0
454	44	0
462	122	0
489	338	0
684	1	1
737	98	0
757	133	0
771	152	0
782	122	0
827	18	0
835	52	0
851	63	0
874	91	0
909	130	0
1011	93	0
1342	14	0
1372	1	1
1387	53	0
1440	113	0
1491	110	0
1552	55	0
1553	1	1
1942	2	0

2101	2	0
2264	259	0
2523	112	0
2824	95	0
2877	1	1
2997	116	0
3102	194	0
3582	79	0
3822	31	0

Table 4: Census blocks and population serviced by one mile maximal covering solution

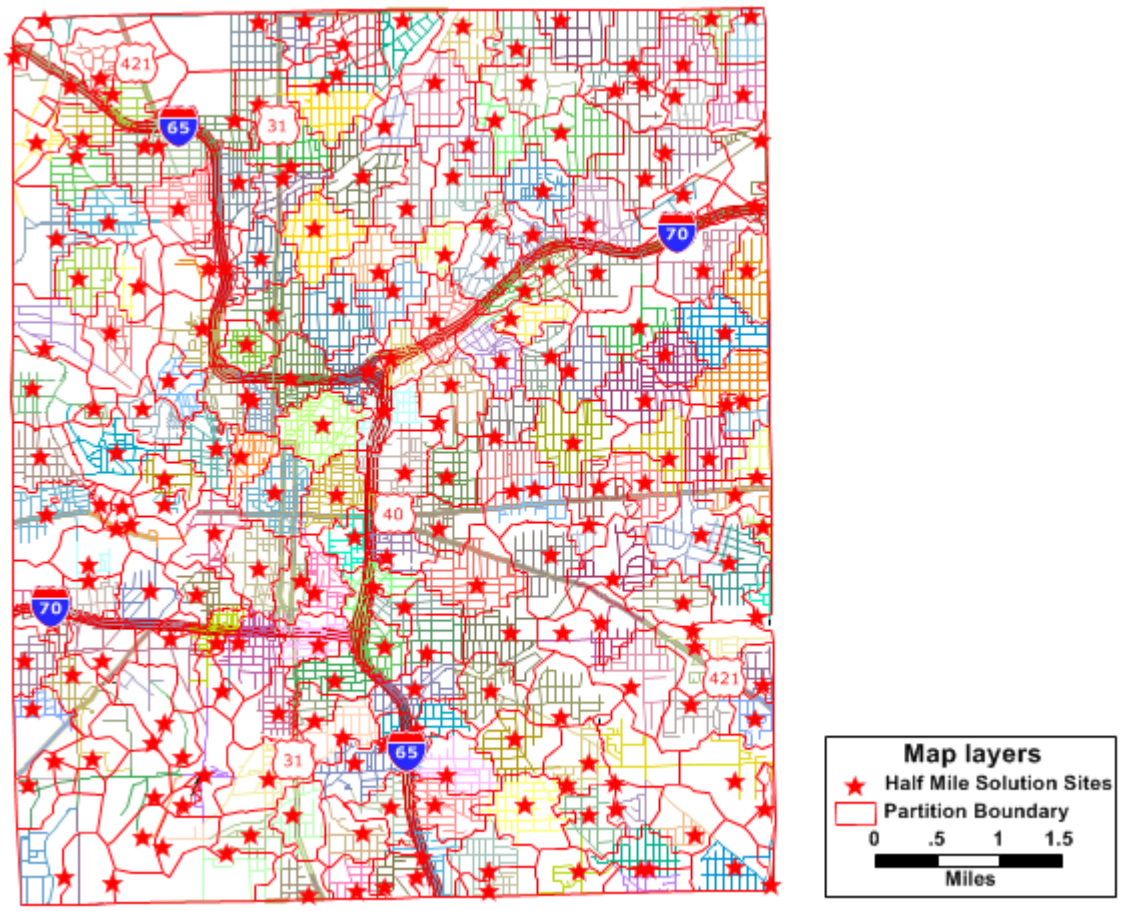

Figure 11: Half Mile Maximal Covering Solution Sites and Network Partitioning

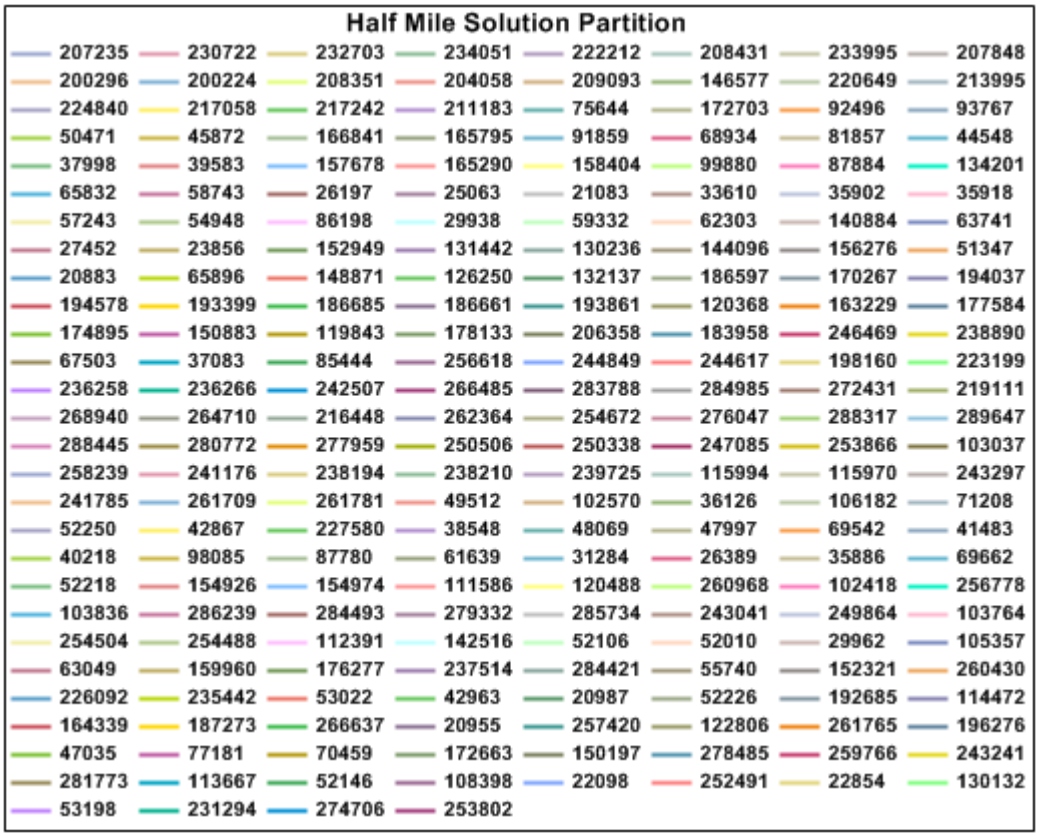

Figure 11 (continued): Half Mile Maximal Covering Solution Sites and Network Partitioning

ID	Census Blocks Serviced	Only Services Self
1	9	0
3	24	0
6	18	0
8	12	0
9	14	0
10	17	0
13	16	0
16	23	0
18	25	0
20	22	0
23	10	0
26	33	0
29	34	0
30	2	0
31	8	0
32	30	0
35	13	0
41	14	0
42	12	0
45	29	0
47	39	0
48	27	0
49	37	0
50	35	0
55	14	0
57	18	0
58	20	0
59	17	0
69	72	0
71	18	0
74	36	0
77	41	0
79	17	0
81	24	0
84	17	0
89	38	0
90	7	0
97	78	0
121	26	0
123	33	0
131	1	1

136	21	0
138	5	0
139	19	0
141	1	1
142	31	0
145	3	0
148	1	1
150	27	0
151	13	0
153	29	0
157	10	0
165	18	0
166	25	0
170	57	0
175	24	0
183	14	0
185	19	0
187	30	0
189	31	0
190	16	0
191	31	0
194	14	0
201	4	0
202	10	0
206	19	0
211	41	0
213	29	0
219	14	0
223	20	0
225	34	0
226	14	0
227	22	0
230	27	0
231	20	0
232	35	0
238	11	0
258	37	0
260	5	0
265	30	0
266	39	0
267	7	0
269	20	0
275	29	0

284	37	0
290	32	0
302	12	0
303	9	0
306	18	0
307	27	0
308	23	0
311	11	0
313	8	0
314	4	0
321	24	0
323	20	0
325	12	0
326	16	0
332	24	0
336	39	0
338	17	0
343	15	0
347	8	0
349	22	0
351	49	0
361	21	0
365	29	0
366	21	0
372	16	0
374	30	0
381	13	0
382	12	0
385	21	0
388	5	0
392	18	0
402	34	0
410	18	0
413	21	0
416	15	0
426	8	0
431	26	0
434	16	0
437	11	0
439	16	0
440	6	0
441	17	0
442	11	0

447	10	0
449	12	0
451	14	0
454	10	0
460	22	0
461	21	0
482	3	0
494	15	0
496	21	0
511	5	0
514	9	0
527	22	0
556	9	0
559	6	0
574	25	0
585	11	0
595	19	0
602	24	0
643	69	0
651	22	0
673	10	0
682	42	0
683	7	0
684	1	1
690	4	0
727	3	0
732	15	0
733	16	0
757	21	0
797	24	0
827	6	0
829	11	0
834	4	0
854	12	0
869	29	0
870	3	0
871	18	0
873	10	0
880	4	0
929	5	0
948	2	0
952	10	0
966	6	0

980	24	0
1007	41	0
1029	6	0
1165	2	0
1190	14	0
1204	27	0
1240	17	0
1301	19	0
1328	62	0
1372	1	1
1374	6	0
1438	12	0
1445	26	0
1475	21	0
1487	28	0
1552	9	0
1553	1	1
1612	25	0
1694	3	0
1756	2	0
1763	19	0
1776	38	0
1812	18	0
1837	30	0
1909	21	0
1942	2	0
1978	25	0
1981	20	0
1994	31	0
2093	33	0
2101	2	0
2216	29	0
2254	9	0
2296	23	0
2353	29	0
2465	6	0
2528	14	0
2558	6	0
2573	6	0
2626	31	0
2846	4	0
2877	1	1
3319	18	0

3575	23	0
3608	1	1
3817	31	0
3822	9	0
4001	17	0
4097	38	0
4117	29	0

Table 5: Census blocks and population serviced by half mile maximal covering solution

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CURRICULUM VITAE

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EDUCATION

Master of Science in Geographic Information Science, Indiana University-Purdue University Indianapolis

(August 2014 – August 2017)

Bachelor of Arts in Geography and Economics, Indiana University-Purdue University Indianapolis

(August 2010 – May 2014)

PROFESSIONAL EXPERIENCE

Thompson Thrift Retail Group, Indianapolis, IN

(February 2016 – Present)

Market Research Analyst

- Perform market studies and assist in performing appraisals of proposed and existing real estate developments
- Conduct demographic analyses to determine target Metropolitan Statistical Areas ready for retail development
- Build and manage geospatial databases tracking current and prospective projects
- Track retail industry trends to determine which retailers are expanding into which markets

Indiana University-Purdue University Indianapolis, Indianapolis, IN

(December 2013 – Present)

Graduate/Teaching Assistant

- Assist instructor in implementation of online curriculum as Introduction to GIS and Computer Cartography shift to an online format
- Produce instructional videos using Adobe Captivate to provide a step-by-step process of assignments for students
- Conduct open lab hours for online students to get in-person assistance with assignments and software issues

Simon Property Group, Indianapolis, IN

(March 2015 – February 2016)

Market Research Intern

- Edit and manage geospatial databases related to company properties using MapInfo Professional and Trade Area Systems
- Analyze sales data geographically for various tenants to find ideal tenant mix in each property
- Create maps and demographic reports to lure tenants to desired properties
- Stay up-to-date with current market trends in retail

Indiana University-Purdue University Indianapolis Campus Facility Services, Indianapolis, IN

(January 2014 – August 2014)

GIS Technician

- Maintain campus basemap in both AutoCAD and ArcGIS SDE
- Produce maps for campus parking, snow removal, and construction
- Assist in locating, copying, and scanning as-built drawings of campus buildings