FLORIDA STATE UNIVERSITY

COLLEGE OF SOCIAL SCIENCES

MODELING CRITICAL VACCINE SUPPLY LOCATION: PROTECTING CRITICAL

INFRASTRUCTURE AND POPULATION IN CENTRAL FLORIDA

By

PAUL J. MALISZEWSKI

A Thesis submitted to the
Department of Geography
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree awarded:
Summer Semester, 2008

The committee members listed below approve that Paul Maliszewski successfully defended his thesis on June 19, 2008.

_____
Mark Horner
Committee Chair

_____
Victor Mesev
Committee Member

_____
Lisa Jordan
Committee Member

Approved by:

_____
Victor Mesev
Chair, Department of Geography

_____
David Rasmussen
Dean, College of Social Sciences

The Office of Graduate Studies has verified and approved the above named committee members.

To my parents

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

BOB – Break of Bulk

CDC – Centers for Disease Control and Prevention

CRI – Cities Readiness Initiative

FEMA – Federal Emergency Management Agency

GIS – Geographic Information System

NAC – Neighborhood Adjacency Constraints

NPS – National Pharmaceutical Stockpile

OR – Operations Research

PCCIP – President's Commission on Critical Infrastructure Protection

POD – Points of Dispensing

SIC – Standard Industrial Classification

SNS – Strategic National Stockpile

UTM – Universal Transverse Mercator

ABSTRACT

Since the launch of the U.S. Department of Homeland Security in 2002, research needs have been established in the areas of disaster preparedness and critical infrastructure protection. Disaster preparedness seeks to lessen the adverse effects of disasters and hazards by planning in advance and responding in a proper manner. Critical infrastructures are those entities deemed necessary for society to function properly. Examples of critical infrastructures include vital stockpiles, transportation networks, emergency services, government buildings, electrical power systems, telecommunications, water supply systems, gas and oil production facilities, chemical and manufacturing plants, defense industrial bases, and other key commercial assets. Recent research has developed location models to aid in the management of many of these critical facilities. However, few efforts have modeled where to locate a future critical vaccine supply facility.

Past high-profile attacks on the United States have been focused on major cities, including Washington, D.C. and New York City. Generally, planned attacks will focus on centralized urban areas in order to cause as much damage as possible. In addition, centralized urban areas are more prone to damage, injuries, and death in comparison with rural areas. As a result, I propose a multi-objective modeling approach for strategically siting a critical vaccine supply facility that integrates disaster preparedness directives and critical infrastructure protection needs with respect to urban concentrations of critical facilities and populations. Specifically, I apply this model to locate the future placement of a critical vaccine stockpile in the greater metropolitan areas of Tampa Bay and Orlando in Central Florida. This research should benefit planners, policy makers, academics and researchers, as well as the welfare of civilians who are vulnerable to attack.

Key words: facility location, critical infrastructure protection, supplies, disaster preparedness.

CHAPTER I: INTRODUCTION

1.1 A Call for Protection

In the wake of recent terrorist events such as those of 9/11, the ability to identify and protect critical infrastructure in a system is an important element of homeland security and a top U.S. national research priority (White House 2001; Critical Infrastructure Protection Program 2006). Critical infrastructure can be defined as, "…those elements of infrastructure that, if lost, could pose a significant threat to needed supplies (e.g., food, energy, medicines), services (e.g., police, fire, and EMS), and communication or a significant loss of service coverage or efficiency" (Church et al. 2004). The interdiction of these elements can also result in significant economic losses (Chopra and Sodhi 2004; Greenberg et al. 2007). The National Infrastructure Advisory Council under The U.S. Department of Homeland Security has developed the *National Strategy for Physical Protection of Critical Infrastructures and Key Assets*, an 83 page document highlighting the importance of protecting critical infrastructure (White House 2003).

Since the start of the 20th century, over one thousand hits against critical infrastructures have taken place worldwide (Kosal 2007). The United States of America has been the target of a number of destructive attacks in the past. Physical attacks are likely to happen again in the future and critical infrastructure is a likely target (Krieger 1977; Church et al. 2004; Torgerson 2004). Past high-profile attacks on U.S. soil include those of foreign military (Pearl Harbor, Honolulu), domestic terrorism (Oklahoma City; Atlanta), and foreign terrorism (New York City; Washington, D.C.) (Falkenrath 2001). These attacks have all been focused on major cities (see Table 1).

Table 1. High-Profile Attacks on U.S. Cities.

Attack Profile	City, State	City Population	Attack Date(s)
Pearl Harbor	Honolulu, Hawaii	377,357	12/7/1941
Alfred P. Murrah Federal Building	Oklahoma City, Oklahoma	537,734	4/19/1995
Centennial Olympic Park Bombing	Atlanta, Georgia	486,411	7/27/1996
World Trade Center	New York, New York	8,214,426	2/26/1993, 9/11/2001
Pentagon	Washington, D.C.	581,530	9/11/2001

Population Data Source: U.S. Census Bureau (2006).

Since major cities are characterized as having large populations with considerable economic and political power, this unfortunately makes them and the critical infrastructure they contain vulnerable to attack (Harrald et al. 2004; Apostolakis and Lemon 2005; Baker and Little 2006).

Although there are numerous recorded accounts of terrorist attacks on U.S. soil, the majority of them were low-profile and mainly consisted of shootings, arson, or small bombs. In some cases, small acts of terrorism may even be considered vandalism. However, the frequency of smaller attacks in the U.S. has fallen dramatically since the 1970's and 1980's while recent terrorist attacks have grown more destructive in the U.S. and internationally, and can be expected to continue in the future (Federal Bureau of Investigation 1999; Savitch and Ardashev 2001; Loukaito-Sideris et al. 2006) (see Figure 1). Consequently, larger types of attacks are worth paying more attention to because of the increased amount of destruction associated with them and their expected growth in frequency.
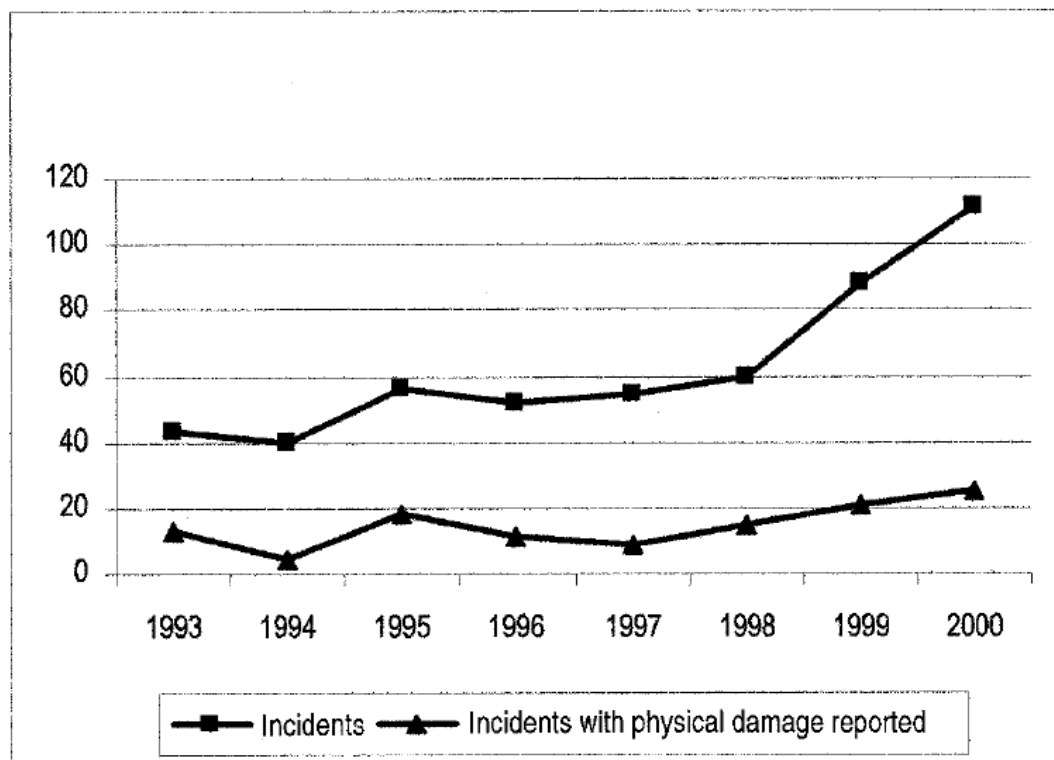
Figure 1. Terror incidents and physical damage; 1993-2000. Adopted from Savitch and Ardashev (2001). *Source:* U.S. Department of State (1993 – 2000).

1.2 Urban Vulnerability

Vulnerability is a broad concept and is difficult to succinctly define. Standard dictionaries typically define vulnerability as the susceptibility to attack, however, this definition is shortsighted. It ignores the important dimension of damage that also characterizes entities at risk. In other words, an entity may be susceptible to attack; however, this does not imply it is defenseless. Ezell (2007) recognizes this complication and provides a survey of several definitions of 'vulnerability'. Wherein, The National Security Telecommunications Advisory Committee (1997) defines vulnerable systems as "systems that are exposed, accessible, and therefore are susceptible to natural hazards as well as willful intrusion, tampering, or terrorism." In addition, Willis et al. (2005) define vulnerability as "…the probability of damage given an attack." In synthesis, vulnerability can be more precisely defined as the susceptibility to attack *and* the probability of damage given an attack.

Cities are the social, political, and economic centers of the world. Their importance is unprecedented as they are the major signifiers of modern civilization. Unfortunately, their importance also makes them clear targets. Savitch (2003) and Swanstrom (2002) conclude that cities are not only target rich, but the resources they contain are highly accessible for people as well. In comparison with fortified spaces such as military bases and medieval cities, urban areas are open, unprotected targets (Savitch 2003; Swanstrom 2002). So in a sense, urban openness is a source of a cities' strength and their weakness. Further, a city's popularity can also contribute to their weakness as Savitch and Ardeshev (2001) point out:

> Cities are the media centres for the world. They contain international newspapers, news organizations, television and radio broadcasting studios. A terrorist attack in a strategic urban core is a shot heard instantly around the world.

Interesting enough, Savitch and Ardeshev (2001) go on to illustrate that there is no significant link between acts of terrorism and urbanized areas. However, that does not imply that urban areas are not more vulnerable than rural ones. In fact, they go on to conclude that, "the cumulative effect of terror is higher in urban environments." In other words, the damage is much more intense in urban areas than rural ones. Taking a recent eight-year period, they show that incidences in cities accounted for 64% of terror attacks. During this period, incidences in cities also accounted for 61% of total fatalities, 94% of the injuries, and 86% of physical damage (see

Table 2 and Figure 2) (Savitch and Ardashev 2001). Furthermore, they state that there are no specific characteristics (industrial, demographic, or geographical) of cities that are subject to terror. Hence, urban vulnerability is a constant, widespread concern.

Table 2. Terrorist incidents, 1993-2000. Adopted from Savitch and Ardashev (2001).

	Total incidents	Fatalities	Injured	Physical damage
Urban	534	1326	11 762	117
Rural	306	829	769	19
Total	840	2155	12 531	136

Source: US Department of State (1993–2000).

Some researchers believe that urban areas are still hardy to attack. For example, Eisinger (2004) concludes that:

> Business activities have not been, for the most part, affected by recent terrorist acts. Cities remain resilient and growing and skyscrapers are continually being constructed.

Though this statement may be true, it again does not imply that cities are not vulnerable. In fact, if the latter statement is correct then urban densities are, for the most part, still vulnerable. Marcuse has stated that "extreme agglomeration is equated with danger" (Charney 2005). Under any risk of terrorist attack, taller buildings are better targets than shorter ones (Mills 2002) and after the World Trade Center attack, many financial businesses in Manhattan realized the logic for dispersing their operations as there was more safety in spreading out (Charney 2005). In Loukaito-Sideris (2006), a London rail design manager says, "The consequences for not designing for security are more dire than other design aspects, such as good image or accessibility." The London rail system, spatially, "does not have one centralized control room but many scattered in different places." According to London Underground officials, "this is a security measure as terrorists cannot knock out with one blow all of London's public transport." In conclusion, though urban agglomerations may still be resilient and growing, it does not hide the fact that they still remain vulnerable.
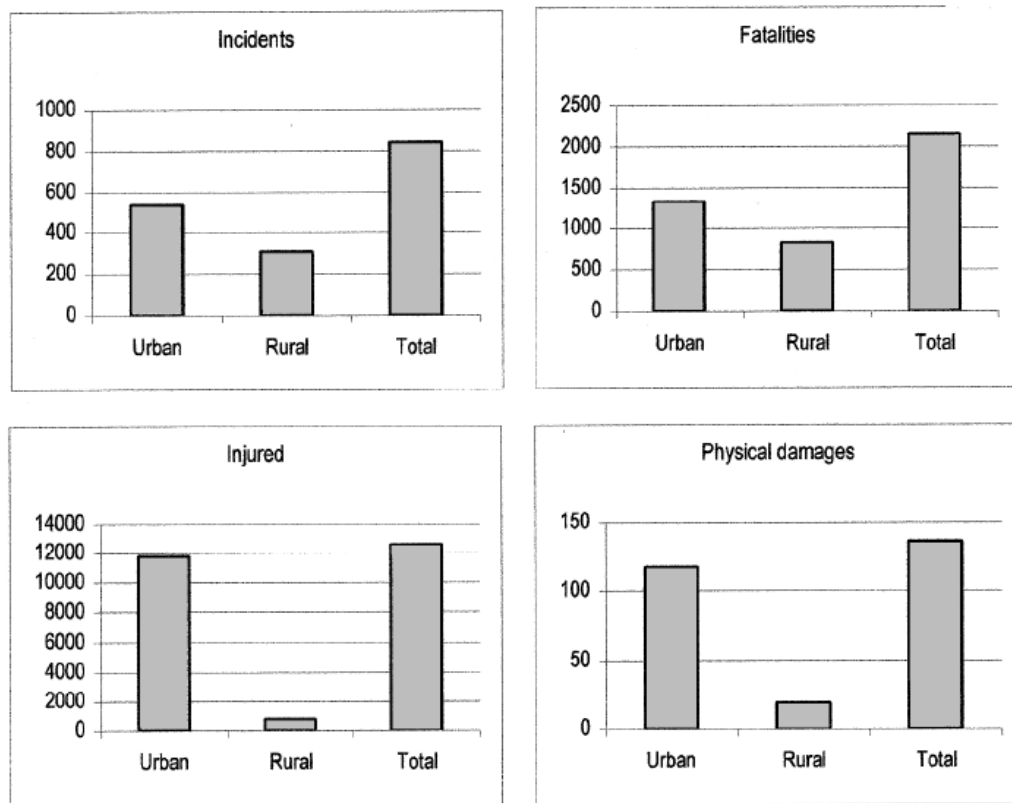
Figure 2. Terror and urban-rural cleavage, 1993-2000. Adopted from Savitch and Ardashev (2001). *Source:* **U.S. Department of State (1993 – 2000).**

1.3 A Call for Disaster Preparedness

Since the mid-1990's, the U.S. government has begun initiatives to prepare for highly destructive acts of terrorism, especially chemical and biological warfare (Falkenrath 2001; Centers for Disease Control and Prevention 2007). The Centers for Disease Control and Prevention (CDC) have classified biological agents as one of three priority categories for initial public health preparedness efforts (Federal Emergency Management Agency 2005). As Monath and Gordon (1998) put it, "heightened tensions surround the threat of biological warfare and terrorism." In addition, the authors affirm that the "Biological and Toxin Weapons Convention…lacks any international compliance regime to bolster its broad prohibitions against the development, production, stockpiling, and weaponization of offensive biological weapons" (Monath and Gordon 1998).

5

In 2001, weapons grade anthrax, a deadly infectious disease, was mailed in letters through the course of several weeks to Washington D.C. and New York City—22 people became infected and 5 died (Daschle 2006). The CDC recognizes that, "…a large-scale aerosol release of anthrax is well within the technical capability of al-Qa'ida and other foreign or domestic terrorist organizations" (Centers for Disease Control and Prevention 2007). In 2003, the Centers for Disease Control and Prevention reported on the level of preparedness for 34 major U.S. cities. The report states that major U.S. cities were inadequately prepared for dispensing vaccines to their populations (Centers for Disease Control and Prevention 2007). A model developed by Nathaniel Hupert at Cornell shows that a delay in dispensing antibiotics to populations will cost the lives of many people exposed to anthrax. If an entire city was exposed to an aerial release of anthrax, a five day delay would result in 8% of the exposed population dead (Centers for Disease Control and Prevention 2007). This lack of security exacerbates the need for a high level of disaster preparedness, particularly for the threat of biological weapons. Furthermore, the result of such an attack would require communities to supply mass prophylaxis treatment to exposed populations (Federal Emergency Management Agency 2005).

1.4 Critical Vaccine Supplies

This thesis focuses on the urban spatial orientation of the first element that defines critical infrastructure: supplies. Notable critical supplies include food, water, medicine, energy, and vehicles. Specifically, I focus on situating vaccine supplies. Critical vaccine supplies can be stockpiled in storage facilities having designated use for a crucial time of need (Havlak et al. 2002; Bravata et al. 2006; McGuire 2006). The vaccines used in these stockpiles are not only designated for emergencies, but are also distributed to pharmacies and clinics for sale before they expire (Havlak et al. 2002). So in a sense, the may serve as distribution nodes even in times of peace.

Starting in 1998, the United States Congress authorized funding for the National Pharmaceutical Stockpile (NPS) program, under the CDC. In 1999, they built eight, 12-h push-packages across the United States. A 12-h push package is a 50 ton stockpile of over 100 cargo containers that holds various medical supplies ranging from prophylaxis to surgical equipment designed to reach anywhere in the United States within 12 hours. These push-packages require 12-15,000 square feet of floor space for proper storage. In 2003, The NPS evolved into the

Strategic National Stockpile (SNS) program, which now manages twelve, 12-h push packages. Originally allocated $50 million per year from the United States Congress, the SNS now operates at over $600 million in funding. In fall 2001, the stockpile program was tested; a 12-h push package arrived in 7 hours to New York City from its designated location.

In 2004, the CDC coordinated the Cities Readiness Initiative (CRI), a federally funded effort to prepare major U.S. cities for a large-scale bioterrorist disaster by dispensing emergency supplies for all of the population within 48 hours. This was largely in response to the recognition that major U.S. cities were inadequately prepared for the dispensing of antibiotics during a large-scale disaster.

> In December 2004, the Trust for America's Health released a fifty-state report card on states preparedness to protect the public against bioterrorism. Just six states were judged to be "adequately prepared to administer and distribute vaccines and antidotes in an event of an emergency" and only one-third to "have sufficient bioterrorism lab response capabilities." (Caruson et al. 2005).

Even in 1997, the President's Commission on Critical Infrastructure Protection report that "Emergency responders are inadequately trained and equipped to respond to a chemical, biological, or nuclear attack on a civilian target." Furthermore they conclude that stores of antidotes should be available on a local level and that a comprehensive Geographical Information System (GIS) should be developed to help assist in systems planning (President's Commission on Critical Infrastructure Protection 1997). The CRI project began with 21 U.S. cities and has now expanded to over 70 major cities (See Table 3 and Figure 3). This project is still in the early stages of development and the CDC is currently working with individual states to increase their capacity of delivering medical supplies by establishing stockpile programs similar to the SNS.

Although the CRI program is still in the works, one should take important notice that it took 7 hours for a 12-h push package to reach New York City from its original location. To satisfy the CRI goal of dispensing vaccines to all populations within 48 hours, additional stockpiles may need to be placed closer to major cities than initially planned by the SNS in order to secure a quick delivery on top of the time necessary for dispensing supplies. Furthermore, this should be a statewide effort, since the closest stockpile allocated to a major city will most likely be in the same state, should it meet the dispensing time requirement of 48 hours. Nevertheless, in

the spatial sense of an emergency supplies, closer is better, since the faster emergency supplies are delivered, the better the chance of alleviating casualties.

Table 3. Cities Readiness Initiative Table. *Source:* CDC (2007).

Figure 3. Cities Readiness Initiative Map. *Source:* CDC (2007).

1.5 The Spatial Dynamics of Critical Vaccine Supplies

The nature of critical vaccine supplies embodies a unique dynamic of being both part of a critical infrastructure and a plan for disaster preparedness. The fundamental dynamics associated with critical stockpiles creates an unusual challenge in how a stock should be located and allocated because of the requirements for them to serve surrounding populations in addition to their specific need for protection.

In a spatial sense, certain critical infrastructures such as communications and services are difficult to protect; they must be central in location due to the nature of the services (Grubesic and Horner 2006). However, backup supplies do not need to be completely central in location, but close enough to be available for distribution in a time of need, such of that as a physical attack (i.e. bombing raid, biological or chemical warfare) (Need and Mothershead 2006). However, there is a debate on whether critical vaccine stockpiles should be centralized or decentralized in location (see Havlak et al. 2002; Bravata et al. 2006; McGuire 2006).

I introduce a location model that seeks to protect critical vaccine supplies by placing them in a way to decrease military or terrorist threat that could potentially destroy them. In addition to minimizing potential threat against losing these critical vaccines, I introduce a model which seeks to maximize the facility's supply access to surrounding populated areas by minimizing its average distance to them. This is the first known attempt in the academic literature that seeks to satisfy the problem of locating critical supply infrastructure for protection with regards to supply access.

1.6 Organization of Thesis

This chapter has introduced a general, underlying framework and rationale for siting critical supply infrastructures. In particular, this chapter introduces the major dimensions of protection, access, and vulnerability between populations and critical supply facilities in urban areas. In Chapter 2, I give a background and literature review in critical infrastructure protection, disaster preparedness, and location modeling. In Chapter 3, I identify the research aims of this thesis and document the methods to accomplish those goals. Chapter 4 provides a case study and illustrates the study area, data, and guides the analysis of the methodological results for the case study shown in Chapter 5. Specifically, I present two case studies in Central Florida, at two

different scales. The first area is along the I-4 corridor incorporating the greater Tampa-Orlando conurbation. The second is the Orlando metropolitan area. There are 941 nodes in the first area and 268 nodes in the second area, organized by the centroid of each census tract. My data includes U.S. Census derived population data, business/organization data from the InfoUSA 2007 database, and a matrix of Euclidean distance data between centroids. Chapter 5 gives the results of the case studies and highlights trends among the model's outcomes. Finally, Chapter 6 outlines the conclusions of this thesis and gives a discussion for relevant outcomes, future work, and overall significance of the project.

CHAPTER II: BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter gives a general background of location modeling and reviews a select portion of the literature in the fields of location modeling, critical infrastructure protection, and disaster preparedness. First, I give a background of operations research (OR) and location modeling and review some relevant, well-known location models within OR. Then, I review some recent research approaches in the fields of critical infrastructure protection and disaster preparedness and discuss some OR methods utilized to help manage the problems in these areas. Finally, I look at how location models have combined both critical infrastructure protection and disaster preparedness directives, and where my work fits in.

2.2 Location Modeling and Analysis

Location analysis is underpinned by location theory, pioneered by the German geographer, Walter Christaller, in the early 1900's, who sought to develop the laws of spatial organization through graph models. Some early practical applications of location theory were applied by the German economist, Alfred Weber, who sought to find the most efficient points of production between raw material origins and market destinations (Ghosh and Rushton 1987).

In the 1960s, OR approaches were adopted by location analysts (Ghosh and Rushton 1987; Brandeau and Chui 1989). OR techniques grew out of World War II when the governments of the United States and the United Kingdom needed to find ways to best allocate scarce military resources to aid in securing their defeat against Nazi Germany. Essentially, OR techniques incorporate mathematical modeling and computer based simulations to help decision makers find optimal solutions for real-world sized problems (Jaiswal 1997; Larson 2005). Optimization, a type of mathematical modeling used in OR, is a process which seeks the best solution for a given decision problem (Malczewski 1999). In recent years, OR methods have commonly been employed in the problems of homeland security (Wright et al. 2006).

Today, location analysts often use OR techniques and location modeling, incorporating spatial data with the decision making of the location and allocation of resources (Ghosh and Rushton 1987; Brandeau and Chui 1989; Mirchandani and Francis 1990). Objectives in location modeling are commonly functions of distance, cost, time, and/or demands (Malczewski 1999;

Sule 2001). With the development and growth of computers, location analysts have been able to solve larger and more complex problems in reasonable amounts of time (Zhan and Moon 1998). Subsequently, many researchers in the field have developed a vast array of decision models and efficient algorithms for solution acquisition.

In a very basic sense, location models can be classified into single or multi-objective models. An example of a single objective model is the classic p-median problem (see Hakimi 1965; ReVelle and Swain 1970), which seeks to locate a facility by minimizing the average weighted distance from all demand points to a located facility (Ghosh and Rushton 1987). The p-median problem is useful in marketing and emergency services where a facility's access to people is crucial. Oppong and Hodgson (1994) used it to find the optimal hospital location that minimized travel distance to all user areas in Ghana. A subsequent, opposite approach in single-objective facility location models derives from Church and Garfinkle's p-maxian problem (1978), which seeks to maximize the average weighted distance from all demands to a located facility. This model is used primarily in locating obnoxious facilities (e.g. nuclear power plants, chemical factories, waste disposal sites), where the facilities are essentially undesirable to nearby populations because they expel waste or pollutants (see Erkut and Neuman 1989). Since the only objective in these models is to minimize *or* maximize weighted distances to demands, they would be classified as single objective models.

Established single-objective models have logically led to the development of multi-objective models, which seek solutions for different and often conflicting objectives (Cohon 1978; Ghosh and Rushton 1987; Malczewski 1999; Kuby et al. 2005). Multi-objective models tend to be more mathematically complex than single objective models because of the dynamics incorporated in obtaining a solution (Cohon 1978; Mirchandani and Francis 1990). One such example of a multi-objective model would be locating a semi-obnoxious facility, which may not be completely desired or undesired (see Melanchrinoudis 1999; Melanchrinoudis and Xanthopulos 2003; Rakas et al. 2004). To illustrate, consider an airport, where jet noise may be undesirable, but travel costs from demands to the facility must be partially minimized.

2.3 Critical Infrastructure Protection

After the attacks on September 11, the body of literature on the topic of homeland security has grown considerably. The areas include disaster prevention (mitigation), disaster

preparedness and response (emergency management), critical infrastructure protection, and cyber-security (information protection). Critical infrastructure protection, in particular, is a natural home for OR, because many of the problems necessitate optimal solutions. As a result, specific operations methods are being introduced for ways of protecting critical infrastructure (Wright et al. 2006).

The field of critical infrastructure protection itself has seen much advancement in the literature. Many researchers have focused on identifying which infrastructures of society are deemed critical for it to function properly (see Table 4) (see White House 2003; Church et al. 2004; Amin 2005; Sternberg and Lee 2006; Garb et al. 2007; Greenberg et al. 2007). On a more micro-scale, the Federal Emergency Management Agency (2005) outlines methods for identifying the critical assets and functions within and around buildings. In a similar scope, Greibel and Phillips (2001) and Dunbobbin et al. (2004) offer strategies for the critical assessment and protection of courthouses and chemical facilities, respectively.

The table of critical infrastructures (Table 4) is defined by ten selected authors for review. Some researcher's critical infrastructure lists are broad and short (e.g. Church et al. 2004) while others are longer and more descriptive (e.g. Sternberg and Lee 2006), depending on the author's preference and focus. Critical infrastructure systems such as energy, transportation, emergency services, communications, government buildings, and water tend to be recognized as very important. Some entities like schools, stadiums, arenas, and other places where large amounts of people congregate are not consistent among the lists. This might be because they are not defined as 'complex infrastructures'. However, they might be of concern because they are likely targets as well (Sternberg and Lee 2006).

Also, many researchers identify the challenges and dimensions of protecting critical infrastructure (see Havlak et al. 2002; Cutter et al. 2003; Farrell et al. 2004; Goodman et al. 2007) and suggest strategies (see Ramberg 1982; Griebel and Phillips 2001; Farrell et al. 2004; Dunbobbin et al. 2004; Torgerson 2004; Amin 2005; Bravata et al. 2006) without proposing explicit mathematical models. Wright et al. (2006) give a review of operations research methods in the field of homeland security, including that of critical infrastructure protection. It is important to note that Wright et al. (2006) especially recognize that operations research methods in the area of critical infrastructure protection are lacking.

Table 4. Critical Infrastructures and Author Recognition.

Critical Infrastructure (*)	Authors (Date)
Agriculture and Food (8)	White House (2003); Conrad et al. (2006); Church and Scaparra (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Church et al. (2004); Grubesic and Murray (2006)
Schools (3)	Sathe and Miller-Hooks (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006)
Water (10)	White House (2003); Sathe and Miller-Hooks (2007); Amin (2005); Conrad et al. (2006); Church and Scaparra (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Church et al. (2004); Grubesic and Murray (2006)
Public Health (8)	White House (2003); Conrad et al. (2006); Church and Scaparra (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Church et al. (2004); Grubesic and Murray (2006)
Emergency Services (9)	White House (2003); Sathe and Miller-Hooks (2007); Conrad et al. (2006); Church and Scaparra (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Church et al. (2004); Grubesic and Murray (2006)
Defense Industrial Base (5)	White House (2003); Conrad et al. (2006); Sternberg and Lee (2006); Church et al. (2004); Grubesic and Murray (2006)
Telecommunications (8)	White House (2003); Sathe and Miller-Hooks (2007); Amin (2005); Conrad et al. (2006); Sternberg and Lee (2006); Cutter et al. (2003); Church et al. (2004); Grubesic and Murray (2006)
Energy (8)	White House (2003); Sathe and Miller-Hooks (2007); Amin (2005); Conrad et al. (2006); Sternberg and Lee (2006); Cutter et al. (2003); Church et al. (2004); Grubesic and Murray (2006)
Transportation (8)	White House (2003); Sathe and Miller-Hooks (2007); Amin (2005); Church and Scaparra (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Grubesic and Murray (2006)
Banking and Finance (7)	White House (2003); Amin (2005); Conrad et al. (2006); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Grubesic and Murray (2006)
Chemicals/Hazardous Materials (5)	White House (2003); Conrad et al. (2006); Sternberg and Lee (2006); Cutter et al. (2003); Grubesic and Murray (2006)
Postal and Shipping (3)	White House (2003); Cutter et al. (2003); Grubesic and Murray (2006)
National Monuments and Icons (6)	White House (2003); Sathe and Miller-Hooks (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Church et al. (2004); Grubesic and Murray (2006)
Dams (4)	White House (2003); Sathe and Miller-Hooks (2007); Sternberg and Lee (2006); Grubesic and Murray (2006)
Government Facilities (7)	White House (2003); Sathe and Miller-Hooks (2007); Conrad et al. (2006); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Grubesic and Murray (2006)
Key Commercial Assets (5)	White House (2003); Federal Emergency Management Agency (2005); Sternberg and Lee (2006); Cutter et al. (2003); Grubesic and Murray (2006); Church and Scaparra (2007)
Events and Attractions (3)	Sathe and Miller-Hooks (2007); Federal Emergency Management Agency (2005); Sternberg and Lee (2006)

*Number of authors recognized in selected review.

However, various approaches have been employed in the critical infrastructure protection field. Energy security tends to be a popular focus because of many other infrastructures' dependencies on power (Amin 2005; Conrad et al. 2006; Min et al. 2007). Lovins and Lovins (1982) recommend a decentralized energy supply. Specifically, they call centralized power "the root of the problem" (Lovins and Lovins 1982). Additionally, Lovins and Lovins (1982) and Raas and Long (2007) recognize that in militarized landscapes, like the Middle East, planners strategically place energy supplies for redundancy and concealment. Ramberg (1982) suggests several strategies for civil and military defense of nuclear reactors, including the spatial dimensions of facility protection. Liu et al. (2000) and Li et al. (2005) introduce infrastructure defense systems for electric power grids. While not entirely focusing on energy protection, The President's Commission on Critical Infrastructure Protection (PCCIP) recognizes that geographical dispersion and redundancy of critical infrastructures assist in providing system reliability and continuity if a single entity were interdicted.

Several articles propose explicit mathematical models for critical infrastructure protection. In the context of electric grid security, Salmeron et al. (2004) suggest a model, which seeks to identify the crucial components in an energy system that when hardened, will yield the best improvement in security. Brown et al. (2006) propose a similar model and apply it to petroleum reserves in Louisiana. Church and Scaparra (2007), with a like objective, develop a general critical infrastructure protection model that allocates fortification resources to those nodes identified as most vulnerable. It is important to note that these authors use location models to allocate fortification resources, but do not seek to place a future critical facility. Furthermore, they do not address the need to place a critical emergency stockpile.

2.4 Disaster Preparedness and Response

By definition, disaster preparedness seeks to lessen the adverse effects of disasters and hazards by planning in advance and responding in a proper manner. This is often done by managing and executing critical supply and relief programs (Larson 2005). In the disaster preparedness literature, many researchers develop methods to improve operations within a single critical facility (see Asbjornslett and Rausand 1999; Griebel and Phillips 2001; Gazmararian et al. 2002; Giovachino et al. 2005; Lee et al. 2006). For example, Giovachino et al. (2005) propose a model to optimize the operations at a single dispensing site of emergency supplies in the

District of Columbia. On a more macro-scale, some researchers seek to strengthen the medical supply (see National Vaccine Advisory Committee 2003; Klein and Helms 2006), identify challenges (see Havlak et al. 2002; Need and Mothershead 2006; Tegnell et al. 2006), and suggest strategies for improving public health preparedness (see Brand et al. 2006; Bravata et al. 2006).

Some researchers propose explicit mathematical models to locate emergency response units and medical supplies (Sathe and Miller-Hooks 2005; Berman and Gavious 2007; Jia et al. 2007). For example, Sathe and Miller-Hooks (2005) put forward an optimization model to locate emergency services close to other critical infrastructures in case of an emergency. In addition, Farahani and Azgari (2007) implement a multi-criteria coverage model to find the best locations for the least amount of supply facilities in a military logistics system. Jia et al. (2007), provide a similar objective, and apply some coverage models for locating medical supplies. The important thing to note here is that these models are minimizing the weighted distance from supplies to demands. This can be a problem if the facility to be located is deemed "critical" itself and needs to maximize its distance to other critical entities. Without this objective, a critical supply facility may pose a threat to itself and other nearby critical entities.

2.5 Location Modeling for Critical Infrastructure Protection and Disaster Preparedness

Location models can also entwine both critical infrastructure protection and disaster preparedness problems. This is important to note, because sometimes the two are inseparable, especially for critical stockpiles. Currently, government programs are actively taking measures to move to an 'all-hazards' approach in planning for disaster preparedness and critical infrastructure protection, meaning both directives are to be carried in the same plan (Gerber et al. 2005; U.S. Department of Homeland Security 2007).

Although no mathematical models are addressed, FEMA (2005), Larson (2005) and Lane et al. (2006) consider that because of the recent experience with terrorism, some critical stockpiles should be located away from manufacturers' sites or in multiple locations throughout the country. Again, Sathe and Miller-Hooks (2005) suggest a model to locate emergency services close to other critical infrastructures in case of an emergency. Berman and Gavious (2007)

propose a game theory model that locates a supply facility; however, their approach and methods differ from mine, in that I assume an attacker does not know where a facility is located.

As reviewed so far, certain approaches in both critical infrastructure protection and disaster preparedness incorporate location modeling methodologies. The spatial orientations of the two, however, create a conflict. In disaster preparedness, the primary objective is to minimize weighted distance to demands, thus increasing access. In critical infrastructure location, the main objective is to maximize weighted distance from vulnerable entities and facilities of its own kind, thus increasing protection. As a result, a multi-objective model is necessary to incorporate the dimensions of critical infrastructure protection and disaster preparedness directives for locating a future critical vaccine supply facility.

2.6 Summary of Literature Review

Critical infrastructure protection is a burgeoning field, as highlighted by the recent contributions in the literature (see Table 5). The research reviewed thus far has addressed an array of critical infrastructure problems with an assortment of methods. However, the literature does not exhaust the research opportunities in the field. Table 5 helps illustrate what researchers have done in the fields of location modeling, critical infrastructure protection, and disaster preparedness. As Wright et al. (2006) had mentioned about the lack of research in critical infrastructure protection and operations research, you can see from Table 5 that the earliest found record of combining location modeling and critical infrastructure protection was in 2004. Only in 2006 have location modeling, critical infrastructure protection, and disaster preparedness been incorporated together for analysis. My proposed research now can help fill a void in the body of literature between these three topic areas. Furthermore, my research can help elaborate on the theme of critical vaccine location and protection—an area that has potentially been overlooked.

From the literature, I have recognized four different types of approaches for protecting critical infrastructures: 1) Physical hardening/fortification with construction materials and design. 2) Architectural design and layout of both the building and the perimeter. 3) Security initiatives (e.g. guards, locks, passwords, etc.). 4) Geographical/spatial positioning of critical assets (e.g. dispersion, redundancy, decentralization, and deconcentration).

Table 5. Literature Review; x denotes a major topic of the research.

Author(s)	Location Modeling	Critical Infrastructure Protection	Disaster Preparedness
Malczewski (1999)	x		
Ghosh and Rushton (1987)	x		
Brandeau and Chui (1989)	x		
Mirchandani and Francis (1990)	x		
Sule (2001)	x		
Cohon (1978)	x		
The White House (2003)		x	
Federal Emergency Management Agency (2005)		x	
Amin (2005)		x	
Sternberg and Lee (2006)		x	
Greenberg et al. (2007)		x	
Cutter et al. (2003)		x	
Farrell et al. (2004)		x	
Goodman et al. (2007)		x	
Ramberg (1982)		x	
Dunbobbin et al. (2004)		x	
Torgerson (2004)		x	
Conrad et al. (2006)		x	
Raas and Long (2007)		x	
Lui et al. (2000)		x	
Li et al. (2005)		x	
Min et al. (2007)		x	
Lovins and Lovins (1982)		x	
Asbjornslett and Rausand (1999)			x
Need and Mothershead (2006)			x
National Vaccine Advisory Committee (2003)			x
Klein and Helms (2006)			x
Tegnell et al. (2006)			x
Brand et al. (2006)			x
Church et al. (2004)	x	x	
Salmeron et al. (2004)	x	x	
Brown et al. (2006)	x	x	
Church and Scaparra (2007)	x	x	
Bravata et al. (2006)		x	x
Havlak et al. (2002)		x	x
Griebel and Phillips (2001)		x	x
Lane et al. (2006)		x	x
Garb et al. (2007)	x		x
Larson (2005)	x		x
Gazmararian et al. (2002)	x		x
Giovachino et al. (2005)	x		x
Lee et al. (2006)	x		x
Farahani and Azgari (2007)	x		x
Jia et al. (2007)	x		x
Sathe and Miller-Hooks (2007)	x	x	x
Berman and Gavious (2007)	x	x	x
Wright et al. (2006)	x	x	x

In a traditional sense, we think of protecting infrastructure as fortifying it with some physical means (hardened materials and structure design) or security initiatives to ward off potential human threats on the ground. However, resilience in these measures is limited (Amin 2005), as seen in the events of September 11, 2001. With recent advancement in weapons development, even the most hardened building is susceptible to annihilation (Krieger 1977; Ramberg 1982; Raas and Long 2007).

The White House has identified over hundreds of thousands of individual critical infrastructures within the United States, and Sternberg and Lee (2006) gave a conservative estimation of 50,000 critical facilities in the United States. Hardening these critical infrastructures with fortification resources could get quite expensive and an attempt to fortify all of them with physical materials is impractical. Subsequently, with limited fortification resources, other inexpensive alternatives for protecting critical infrastructures become viable options. Spatial protection does not require additional materials for fortification, so resources can be saved in this protection sense. Land values are significantly less costly away from densely urbanized areas (Mills 2002) and would also help to further reduce the costs of protection.

To better critical infrastructure programs, it is imprudent to be narrow in approach on how to protect particular facilities that are necessary for society to function properly. Using a multi-objective location model to identify the potential locations for minimizing facility vulnerability and maximizing supply access provides an additional method for siting critical supply facilities. Incorporating the dimension of space to see how certain places are more vulnerable than others to attack allows for an alternative method for protecting a future critical stockpile.

CHAPTER III: RESEARCH AIMS AND METHODS

3.1 <u>Research Aims</u>**:** To determine where to locate a critical supply facility in order to minimize its vulnerability from human-made attacks and maximize its access to populations.

Question: 1) How do I locate a critical supply facility in order to minimize its vulnerability to human-made attacks and maximize its accessibility to population demands?

Specific Goals: 1) Locate a facility to minimize its vulnerability to attack. 2) Locate a facility for redundancy to increase system reliability. 3) Locate a facility to maximize its accessibility to population demands.

In order to reduce facility vulnerability, maintain system reliability, and provide supply access to populations, Goals 1-3 are to be pursued. Goal (1) seeks to locate a facility away from vulnerable entities that are more likely to be attacked, hence the idea of decentralizing facility location. Goal (2) stipulates that multiple facilities should not be located in clusters in order to maintain system reliability from cascading failure, thus the idea of deconcentration. Goal (3) is a trade-off goal that requires the facility to be spatially accessible to population demands.

As an example, consider some hypothetical area, in which a government wants to place their new state-of-the-art vaccine stockpiles for all the population of the area. The existing clinics and hospitals that carry vaccines may not be of sufficient supply to everyone in case of a large-scale emergency. Consequently, to prepare for a disaster, the government decides to place additional stockpiles. Furthermore, they have reason to believe that an adversary has intentions to disrupt their new network by means of destruction. The enemy has the weaponry to destroy their stockpiles, but does not know exactly where they are located. So the question remains, how does the government place these stockpiles to reduce vulnerability and maintain system reliability to serve the population? First, they need to locate them in less vulnerable areas. Second, they must locate them so that the system is reliable; hence, they must disperse like facilities, so that if the attacker determines the location of a stockpile, they will have a redundant system to prevent widespread failure. Third, they must locate them in order to provide access to the surrounding population. This is a starting point for developing the notation of a critical stockpile location problem in the context of a physical human-made threat.

3.2 Methods

3.2.1 Introduction

Emergency supplies are a part of a critical infrastructure network. Infrastructure is defined as a complex system based on a composition of nodes and links. In a location modeling context, the links and nodes of an infrastructure system are the fundamental units in the location and allocation of resources (Sule 2001). Links can be defined as the connectors in a network (i.e. roads, cables, pipelines, etc.); nodes can be represented as the fixtures in a network, often designated as facilities or populations (Malczewski 1999). These two components are interconnected and functionally interdependent within an infrastructure system (Conrad et al. 2006; Min et al. 2007). It is also important to note in the context of critical infrastructure protection, that nodes are just as, if not more important than links in a system, because often times, these are the beginnings, intermediaries, and endpoints of a distribution system (Sternberg and Lee 2006).

3.2.2 Modeling Facility Location

Decision makers are usually faced with a number of different factors that influence the location of a facility. In order to determine those influential factors, the key functions of a facility must be recognized. Essentially, the function of facility is the purpose it serves and how it can best meet those needs. To satisfy those function requirements, decision makers must have information about the surrounding environment that will help determine the most suitable locations. These environmental factors often include roads, populations, landforms, land usage, markets, resources, and even the law. In the context of critical facilities, security is an important consideration in determining their locations. In regards to supply relief points for disaster preparedness, surrounding populations are essential in determining their locations. So in the sense of locating critical vaccine stockpiles for their intrinsic function, security and surrounding populations are the two deep-seated factors influencing their locations.

To satisfy the goals of these two functions for locating a critical supply facility, they need to be represented mathematically in an optimization model. In order to minimize its weighted distance to populations and maximize its weighted distance from vulnerable areas, a mathematical representation must be formulated. The model this thesis introduces is an extension

to the *p*-median problem that can be found in much of the facility location literature (Hakimi 1965; Harvey et al. 1974; Oppong and Hodgson 1994; Pirkul et al. 1999). Again, the *p*-median minimizes average weighted distances to demands (i.e., populations), so the extension to this model can be seen as adding a trade-off particularly for this problem situation. The undesirable facility location literature is useful for positioning the proposed model, particularly for the trade-off. Undesirable facility location problems seek to locate facilities as far from populations as possible in order to minimize the menace associated with such facilities (Church and Garfinkle 1978; Drezner and Wesolowsky 1985; Erkut and Neuman 1989). One example of such a location problem is the *p*-maxian, where the weighted distances from a facility are to be maximized from some demand vector (e.g. populations). However, critical infrastructure facilities are not necessarily entirely undesirable. These facilities are more appropriately classified as semi-desirable, where they may pose a threat (they are the target of attack), but are desirable for populations so they should be as close to populations as possible. Subsequently, the *p*-maxian will be used to employ the trade-off goal of protection; this is the key element in developing the multi-objective model.

3.2.3 The Critical Supply Facility Location Model

Minimize

$$Z_1 = \sum_i^n \sum_j^m P_i D_{ij} X_{ij} \tag{1}$$

Maximize

$$Z_2 = \sum_i^n \sum_j^m V_i D_{ij} X_{ij} \tag{2}$$

Subject to

$$\sum_j^m X_{ij} = 1, \forall_i = 1,\dots,n \tag{3}$$

$$X_{jj} - X_{ij} \geq 0, \forall_{i,j} \text{ and } i \neq j \tag{4}$$

$$\sum_{j=i}^m X_{jj} = f \tag{5}$$

$$X_{ij} = 1,0, \forall_{i,j} \tag{6}$$

Where

$\quad i =$ Node of origin
$\quad n =$ Set of all origins

j = Node of destination

m = Set of all destinations

D_{ij} = Distance matrix between all nodes

P_i = Vector of population

V_i = Vector of vulnerabilities

f = User specified number of facilities to be located

X_{jj} = Facility location; $\begin{cases} 1 = \text{if facility is located at node } j \\ 0 = \text{Otherwise} \end{cases}$

X_{ij} = Decision variable; $\begin{cases} 1 = \text{if demands at node } i \text{ are served by facility at node } j \\ 0 = \text{Otherwise} \end{cases}$

The multi-objective problem stated above is similar to some previous established models. The first equation (1) shares commonalities with the p-median in that the objective function seeks to minimize weighted distances from population demands to a facility, thus maximizing access. The second equation (2) is similar to the p-maxian problem in that the trade-off objective function seeks to maximize weighted distances from critical entities to a facility, thus minimizing vulnerability. Constraint (3) stipulates that each node on the network must be assigned to one facility. Constraint (4) requires demand nodes to be assigned to a node where a facility is opened up. Constraint (5) limits the number of facilities, f, to be located as specified by the user. Constraint (6) is a binary constraint, stating that a facility is either to be located, *one*, or otherwise not, *zero*.

3.2.4 Modeling for Multiple Facilities

Decision makers are sometimes faced with the problem of locating multiple facilities. Depending on the function of a facility, there may be certain requirements for the locations of multiple facilities. For example, a company may want to disperse their facilities to increase their competition amongst other businesses for customers. In the context of critical facilities, a government may want to disperse facilities for security purposes.

Dispersion among multiple facilities is an important part of this research, because security is a primary goal. In addition to maximizing distances to other critical entities and minimizing distances to populations, the distances between each stockpile should be constrained in order to facilitate the dispersion of like facilities, because clustering of like facilities increases vulnerability to system failure as well (Lovins and Lovins 1982; Erkut 1990; Liu et al. 2000;

Larson 2005; Li et al. 2005; Goodman et al. 2007). The goal of facility dispersion takes on two forms in the model, depending on how many facilities are being placed. If one critical stockpile facility is to be located, then the aspiration of dispersing like facilities will be obtained through goal (1), where the distance from the proposed facility to other existing critical entities, such as hospitals and clinics, will be maximized. If two or more facilities are to be located, a distance constraint should be implemented to separate those proposed facilities from each other, in addition to dispersing them from the existing critical facilities in goal (1).

Depending on the policies put in place for developing a stockpile program, a government may want to place several stockpiles instead of concentrating all vaccine stock into one facility. Given the Cities Readiness Initiative is a new endeavor, it is unclear whether certain placement policies are being implemented. Furthermore, different state governments may value certain policy situations more than others for managing emergency stockpiles. For example, Pennsylvania government officials may decide to concentrate all critical vaccine stock into one large facility, where California government officials may decide to have several smaller facilities scattered throughout the state in separate locations. Nevertheless, if a state government is seeking to deconcentrate its vaccine stock, they should disperse the facilities proposed to be placed in that particular area. Employing facility dispersion for locating two or more facilities in this model is a challenge given that it already contains two objectives. However, there are two options I will explore to satisfy the problem of locating multiple facilities, given that facility clustering is undesirable and should be avoided.

The first option is to implement a minimum distance constraint among the multiple facilities proposed for placement. *Neighborhood Adjacency Constraints (NAC)* can be used to employ this goal (see Murray and Church 1997). *NACs* prohibit locating any two facilities within some user specified distance *R*. The advantage of having this option is that it will not alter the formulation of the objective function, since it is simply constraining what the objective function values can take. The drawback of this option is that the distances between facilities are not optimized like goals (1) and (3), but are separated by some user-specified distance, *R*. In other words, it does not exactly follow suit with the other goals, because with this approach, that the distance between sited facilities is not necessarily optimized.

The *Neighborhood Adjacency Constraint* is formulated as follows:

$$h_j X_{jj} + \sum_{i \in H_j} X_{ii} \leq h_j, \ \forall_j = 1,\ldots,m \tag{7}$$

Where

$$H_j = \{i \mid D_{ij} \leq R \ \& \ i \neq j \}$$

h_j = minimum coefficient necessary to impose locational restrictions

Again, this constraint (7) prohibits locating any two facilities within some user specified distance *R*. As noted before, the downside of this option is that it does not follow suit with the other goals in that there is not an optimal answer for dispersing facilities, but only restricted by some distance *R* as defined by the user. However, the advantage is that it is relatively simpler from a computational standpoint than adding another objective.

The second option for constraining interfacility distances is to incorporate another objective which seeks to maximize the minimum distance apart between two facilities being placed. This type of objective is formulated as the *p*-dispersion problem. The *p*-dispersion problem is often motivated by military operations, where strategic facilities, such as missile silos, should be dispersed to help defend against simultaneous enemy attacks (Erkut and Neuman 1989; Erkut 1990; Daskin 1995). The advantage of this option is that it is optimizing (i.e. maximizing) the distance between two facilities, thus analogous to the other goals in that it seeks to find the 'best' solution. The drawback, however, is that incorporating another objective makes finding a valid solution more difficult because of the problem structure. The complication of this problem results from the fact that the first two objectives are relatively direct trade-offs, where if one is increasing accessibility, then vulnerability increases, thus reducing protection. However, when adding the third objective and one increases interfacility dispersion (increasing protection) in the model, one is not necessarily decreasing access. So in a real-world sense, it is not a direct trade-off because the two are independent, whereas the model treats them as if they are direct trade-offs.

The *p*-dispersion problem is formulated as follows:

Maximize

$$Z_3 = Q \tag{8}$$

Subject to

$$\sum_{j=i}^{m} X_{jj} = f \tag{9}$$

$$Q + (M - D_{ij}) \cdot X_{ii} + (M - D_{ij}) \cdot X_{jj} \le 2M - D_{ij}, \forall j; \forall i < j \tag{10}$$

$$X_{ij} = 1,0, \forall_{i,j} \tag{11}$$

Where

$M =$ Some large number; such that $M \ge \max_{i,j} \{ D_{ij} \}$

All other notation previously defined

Again, the *p*-dispersion objective function (8) maximizes the minimum distance, *Q*, between any two facilities that are to be located. Constraint (9) stipulates that *f* facilities are to be located. Constraint (10) defines the minimum distance between facilities in terms of the selected facility locations. Constraint (11) is simply a binary constraint, stating that a facility is either to be located, *one*, or otherwise, *zero*.

3.3 Summary of Research Aims and Methods

This chapter introduces the research aim of this thesis with a hypothetical example in which a government may want to place future critical emergency supplies. Three specific goals are identified which include (1) the spatial decentralization of a stockpile from other critical facilities, (2) the deconcentration of a critical stockpile into separate/dispersed locations, and (3) locating the stockpiles for accessibility for demand populations.

This chapter also introduces spatial optimization approaches for satisfying the previously identified goals. In particular, the Critical Supply Facility Location Model is presented. This model takes a multi-objective approach given there are three goals to satisfy. The first objective is to minimize population weighted distances to a supply facility. The second objective is to maximize vulnerability weighted distances to a supply facility. The third goal is proposed to be satisfied by either interfacility distance constraints or by maximizing interfacility distances.

Following this introduction of methods for the research aim, the next chapter introduces a case study in Central Florida, presents the data to be used, and documents a procedure for trade-off analysis.

CHAPTER IV: CASE STUDY

4.1 Study Area

4.1.1 Introduction

The model introduced in the previous chapter is applied to a case study in the state of Florida. There are several reasons why Florida is an appropriate study area for the application of this model. Firstly, Berman and Gavious (2007) apply a game theory model for locating supply facilities on a nation-wide extent. So in a sense, my methods and disaggregation of scale present somewhat of a new challenge. In addition, The SNS already has twelve strategically located vaccine stockpiles (12-h push packages) across the United States. Since the CDC is now encouraging states to increase their capacity of delivering medical supplies for disaster preparedness (Centers for Disease Control and Prevention 2007), it would be suitable to apply this thesis at most, at a state level. In an event of a bioterrorist attack, The U.S. Department of Homeland Security has concluded that vaccine resources should be distributed to demands within 12-48 hours, which can be located regionally. However, an optimal location should be located within 15-20 miles from the event site (U.S. Department of Homeland Security 2007).

One of Florida Department of Health's strategies for the management and distribution of medical supplies is to maintain stockpile of radiological, chemical, and biological countermeasures sufficient for initial response as outlined in their mass prophylaxis plans in addition to their strategy of sustaining and improving mass prophylaxis treatment (Florida Department of Health 2007). Furthermore, Florida has a significant position within in the United States as I will discuss in the following paragraph.

4.1.2 Vulnerability in Florida

Florida is located in the southeastern part of the United States. In terms of population, Florida is the fourth largest state (18 million) and has the third highest rate of growth within the United States (U.S. Census Bureau 2006). The U.S. Census (2006) urbanized estimate for the state was at 84% and is 8th in the United States according to population density (Caruson and MacManus 2007), suggesting the large majority of the population lives in and has developed relatively dense urban areas. These are significant demographic facts that help shed light on the vulnerability dynamics of the state.

Florida's vulnerability to attack has been recognized by several researchers and local government officials in Florida. According to a study done by Caruson et al. (2005), Florida has a higher than average vulnerability to attack ranking as compared with the rest of the United States. According to another study by Caruson and MacManus in 2007, the state's own assessment affirms that the potential for terrorist attacks remain high in Florida and its citizens are thus concerned:

> Floridians are well aware of the vulnerability of the state to an attack and homeland security consistently ranks as an important public policy concern (Caruson and MacManus 2007).

4.1.3 Central Florida

In this thesis, I analyze two different sized areas in the central region of Florida (see Figures 4 and 5). The larger study area includes the greater metropolitan areas of Tampa Bay and Orlando and the smaller study area will look at the Orlando metropolitan area. In regards to the larger study area, the Tampa Bay and Orlando metropolitan areas together make up a conurbation of the greater I-4 corridor with central focuses on the downtowns of Tampa and Orlando. The I-4 corridor extends across the counties of Hillsborough, Polk, Osceola, Orange, Seminole, and Volusia. I-4 does not traverse Pinellas County; however, I include it since it is a part of the Tampa Bay metropolitan area. The estimated population of the Tampa-Orlando conurbation is over 5 million people (U.S. Census Bureau 2006). In 2005, Tampa and Orlando were added to the Cities Readiness Initiative (CRI), a federally funded program to prepare major U.S. cities and metropolitan areas for a large-scale bio-terrorist disaster by dispensing vaccines and other medical supplies to the population (Centers for Disease Control and Prevention 2007).

For the smaller study area, I look at the Orlando metropolitan area (See Figure 5). The greater Orlando metropolitan area consists of Lake, Orange, Osceola, and Seminole counties. However, I only include the counties of Orange and Seminole because it enables for a more uniform study area (see Figures 35, 36, and 37 in Appendix A).
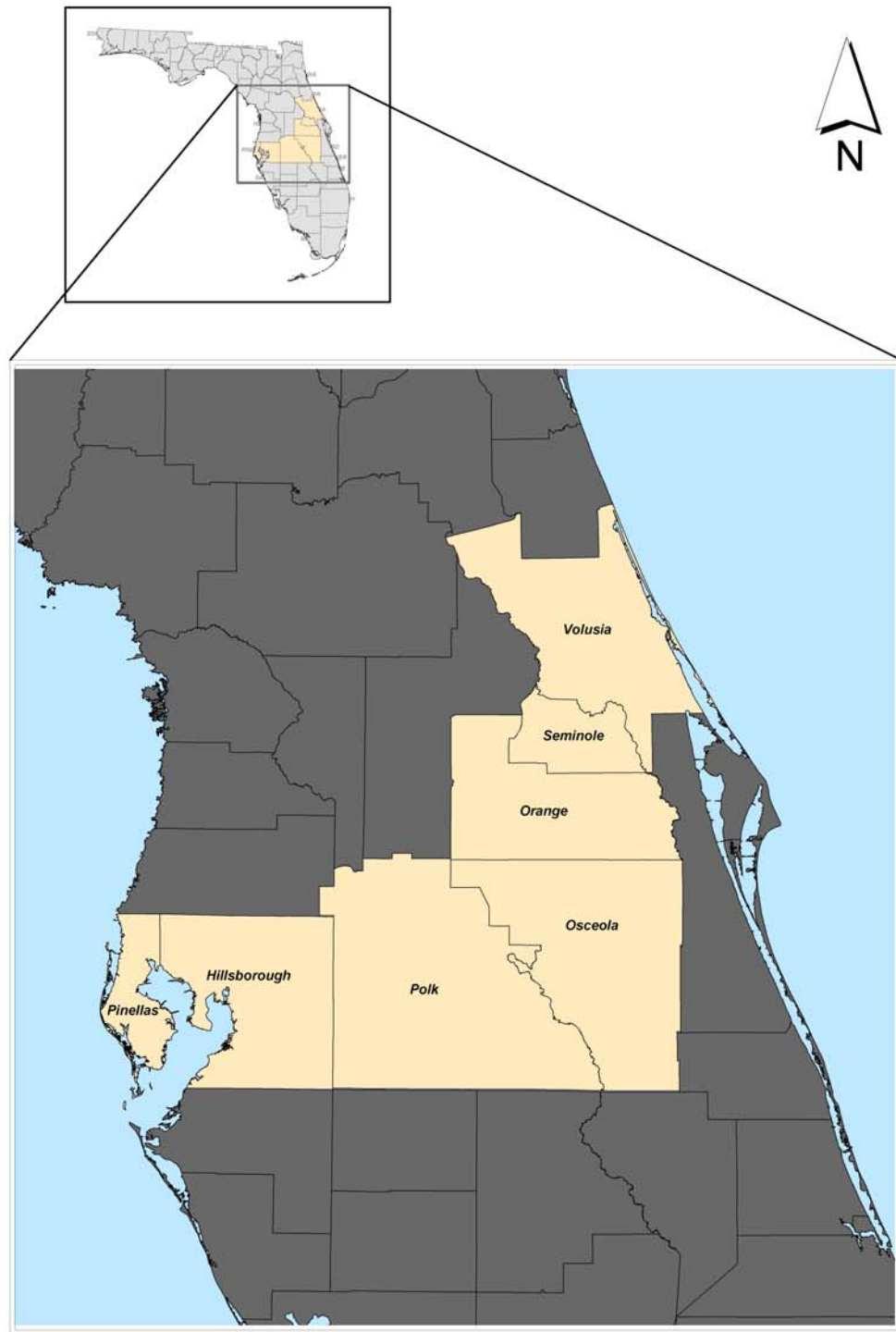
Figure 4. Highlighted Large Study Area in Central Florida.
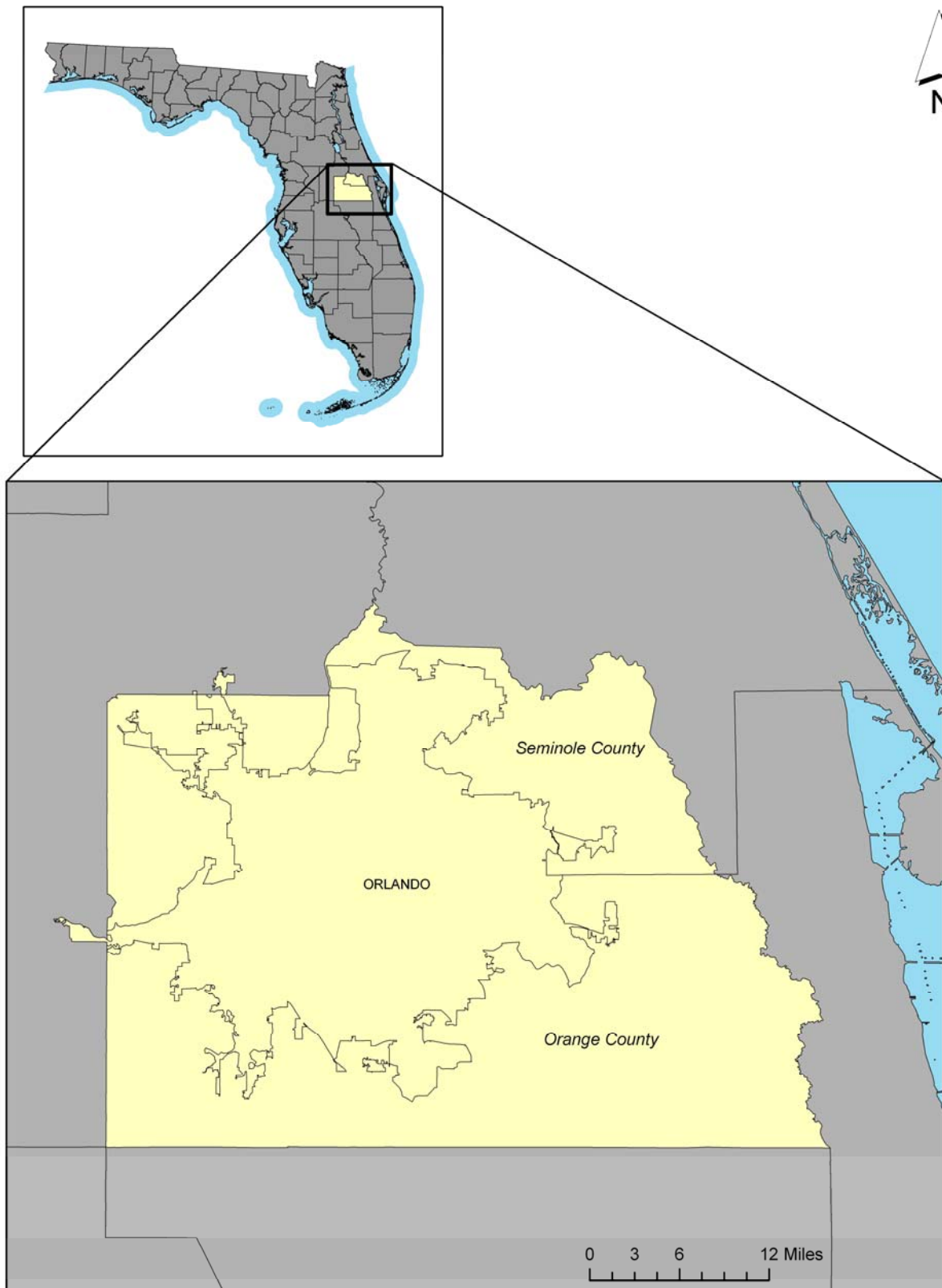
Figure 5. Highlighted Small Study Area of the Orlando Metropolitan Area.

4.1.4 Tampa Bay Area

Tampa is located in Hillsborough County. In regards to critical infrastructure, Tampa contains the MacDill military base, several large office buildings including the Bank of America high-rise building, and other institutions where large numbers of people congregate, such as the amusement park of Busch Gardens. In 2002, the Bank of America tower in downtown Tampa was subject to an airborne attack (Wald 2002). A high school student flying a Cessna plane intentionally crashed into the building. The damage was minimal, and they only person killed was that of the pilot. However, it is important to point out that this pilot had intentions of destruction, and had gravitated to an area that was vulnerable to attack. Fortunately for the people of Tampa, the pilot was irrational and his plans for maximizing destruction were ill-conceived. Along with Miami, Tampa has also been recognized as having the highest at-risk populations within the state of Florida (Caruson et al. 2005).

4.1.5 Orlando Area

Orlando is comparable to Tampa. Located in Orange County, Orlando has a bustling greater urban area containing nearly two million residents. Home to several world famous theme parks like Walt Disney World and Universal Studios, Orlando attracts a sizable portion of the 48 million tourists that visit Florida annually (Caruson and MacManus 2006). Orlando can also be thought of as a central hub in the distribution of goods and services throughout the rest of Florida with the Florida Turnpike serving as a key route leading to Miami from the North. Alongside Jacksonville, Orlando ranks as the most vulnerable cities in Florida in terms of the likely physical targets they contain (Caruson et al. 2005).

4.1.6 Summary

A case study in Central Florida allows for a new approach in methods and scale in regards to research in the spatial dimensions of critical infrastructure protection and disaster preparedness. As documented earlier in this chapter, Florida holds a significant position as a case study, given that urban vulnerability is a special concern within the state. Caruson et al. (2005) show that east-central (Orlando) and west-central (Tampa) were below the state average rating for emergency readiness. Their results also suggest that those regions with higher levels of preparedness indicate a higher level of intergovernmental cooperation (federal, state, county, and

municipal). In other words, those urban areas that are less prepared (i.e. Tampa and Orlando) should cooperate and seek assistance from federal programs such as the Cities Readiness Initiative under the Centers for Disease Control and Prevention for disaster preparedness.

4.2 Data

4.2.1 Introduction

Finding an optimal critical supply facility location necessitates an analysis of the potential location points and its surrounding demands and repellants. In this case, the potential facility location points must be able to serve all the population while having its location constrained to areas less vulnerable to attack. The areas vulnerable to attack include places with important entities and are a function of their relative degree of clustering. These vulnerable entities can be buildings, monuments, skilled/educated populations, tourist hotspots, and notable cities (e.g. capitols) (Sternberg and Lee 2006).

To obtain vector data for these vulnerable areas, it is necessary to understand which scale should be used for measurement and at what level of detail data should be gathered and stored. As previously stated, nodes are often represented as individual facilities. However, since nodes are representations of real objects, they can also be a point within an aggregate unit, such as a city within a state, or some other political unit of area. Scale is important to recognize in this sense because if a planner is looking to find the location of a new facility within a very large area (e.g. state), it may not be feasible to incorporate very small units of analysis (e.g. parcel of land) (see Smelser and Baltes 2001, pp. 13501-13504).

For this case study, I use individual critical facilities aggregated into census tracts to help define a vector of vulnerability for the study area. Population data will also be aggregated into census tracts in the study area. There are 941 census tracts within the seven counties of the larger study area and 268 census tracts within the two counties (Orange and Seminole) of the smaller study area. For application, the model seeks to decentralize a critical vaccine supply facility away from vulnerable areas that are characterized by having critical facilities. Specifically, this model will minimize the distances to demand points (population) subject to the protection trade-off that will require the facility distance to be maximized from other critical facilities, and away from other facilities of its own kind.

4.2.2 Critical Facilities in Central Florida

Before running the model with real network data through optimization software, I review its existing critical infrastructure layout by identifying where the critical nodes are located. This was done by gathering information on the most important facilities identified in the InfoUSA 2007 database that contains records of over 840,000 businesses located in Florida.

There are several established indicators that are useful for determining a critical facility (see Table 6). FEMA (2005) states, "The level of [critical] assessment of a given building is dependent on a number of factors". These factors include the type of building, location, type of construction, number of occupants, and economic life (Federal Emergency Management Agency 2005). In addition to those listed, I include the size of the building as an indicator of criticality. Based on the critical infrastructures listed in Table 4 and the guidelines established by FEMA (2005), I filtered a comprehensive database of critical facilities from the InfoUSA 2007 database. These facilities include the largest square footage, the largest numbers of employment, the largest economic assets and income, and other data that might suggest a critical facility, such as Standard Industrial Classification (SIC) codes. These SIC codes can be classified under any number of different critical key words. Examples include 'hospitals', 'distribution centers', and 'government offices'.

Table 6. Criticality Indicators.

Criticality Indicator	Measure
Type of Building	Standard Industrial Classification (SIC)
Location	Address/Coordinates
Type of Construction*	Material
Number of Occupants	Employee Count
Economic Life	Dollar Assets and Income
Building Size	Square Footage

* This is difficult data to obtain, thus is excluded from this study.

A relatively conservative approach was used to query the InfoUSA 2007 database for critical facilities. A critical facility was designated as one that had a critical Standard Industrial Classification (See Table 15 in Appendix A for SIC codes used), over 25 employees, 1 million

dollars in sales volume, and 10,000 square feet of floor space. This query produced 3,118 critical facilities within the larger study area. An initial stricter approach was set at 100 employees, 10 million in sales volume, and 40,000 square feet of floor space which produced 1,186 critical facilities. However, this dataset was not used for the sake of including critical facilities that may have been left out of the stricter query. As seen in Figures 32, 33, and 37 (See Appendix A), majority of these critical facilities are located near the urban centers of Tampa and Orlando. Subsequently, it should be no surprise that these two cities have been given high vulnerability ratings.

4.2.3 Populations

For the population vector, I simply use the human residents within the study area. I retrieved year 2000 population data by census tract from the U.S. Census Bureau. After querying down the data to those critical facilities most relevant, I geocoded them and the populations by the centroid of their coinciding census tract.

4.2.4 Distances

A more fundamental aspect of location modeling that is also incorporated in this model is the shortest path. The shortest path is simply the shortest distance or time from one point to another. In the context of a GIS, these are nodes on a network. And for this particular situation, the nodes represent populations and vulnerable entities (see Figure 6). The shortest path can also be measured in time or cost depending on your data and application. But for this study, distances are sufficient.

To obtain distance data, the separation between individual locations needs to be measured. It is important to consider which map projection should be used for collecting distance data. Distance measurements may be skewed if the wrong projection is used. Universal Transverse Mercator (UTM) Zone 17 is used by the Florida Department of Transportation to accurately measure roadway mile posts. As a result, the UTM Zone 17 projection was also used in this study.

The separation between a candidate vaccine facility location and other critical facilities is measured in straight line (Euclidean) distances. The rationale behind this is I am assuming an airborne attack. Airborne attacks are likely to cause the most damage so I focus on these instead.

Airplanes are not constricted to road networks, so they are able to fly from point to point, thus straight line distances are most appropriate. The separation between multiple facilities to be placed will also be measured in Euclidean distances. This is an acceptable distance measure when locating facilities for defense (Erkut 1990). The separation between candidate locations and population demands can either be measured in straight line or network distances, depending on how the supplies are delivered. In 2001, a 12 hour push package of emergency supplies from the Strategic National Stockpile was delivered by a combination of air and land vehicles (Need and Mothershead 2006). If they are sent by truck, network distances should be used since they would travel by road. If they are delivered by air, they should be measured by straight line distances.
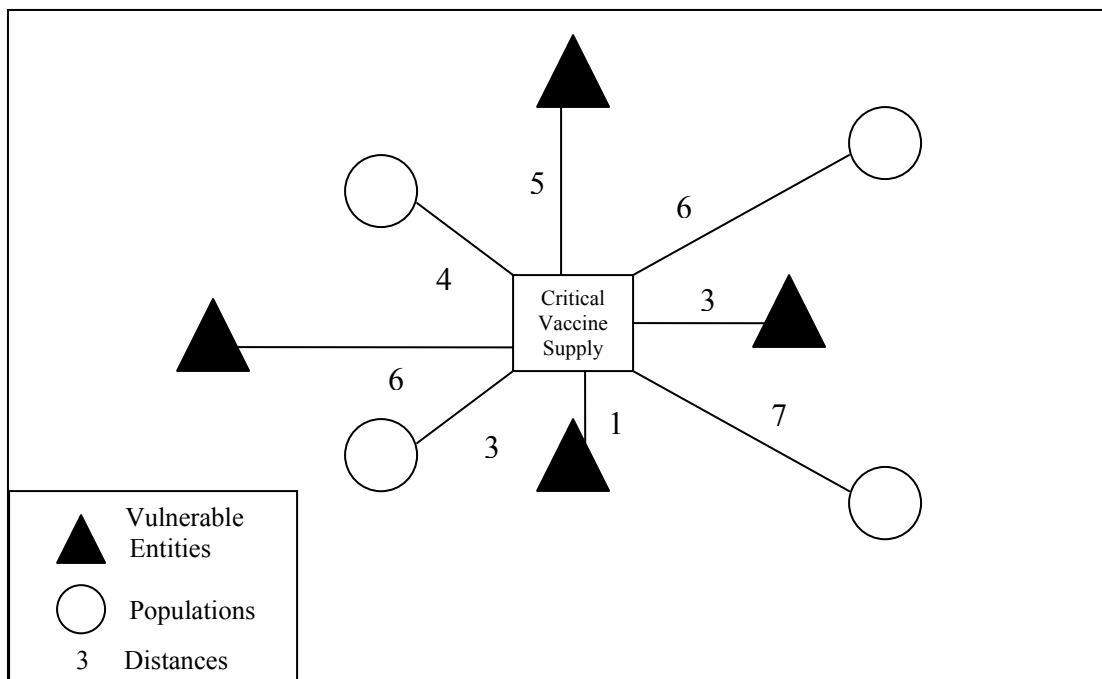
Figure 6. Strategic Vaccine Supply Diagram.

4.2.5 Data Standardization

After the vector data of population and critical facilities were collected, I used an evaluation measure that assigns associated weights to each attribute per census tract (see Figure 7). Given the differentiation of data values between population and critical facilities, the

associated attribute values must be transformed into comparable units. Linear scale transformation is the simplest way to standardize data (Malczewski 1999). I used the score range procedure:

$$x'_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}}$$

where $x_j^{max} - x_j^{min}$ is the range of a criterion and the standardized score is calculated by dividing the difference between a given raw score x_{ij} and the minimum score x_j^{min} for the criterion by the score range of a criterion. This algebraic formula is implemented to standardize each vector of data into a score range of 0 to 1, where a higher number on the scale indicates a higher level amount of population or critical facilities. Since this procedure standardizes differing scales of measurement, it helps eliminate any skewing of results (Malczewski 1999). Furthermore, this provides me with the spatial data needed to solve the problem of locating a future critical vaccine stockpile.

V=.1 ● P=.1	V=.2 ● P=.3	V=.6 ● P=.8	V=.2 ● P=.4
V=.7 ● P=.7	V=.8 ● P=.7	V=.3 ● P=.6	V=.1 ● P=.3
V=.7 ● P=.8	V=.3 ● P=.5	V=.1 ● P=.1	V=.1 ● P=.2

Figure 7. Vector Attribute Diagram.

□ = Census tract

● = Centroid of census tract

V = Vulnerability Attribute Measure

P = Population Attribute Measure

36

4.3 Trade-off Analysis

4.3.1 Introduction

After a thorough analysis of the existing critical infrastructure network layout, I propose a hypothetical situation in which a planner would like to locate a 'key' vaccine supply facility taking into consideration some means of protection for the facility. Specifically for this situation, the planner would be protecting by means of location, which is locating the facility to reduce vulnerability to attack from a human-made air strike. Taking protection into account in the model will affect the location of the desired facility. If protection was not in mind, a simple minimization model of distance to demands would work. However, a trade-off is put in place in order to reduce vulnerability. The trade-off will employ the concept of decentralization and deconcentration in the model. This means the facility location would be constrained by some function of vulnerability by the decision maker. Ideally, the decision maker would like to minimize vulnerability and maximize access; however that creates conflicting objectives in the function of the model. Consequently, it is necessary to run different policy objectives—one that emphasizes access in contrast to vulnerability, and vice versa. Running different policy scenarios allows for an evaluation of alternative solutions and possibly help decision makers determine the best policy for action (Cohon 1978; Malczewski 1999; Wallace and De Balogh 1985; Bravata et al. 2006; McGuire 2006). As a result, a weighting method is employed in the objective function to allow the user to adjust how much weight each objective is desired (see Figure 8) (see Malczewski 1999; Malczewski 2000; Malczewski et al. 2003; Kuby et al. 2005).

Decrease
Vulnerability
$w=0$

Increase
Access
$w=1$

Equal
Weights
$w=0.5$
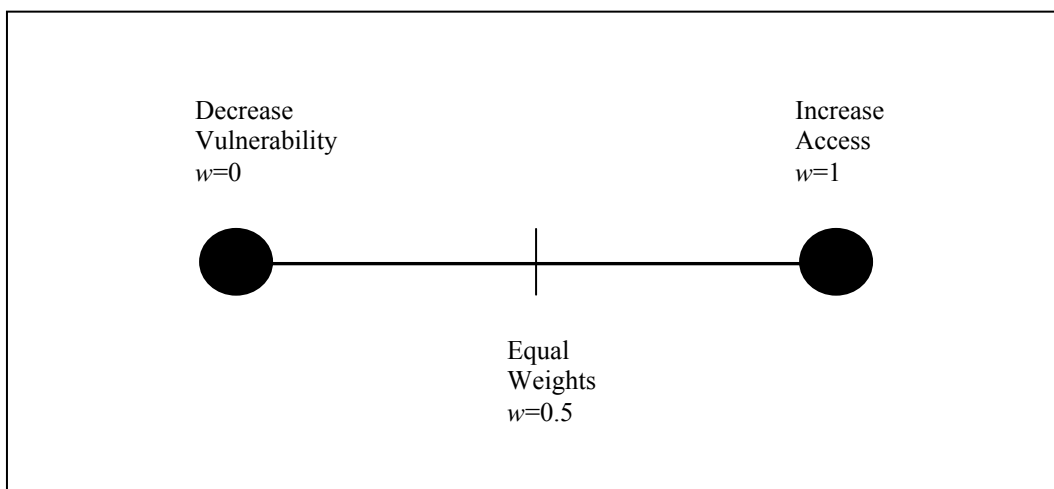
Figure 8. Trade-off weighting; $Z = w - (1-w)$.

4.3.2 Trade-off Analysis for Single Facility Location

Given the problem has multiple objectives, the most direct way of solving it is by using the weighting method where *w* is the user specified weight on the objective and $0 \leq w \leq 1$ (Horner and Downs 2007). This allows for the two objectives to be combined into a single objective, Z_c such that

$$Z_c = w(Z_1) - (1-w)(Z_2) \tag{12}$$

To solve the multi-objective problem, the conflicting objectives are then combined into a single weighted objective (13), with the maximization objective subtracted from the minimization objective and solved for a range of weights *w*.

Minimize

$$Z = w\sum_{i}^{n}\sum_{j}^{m}P_i D_{ij} X_{ij} - (1-w)\sum_{i}^{n}\sum_{j}^{m}V_i D_{ij} X_{ij} \tag{13}$$

To obtain the range of solutions for locating a critical vaccine facility, each standardized vector of attribute data (P_i, V_i) is inputted into their corresponding objective functions with the specified weighting, *w*, and solved using CPLEX, an optimization software, subject to their constraints.

4.3.3 Trade-off Analysis for Multiple Facility Location

Following the analysis of single facility location solutions, I explore two options (*Neighborhood Adjacency Constraints* and *p*-dispersion) for solving the problem of locating multiple facilities. For the first option, objective (13) is simply exercised subject to *Neighborhood Distance Constraints* in equation (7). To find the locations of multiple facilities with the second option, the *p*-dispersion objective function is weighted among the other two objectives and combined into a tri-objective model (see Figure 9) (14):

$$Z_T = w(Z_1) - \left(\frac{1-w}{2}\right)(Z_2) - \left(\frac{1-w}{2}\right)(Z_3) \tag{14}$$

Where the three objectives are weighted and combined into a single objective (15) to be minimized:

Minimize

$$Z = w\sum_{i}^{n}\sum_{j}^{m}P_{i}D_{ij}X_{ij} - \left(\frac{1-w}{2}\right)\sum_{i}^{n}\sum_{j}^{m}V_{i}D_{ij}X_{ij} - \left(\frac{1-w}{2}\right)Q \qquad (15)$$

$w = 1$
Increase Access

$w = 1/3$
Equal Weights

$w = 0$
Increase Dispersion

$w = 0$
Decrease Vulnerability
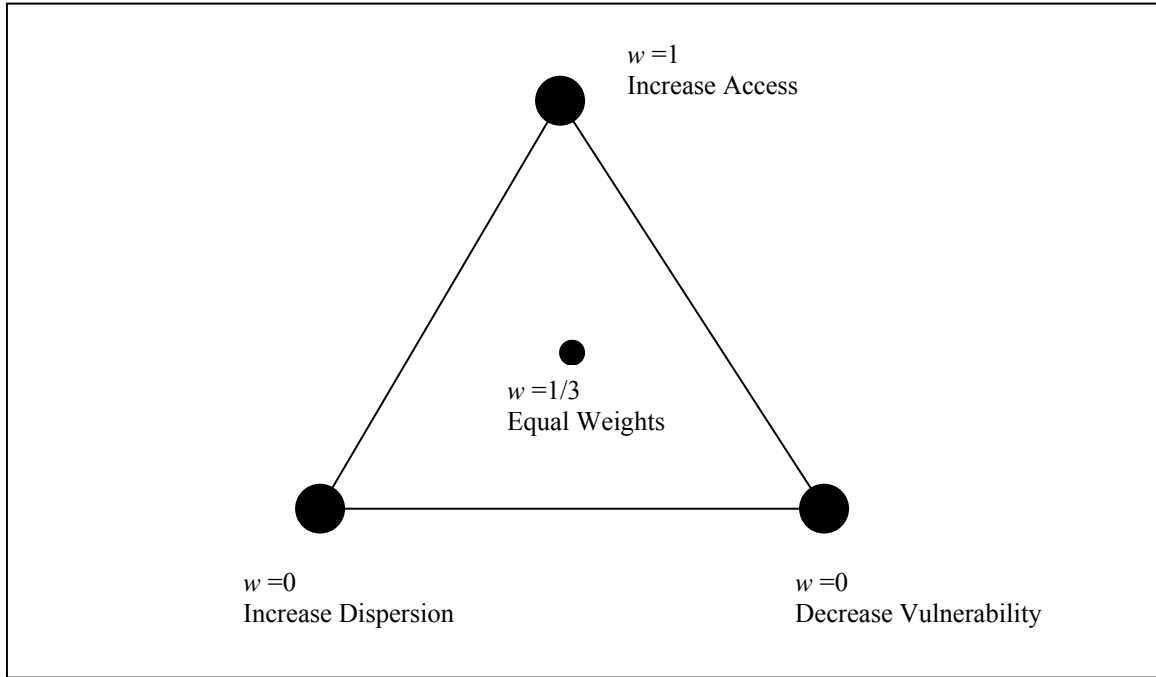
Figure 9. Tri-objective model; $Z_{T} = w - \left(\frac{1-w}{2}\right) - \left(\frac{1-w}{2}\right)$.

As seen in Figure 9, the weights, *w,* can be adjusted by the user to emphasize which objectives are most desired for placing vaccine stockpiles. For example, if one wishes to emphasize access for placing vaccine stockpiles, a higher number on a 0-1 scale should be allocated to the first objective, Z_{1}, thus compromising the weights on the remaining objectives Z_{2} and Z_{3}.

Note that if $w < 1$, then the corresponding weights assigned to Z_2 and Z_3 will default to $\dfrac{1-w}{2}$. If the user wishes to manipulate the weights on Z_2 and Z_3, a secondary weighting scheme (w_2) must be set in place:

let $w = w_1$ and,

$$Z_T = w_1(Z_1) - (w_2)\left(\frac{1-w_1}{2}\right)(Z_2) - (2-w_2)\left(\frac{1-w_1}{2}\right)(Z_3)$$ (16)

and $0 \leq w_2 \leq 2$

where $w_2 = 2$ for emphasis on Z_2 (decrease vulnerability)
$w_2 = 1$ for equal weights on Z_2 and Z_3
$w_2 = 0$ for emphasis on Z_3 (increase interfacility dispersion)

It is important to note that if the user is increasing the weight w on the objective for dispersing multiple facilities for redundancy, it is not necessarily decreasing access from populations in a real world context. This concept is only valid in a theoretical context within the model itself where the weighting mathematics is in the bounds of linearity. In other words, if one is locating facilities for access, it does not necessarily mean the locations of multiple stockpiles will not be separated. This is because the third objective is not a direct trade-off in the real world as the first two objectives are; it is only a trade-off in the model. This complication is the drawback of incorporating the p-dispersion option.

As noted before, there are advantages and disadvantages to each option for addressing the problem of placing multiple facilities. As a result, part of this research is to establish some guidance as to which model works best. Given the number of different options the user has for finding the location of a vaccine stockpile, a type of sensitivity analysis is performed to explore the results and how they vary. These options include varying the weight desired for different/conflicting policy scenarios, and the desired number of stockpiles to be placed subject to a range of some minimum distance, R, apart or the dispersion objective to maximize interfacility distances.

4.4 Expected Outcomes

I expect that the current layout of both the population and the existing critical facilities will have an affect on the placement of a new facility. This is reasonable, since both the population structure and currently existing facilities are what are used to determine the vulnerability of a facility. Specifically, the location constraints will ultimately affect the location of a proposed facility placement on the real network. Furthermore, I expect that with equal weights on the conflicting objectives, the model will locate a future vaccine supply facility in Polk County, strategically situated between Orlando and Tampa. With weights set on emphasizing the minimization of vulnerability, I expect the facility to be located in the southeastern corner of Osceola County. With weights focused on maximizing accessibility, I expect the facility to be located in northern Polk County. An alternative outcome is that the current structure of the population and existing facilities will have no affect on the placement of the facility. However, this is unreasonable since the location constraints are somewhat developed by the user/decision maker. And with a preliminary analysis of the existing structure of major distribution centers, it is likely that the critical facility will not be placed in centralized areas. Another alternative outcome is that the model will fail to generate an optimal solution. If this is the case, another technique must be applied—or another model should be developed. However, it should be noted that the preliminary model was tested on a toy network containing 5 nodes and solved optimally.

It is difficult to foresee what the outcomes would be for multiple facilities. However, I would assume that if there was not an interfacility distance constraint put in place, it is possible for one facility to be placed on top of another one. This is reasonable because without this constraint, the model does not care about interfacility distances and would choose whichever location most satisfies the objective put in place. For example, if we were to use model (13) for locating two or more facilities, and have the weights set on reducing vulnerability to 100%, it is likely for a second facility to be placed on top of the first facility that is far away from a large number of critical facilities near Tampa or Orlando. In other words, a single stockpile could be the only critical facility in that census tract, thus having a very small influence on the placement of a second facility for vulnerability reduction. This is the reasoning behind developing a model for constraining interfacility distances.

CHAPTER V: RESULTS

5.1 Introduction

This chapter documents the results of the previously introduced models applied to two study areas. The spatial data were managed in ArcGIS 9.2, TransCAD and Excel. C++ was used to compile the raw data into linear programming files. The linear programming files were then imported into CPLEX 10.0 and solved for various weights on the proposed objectives. Results were then exported back into ArcGIS 9.2 and Excel for data visualization and representation. This was all carried out on a Pentium 4, 3.2 GHZ processor machine running Windows XP on 3.62 gigabytes of RAM.

Results are presented in the following order. First, in section 5.2, I show the results of the Bi-objective Critical Supply Facility Location Model in the Tampa-Orlando conurbation along the I-4 corridor. In section 5.3, I show the results of the same model subject to Neighborhood Adjacency Constraints of 15 and 30 miles. Following in section 5.4, are the results of the Bi-objective Critical Supply Facility Location Model applied to the smaller area of the Orlando metropolitan area. In 5.5, the same model and area are subjected to Neighborhood Adjacency Constraints of 10 and 20 miles. The subsequent section of 5.6 shows the results of the Tri-objective Critical Supply Facility Location Model.

Because the tri-objective model can have numerous permutations of weights, graphic display can get quite difficult. As result, I show the p-dispersion trade-off among the first two objectives, Z_1 and Z_2, separately. The tri-objective model was tried on the Tampa-Orlando conurbation dataset and no results were reported due to infinite bounds. This can be explained by the 941 node dataset. The p-dispersion problem can be notoriously difficult to solve amongst large datasets, which would explain why the bounds were infinite.

All of these models were run under a large variation of weights and number of facilities. The tables, graphs, and maps are organized in manner so that under f facilities, the weights between 0 and 1 are usually presented in increments of 0.1 with some exceptions.

Important to note is that these results are used for model illustration and should not be used to make actual policy decisions. Additional research in the fields of critical infrastructure and disaster preparedness location would need to be carried out to make actual policy recommendations and decisions.

As explained previously, there are numerous dimensions in protecting critical infrastructure and spatial protection is only one of the possibilities as described in this thesis. This research explicitly addresses the spatial aspects of critical infrastructure protection and disaster preparedness and hopefully opens new avenues of normative spatial modeling to applied problems.

5.2 Results of the Bi-objective Critical Supply Facility Location Model in the Tampa-Orlando Conurbation

The Bi-objective Critical Supply Facility Location Model in the Tampa-Orlando conurbation is run with f at one through five facilities with a variation of weights for each number of facilities. Generally speaking, the weights are run through increments of 0.1, however for $f = 1$, additional runs were allowed to observe the objective functions and node selections in between 0.2 and 0.3 (See Table 7). This range contained several changes but could only be observed at finer values within the two incremental weights. All solution values are optimal.

Graphical and cartographic displays are shown in Figures 10, 11, 12, and 13 to help visualize the results. Figure 10 shows graphs of the non-inferior (pareto-optimal) objective values of Z_1 (access) and Z_2 (protection) to help evaluate the trade-offs the model provides. Some interesting trends take place in the graphs that should be mentioned. First, at $f = 1$, the trade-offs are fairly direct with a slight bend towards the Z_2 objective. This means there is a very slight gain in protection while sacrificing access as the weight increases on Z_2. At $f = 2$, 3, 4, and 5, substantial gains become more apparent as the curve becomes more steep. This suggests that when placing multiple facilities, substantial gains in the trade-offs become more pronounced. For example, where $f = 5$ and $w = 0.5$, 25% of protection is gained while only 4% of access is lost.

Figures 11, 12, and 13 are selected cartographic displays of the results of facility locations and allocations of resources to demands. At $f = 1$ and $w = 1$ (increase access), the facility was placed where I had expected, in northern Polk county, situated between the major urban centers of Tampa and Orlando (See Figure 11). Also, without surprise, multiple facility placements were centered on urban core areas at $w = 1$. For example, at $f = 5$, facilities are

placed at or very near the urban centers of Clearwater, Tampa, Lakeland, Orlando, and Daytona (See Figure 13).

At $w = 0$ (increase protection), some interesting trends have taken place. At $f = 1$ and 2, facilities are placed on the far edges of the study area (See Figure 11). This indicates that distances have a significant affect on the facility placements, because the supply is being allocated the demands on the far opposite side of where the facility is placed even though the area in south-east Osceola County is sparsely populated with critical facilities. Another interesting trend is when $f = 3$, 4 and 5, facilities are packing together in Pinellas county (See Figures 12 and 13). This was not very surprising since the model is only concerned about maximizing weighted distances to demands, not interfacility distances. This result highlights the need for incorporating some type of interfacility distance constraint for placing multiple facilities. Results for interfacility distance constraints are shown in forthcoming sections.

Table 7. Results of the Bi-objective Critical Supply Facility Location Model in Tampa-Orlando Conurbation ($R = 0$ miles).

Number of Facilities (f)	Weight (w)	Z1	Z2	Node(s) Chosen	Time (seconds)	Gap (%)
1	0.000	16393.14	4969.27	2	900.44	0.00
1	0.100	16393.14	4969.27	2	1387.81	0.00
1	0.200	16393.14	4969.27	2	2182.11	0.00
1	0.210	11507.06	3696.69	265	4986.27	0.00
1	0.225	11175.48	3606.45	459	2272.23	0.00
1	0.250	9364.77	3019.08	450	2420.09	0.00
1	0.275	8181.91	2606.16	792	2145.20	0.00
1	0.300	7880.43	2486.91	778	1878.06	0.00
1	0.400	7635.25	2367.84	771	3383.80	0.00
1	0.500	7589.53	2330.58	193	1474.98	0.00
1	0.600	7589.53	2330.58	193	1207.16	0.00
1	0.700	7589.53	2330.58	193	1230.62	0.00
1	0.800	7589.53	2330.58	193	1149.86	0.00
1	0.900	7589.53	2330.58	193	1134.81	0.00
1	1.000	7589.53	2330.58	193	1225.92	0.00
2	0.000	19768.63	6431.63	2, 265	123.94	0.00
2	0.100	16520.13	6260.31	2, 265	266.34	0.00
2	0.200	12429.30	5510.11	2, 458	595.55	0.00
2	0.300	5893.15	3277.45	107, 326	819.47	0.00
2	0.400	4183.78	2374.68	152, 751	685.20	0.00
2	0.500	3534.72	1873.21	619, 740	495.03	0.00
2	0.600	3292.38	1593.99	619, 740	2140.03	0.00
2	0.700	3162.16	1358.88	618, 738	583.84	0.00
2	0.800	3083.06	1126.89	618, 739	2814.23	0.00
2	0.900	3069.59	1067.11	618, 738	3227.11	0.00
2	1.000	3065.07	938.59	618, 738	569.39	0.00
3	0.000	19677.57	6435.90	2, 265, 459	103.75	0.00
3	0.100	15601.48	6221.79	2, 265, 659	236.53	0.00
3	0.200	10704.36	5332.48	2, 459, 570	500.94	0.00
3	0.300	6279.18	3886.75	2, 329, 504	683.02	0.00
3	0.400	4102.24	2731.03	16, 514, 852	738.72	0.00
3	0.500	3220.55	2044.80	33, 503, 740	724.86	0.00
3	0.600	2697.68	1438.83	178, 613, 852	1230.01	0.00
3	0.700	2560.93	1191.53	174, 613, 852	664.77	0.00
3	0.800	2477.99	946.69	174, 613, 852	3054.19	0.00
3	0.900	2464.27	886.06	174, 615, 852	3387.27	0.00
3	1.000	2459.24	735.42	174, 615, 852	3310.78	0.00
4	0.000	19567.16	6435.90	2, 265, 371, 459	96.41	0.00
4	0.100	15228.51	6209.90	2, 265, 620, 781	193.81	0.00
4	0.200	10082.22	5270.85	2, 459, 620, 862	348.42	0.00
4	0.300	5912.56	3922.27	2, 459, 509, 784	432.16	0.00
4	0.400	3761.22	2768.55	15, 349, 501, 862	527.08	0.00
4	0.500	2751.33	1994.98	31, 161, 327, 509	537.01	0.00
4	0.600	2301.25	1483.27	34, 178, 509, 852	875.92	0.00
4	0.700	2130.61	1175.38	34, 178, 509, 852	1964.47	0.00
4	0.800	2029.93	880.47	34, 178, 508, 852	3256.20	0.00
4	0.900	2013.28	806.98	34, 174, 508, 852	2606.22	0.00
4	1.000	2005.82	574.90	34, 174, 508, 852	539.56	0.00
5	0.000	19225.96	6435.90	2, 213, 265, 371, 459	112.67	0.00
5	0.100	15062.77	6205.39	2, 158, 265, 620, 854	147.59	0.00
5	0.200	9944.70	5279.94	2, 158, 265, 620, 838	247.98	0.00
5	0.300	5570.44	3869.17	2, 174, 458, 620, 706	293.81	0.00
5	0.400	3395.27	2699.64	15, 174, 345, 539, 705	330.59	0.00
5	0.500	2433.82	1954.15	31, 174, 349, 509, 709	337.73	0.00
5	0.600	1998.14	1453.87	34, 176, 346, 509, 710	346.69	0.00
5	0.700	1811.79	1117.48	34, 176, 346, 509, 710	953.41	0.00
5	0.800	1700.39	790.98	34, 176, 346, 508, 710	3028.34	0.00
5	0.900	1682.92	713.98	34, 176, 346, 508, 710	1955.63	0.00
5	1.000	1675.22	476.22	34,176, 346, 508, 710	334.77	0.00
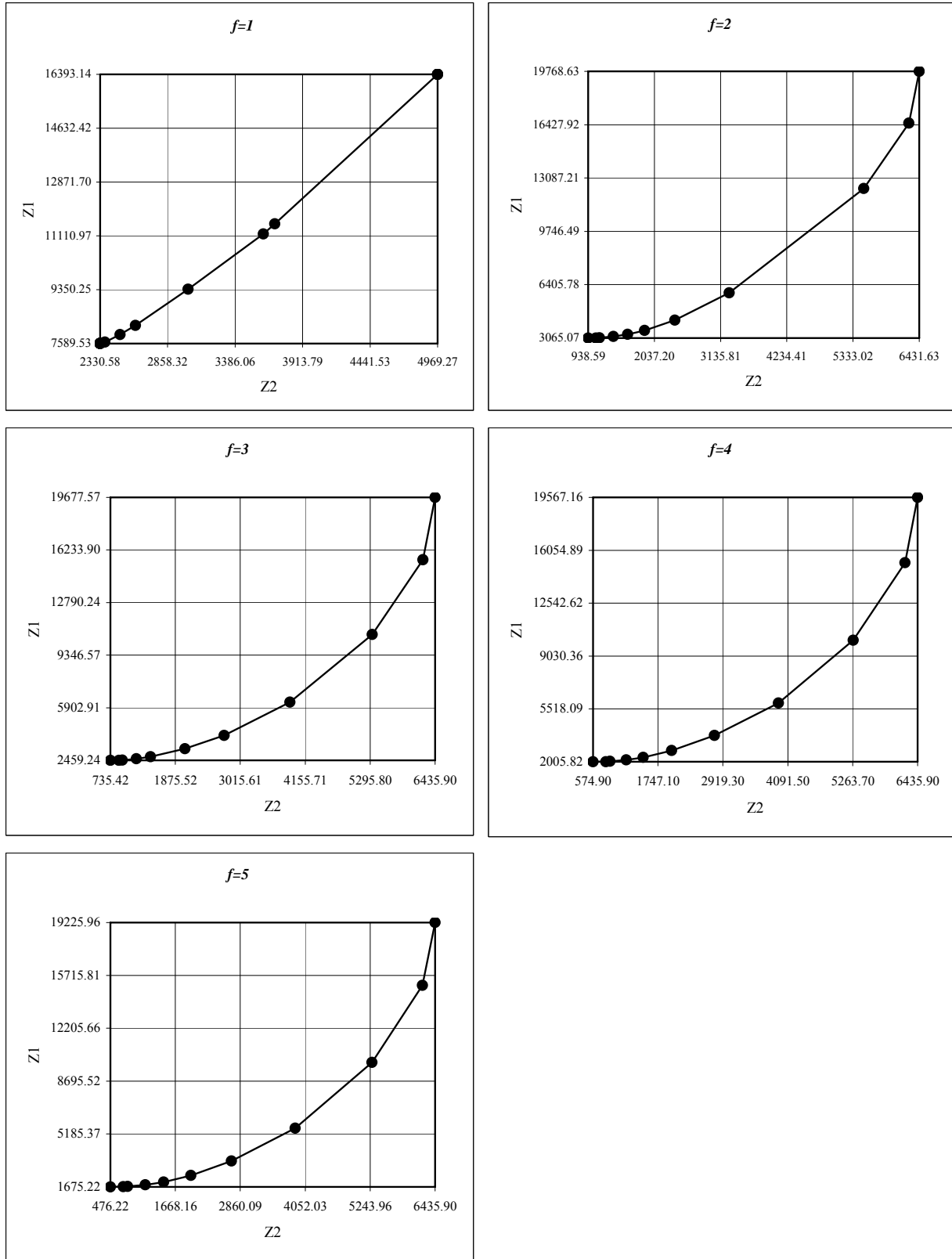
Figure 10. Pareto-optimal Results of the Bi-objective Critical Supply Facility Location Model in the Tampa-Orlando Conurbation (R = 0 miles).
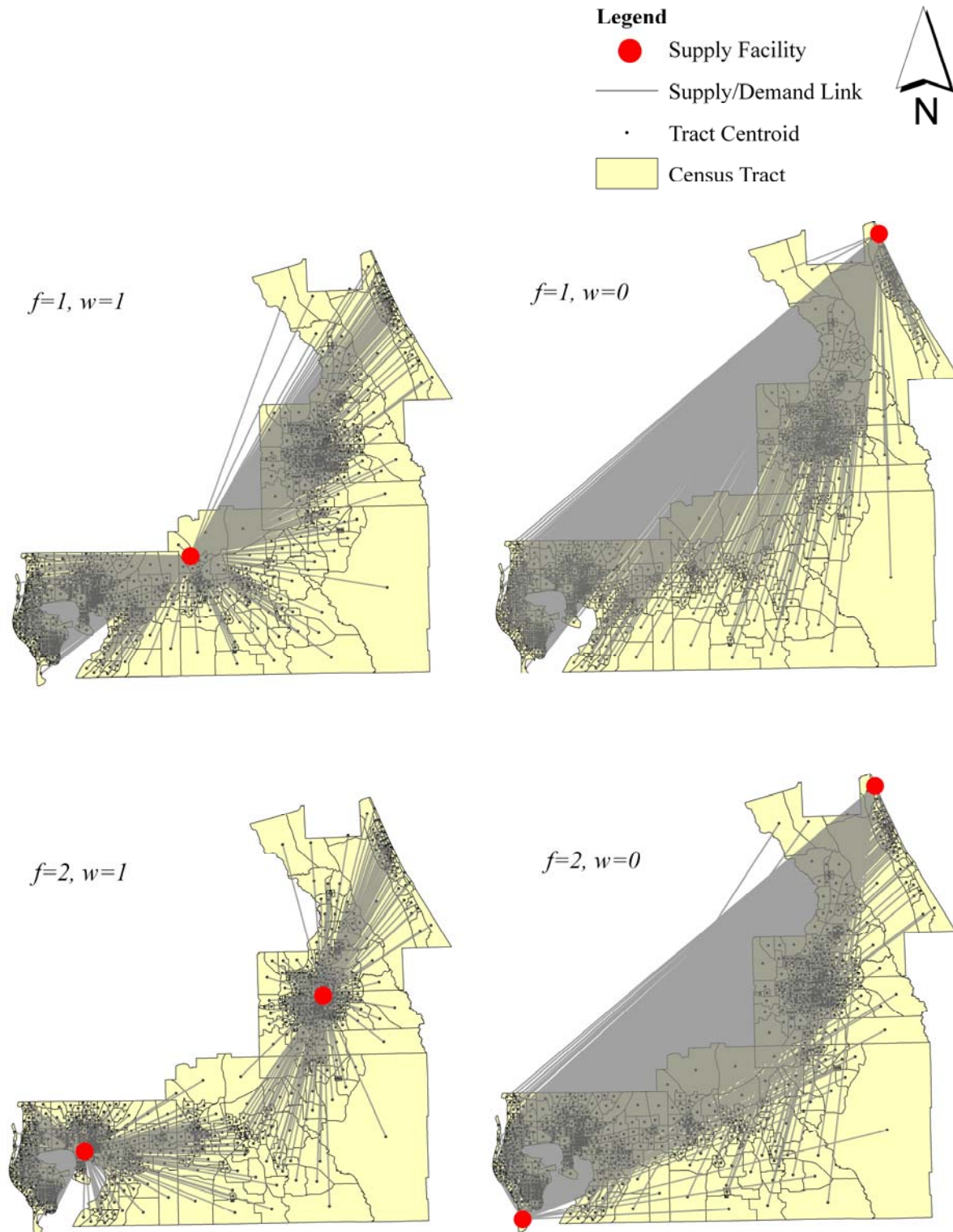
Figure 11. Maps of Facility Location/Allocations (*f* = 1, 2) in the Tampa-Orlando Conurbation.
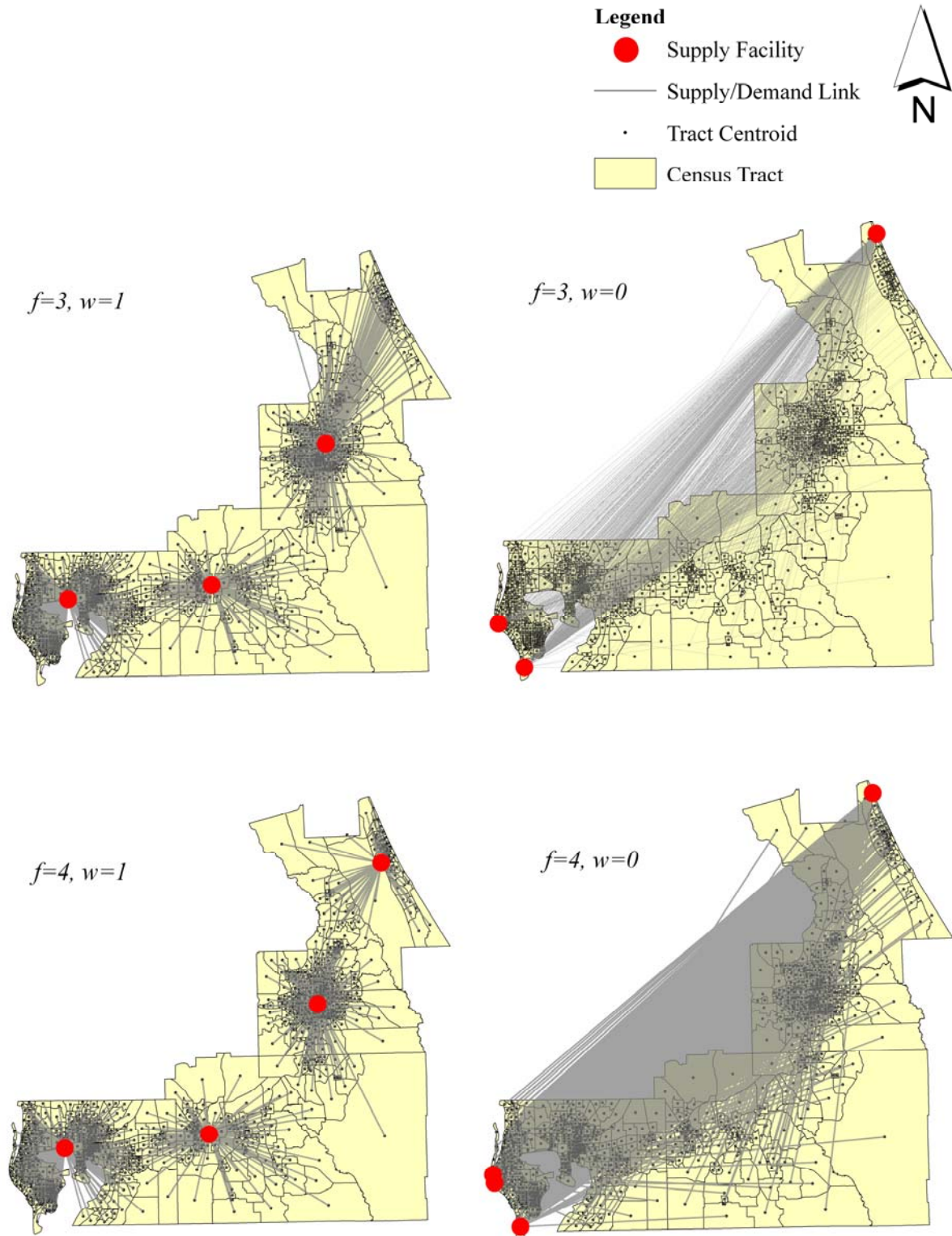
Figure 12. Maps of Facility Location/Allocations (*f* = 3, 4) in the Tampa-Orlando Conurbation.
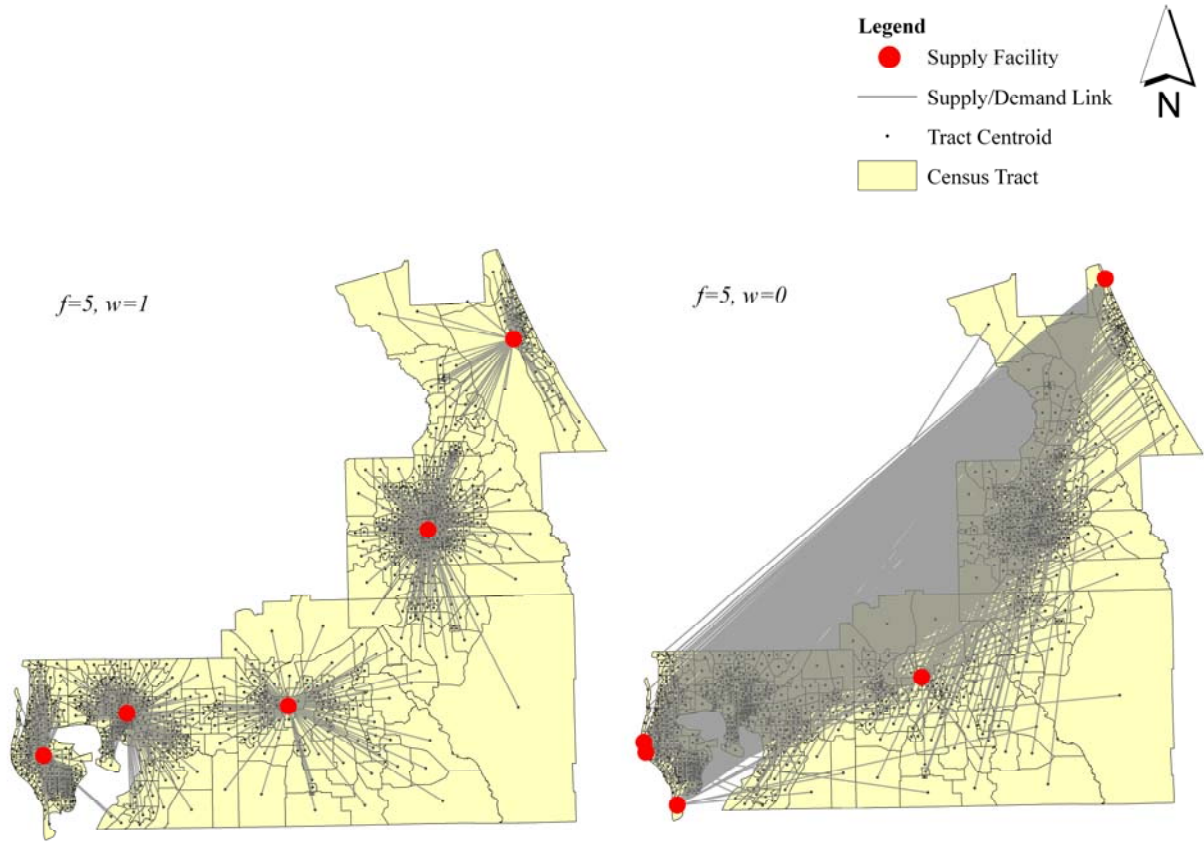
Figure 13. Maps of Facility Location/Allocations ($f = 5$) in the Tampa-Orlando Conurbation.

5.3 Results of the Bi-objective Critical Supply Facility Location Model with Neighborhood Adjacency Constraints in the Tampa-Orlando Conurbation

This section describes the results of the previous model subject to Neighborhood Adjacency Constraints in the Tampa-Orlando conurbation. The model was run at $f = 3, 4$, and 5 subject to 15 and 30 mile interfacility distance constraints. Reported solutions solved optimally.

As noted before, multiple facilities were packing in the Pinellas county area; as a result, a distance constraint would need to be implemented to prevent clustering of facilities. At $R = 15$ miles, solutions were found when weight w increases, however, solution times were long and facility placements did not change because there were all outside the 15 mile buffer (See Table 8). As result, additional runs were not performed. At $R = 30$ miles, solutions were found at $w = 0$, however, as the weight increased, solution bounds became infinite and no values were reported (see Table 9). This may possibly be explained by a combination of the problem size and the fact that as weights increase on Z_1 (access), solutions take longer to obtain. This is because populations tend to reside in every census tract while many census tracts are void of any critical facilities, thus eliminating considerable amounts of pruning for solutions with weight on Z_2 (protection). As seen in Figure 14, facility placements are quite dispersed, with few facilities placed on major urban centers due to the weight on the objective of protection.

Table 8. Results of the Bi-objective Critical Supply Facility Location Model with Neighborhood Adjacency Constraints in Tampa-Orlando Conurbation ($R = 15$ miles).

Number of Facilities (f)	Weight (w)	Z1	Z2	Node(s) Chosen	Time (s)	Gap (%)
3	0.0	20408.20	6434.52	2, 265, 371	75.69	0.00
3	0.1*	15601.48	6221.79	2, 265, 659	336.92	0.00
3	0.2*	10704.36	5332.48	2, 459, 570	710.30	0.00
4	0.0	20397.35	6434.52	2, 256, 265, 371	75.20	0.00
4	0.1*	15228.51	6209.90	2, 265, 620, 781	259.92	0.00
5	0.0	20370.29	6434.52	2, 246, 256, 265, 371	74.95	0.00
5	0.1*	15062.77	6205.39	2, 158, 265, 620, 854	194.66	0.00

*These results are the same where R=0. Additional runs would be unnecessary since they do not appear to be within 15 miles of each other.

Table 9. Results of the Bi-objective Critical Supply Facility Location Model with Neighborhood Adjacency Constraints in Tampa-Orlando Conurbation (R = 30 miles).

Number of Facilities (f)	Weight (w)	Z1	Z2	Node(s) Chosen	Time (s)	Gap (%)
3	0.0	20412.52	6431.63	2, 50, 256	84.31	0.00
3	0.1	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.2	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.3	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.4	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.5	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.6	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.7	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.8	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	0.9	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
3	1.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.0	20411.61	6431.61	2, 70, 256, 265	82.06	0.00
4	0.1	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.2	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.3	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.4	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.5	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.6	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.7	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.8	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	0.9	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
4	1.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.0	20350.94	6431.63	2, 195, 256, 265, 602	85.09	0.00
5	0.1	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.2	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.3	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.4	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.5	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.6	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.7	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.8	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.9	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	1.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible

*Additional distance constraints were run at 45 and 60. No integer solutions are reported due to infinite bounds.
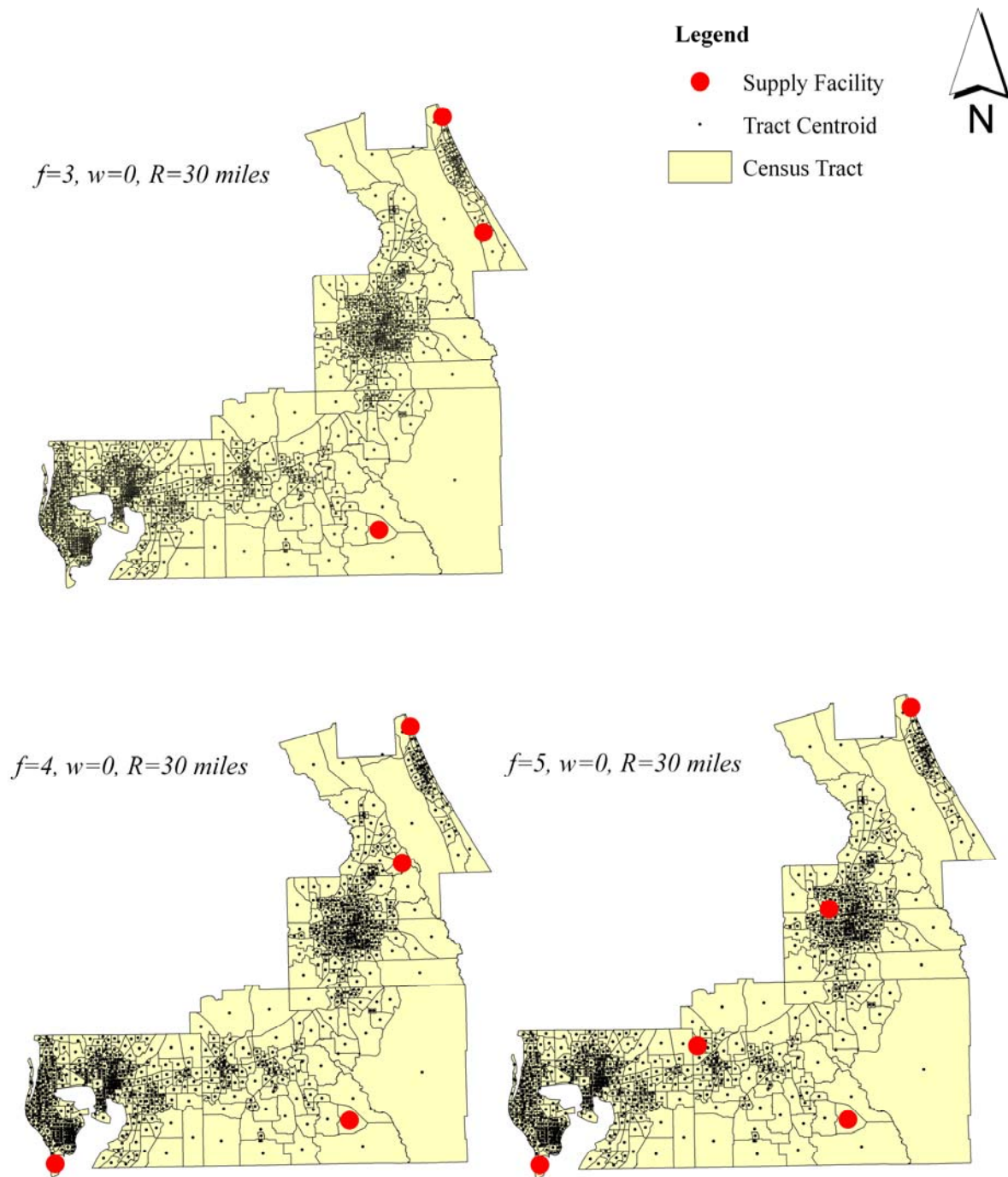
Figure 14. Maps of Facility Locations with Neighborhood Adjacency Constraints (*R* = 30).

5.4 Results of the Bi-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area

This section describes the Bi-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area. This model was also run at f = 1, 2, 3, 4, and 5 with a variation of weights on each number of facilities. Several interesting trends are presented in this section as well. First, problems solved much faster than with the previous study area, since this area contains 268 nodes as opposed to 941. Second, because this study area is a subsection of the larger study area, it can give some insight into whether scaling is an issue with the model's reported objective values and facility placements. Also important to note is that this area is fairly uniform, unlike the larger study area. Downtown Orlando is near the center of the area with suburbs and hinterlands surrounding it. Since this is area is uniform, it makes visualizing the model somewhat more predictable, unlike the original area.

The pareto-optimal graphical display of the objective values of Z_1 and Z_2 show strikingly similar trends with the pareto-optimal graphs of the larger study area (See Figure 15). This conveys to us that scaling does not greatly alter the objective value trends among these two areas. At f = 1, the graph shows a fairly direct trade-off, while at f = 2, 3, 4, and 5, trade-off gains become more substantial where a decrease in access is only a fraction of an increase in protection. For example, at f = 1 and w = 0.3, there is an 8% gain in protection with a 5% sacrifice in access. However, where f = 5 and w = 0.6, there is a 14% gain in protection while only 2% of access is lost.

The cartographic display of solution results, again, is not surprising. With f = 1 and w = 1, the facility is placed in downtown Orlando, thus having minimized access to surrounding populations (See Figure 16). At w = 0, the facility is placed on the fringe of the urban periphery where its critical facility weighted distance is maximized (See Figure 16). An important note to highlight is that even with a fairly uniform area, facilities may still pack together within a particular area. As seen in Figures 17 and 18 where f = 4 and 5, two facilities are slightly clustering towards the southeast corner of the study area. This again highlights the need for some type of interfacility distance constraint.

The trade-off behavior might be explained by a few factors. First, the substantial gains where f > 1, might possibly be explained by the urban geography of the population and critical facilities in Orlando. It appears that critical facilities and the human population have a strong

spatial correlation; however, critical facilities tend to cluster in the downtown area, while populations cluster outside of the downtown area in the suburban periphery (See Figures 36 and 37 in Appendix A). So in a sense of placing two facilities, having them situated on the suburban periphery may be a significant distance away from the critical downtown area while still being able to serve much of the population within accessible distance because populations tend to be located outside the downtown area. This is a possible reason for the why the trade-offs are behaving in this manner.

Second, the trade-off gains may also be explained by the allocations of resources to demands. With a compromise weight on objective Z_1 and Z_2, the model seeks to find non-inferior solutions without concern for nearest facility allocations. This may result in resource allocations bypassing closer demands and assigning to nodes further away from the opened facility since Z_2 seeks to maximize its weighted distance to critical facilities. For example, at $f =$ 2, the model can find a non-inferior solution by allocating resources from one facility at the center of the population with the other facility maximizing its allocations from critical facilities by being placed on the edge of the graph. This allows the model to find a best compromise between access to populations and protection from other critical facilities, thus creating objective values with substantial trade-off gains.

Table 10. Results of the Bi-objective Critical Supply Facility Location Model in Orlando Metropolitan Area ($R = 0$).

Number of Facilities (f)	Weight (w)	Z1	Z2	Node(s) Chosen	Time (seconds)	Gap (%)
1	0.000	1196.05	412.12	217	7.58	0.00
1	0.100	1196.05	412.12	217	24.28	0.00
1	0.200	1167.41	408.06	215	20.34	0.00
1	0.255	973.37	343.02	28	46.94	0.00
1	0.260	708.16	251.73	34	42.76	0.00
1	0.280	531.04	187.66	204	26.98	0.00
1	0.300	476.25	165.47	199	35.42	0.00
1	0.400	441.39	147.96	194	36.38	0.00
1	0.500	437.86	144.71	193	21.06	0.00
1	0.600	437.86	144.71	193	17.83	0.00
1	0.700	437.86	144.71	193	17.25	0.00
1	0.800	437.86	144.71	193	16.73	0.00
1	0.900	437.86	144.71	193	17.23	0.00
1	1.000	437.86	144.71	193	16.39	0.00
2	0.000	1304.27	449.85	215, 246	20.01	0.00
2	0.100	1206.47	444.31	215, 246	60.20	0.00
2	0.200	796.79	369.51	196, 215	13.39	0.00
2	0.300	611.22	309.75	115, 215	13.09	0.00
2	0.400	466. 87	228.35	26, 85	86.98	0.00
2	0.500	358.14	149.46	70, 149	33.25	0.00
2	0.600	348.57	138.60	73, 149	33.27	0.00
2	0.700	342.07	126.60	73, 149	34.02	0.00
2	0.800	338.69	117.12	73, 149	34.09	0.00
2	0.900	337.44	111.20	73, 95	34.08	0.00
2	1.000	337.40	109.54	68, 93	20.02	0.00
3	0.000	1343.52	461.25	26, 217, 246	7.47	0.00
3	0.100	1191.55	453.73	26, 217, 246	56.41	0.00
3	0.200	825.56	393.60	26, 115, 217	9.11	0.00
3	0.300	538.65	297.31	66, 115, 215	14.95	0.00
3	0.400	414.97	231.72	66, 145, 215	101.94	0.00
3	0.500	299.88	142.27	43, 148, 221	26.36	0.00
3	0.600	288.92	128.91	42, 148, 221	25.28	0.00
3	0.700	280.67	113.87	42, 148, 221	27.22	0.00
3	0.800	276.44	101.93	47, 150, 206	31.84	0.00
3	0.900	275.06	95.85	42, 148, 221	30.13	0.00
3	1.000	275.06	95.84	42, 148, 221	32.17	0.00
4	0.000	1354.14	465.53	26, 215, 217, 246	5.11	0.00
4	0.100	1106.91	450.30	26, 196, 217, 246	7.38	0.00
4	0.200	787.50	390.71	26, 105, 120, 217	12.41	0.00
4	0.300	535.01	309.47	9, 100, 205, 217	103.94	0.00
4	0.400	363.54	222.81	52, 148, 215, 221	222.81	0.00
4	0.500	298.71	175.14	9, 178, 206, 236	15.92	0.00
4	0.600	257.49	127.66	37, 178, 221, 235	18.34	0.00
4	0.700	247.00	108.42	37, 178, 221, 235	20.92	0.00
4	0.800	241.09	91.87	37, 178, 221, 235	24.87	0.00
4	0.900	239.34	83.98	37, 178, 221, 235	25.45	0.00
4	1.000	239.24	82.73	37, 178, 221, 236	11.20	0.00
5	0.000	1327.41	467.22	26, 215, 217, 246, 268	4.52	0.00
5	0.100	1115.33	454.91	26, 196, 215, 217, 246	6.86	0.00
5	0.200	772.47	392.58	26, 178, 205, 217, 240	7.30	0.00
5	0.300	492.35	303.01	9, 178, 205, 217, 235	10.06	0.00
5	0.400	329.85	215.17	37, 178, 215, 221, 235	11.59	0.00
5	0.500	273.98	170.61	9, 75, 124, 178, 235	69.41	0.00
5	0.600	240.58	130.10	15, 125, 178, 208, 235	114.95	0.00
5	0.700	225.35	103.26	40, 131, 178, 208, 235	18.16	0.00
5	0.800	219.08	85.58	40, 131, 178, 208, 235	29.66	0.00
5	0.900	217.22	77.20	40, 121, 178, 208, 235	23.22	0.00
5	1.000	217.20	76.94	40, 121, 178, 211, 235	26.56	0.00
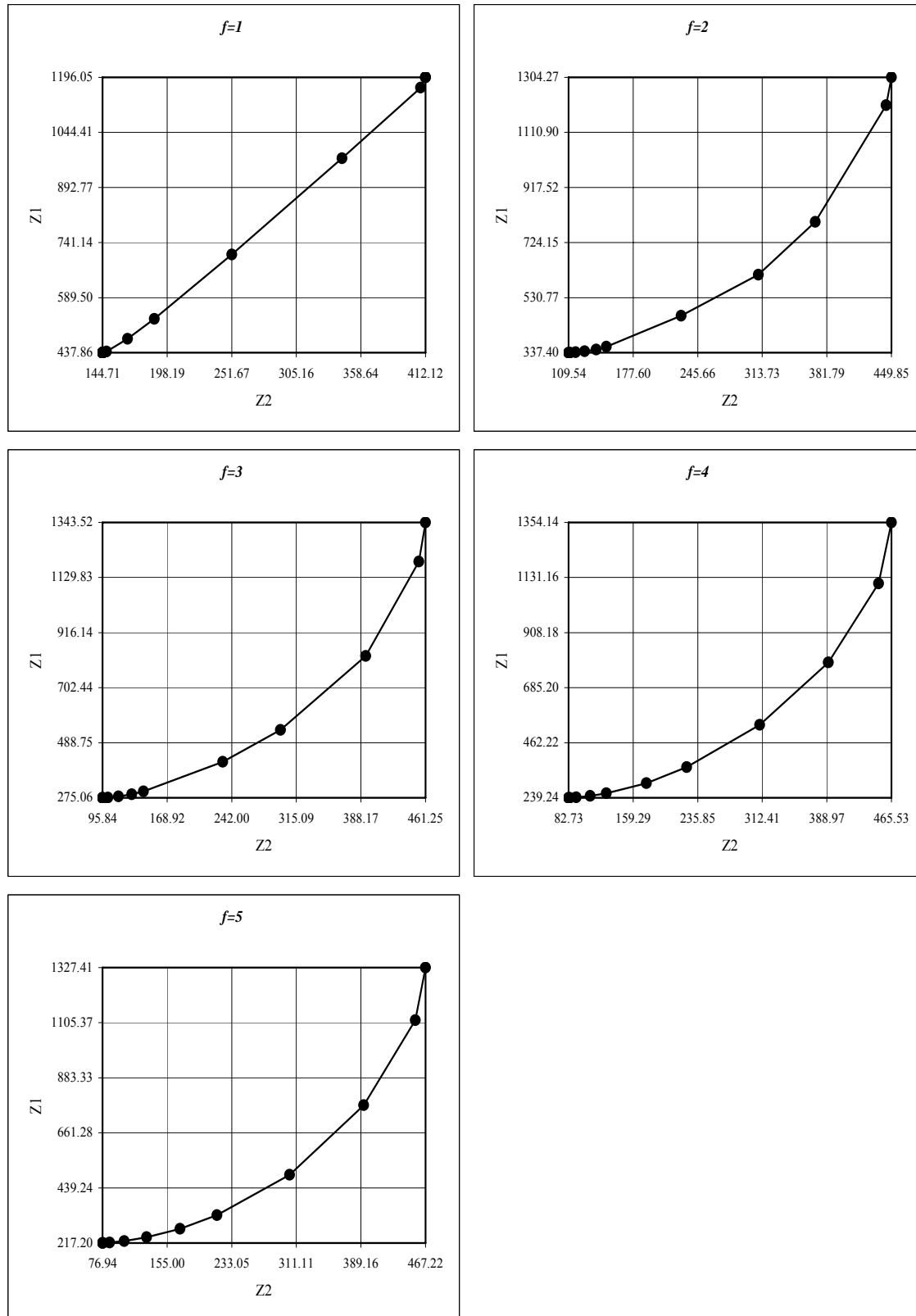
Figure 15. Pareto-optimal Results of the Bi-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area ($R = 0$ miles).
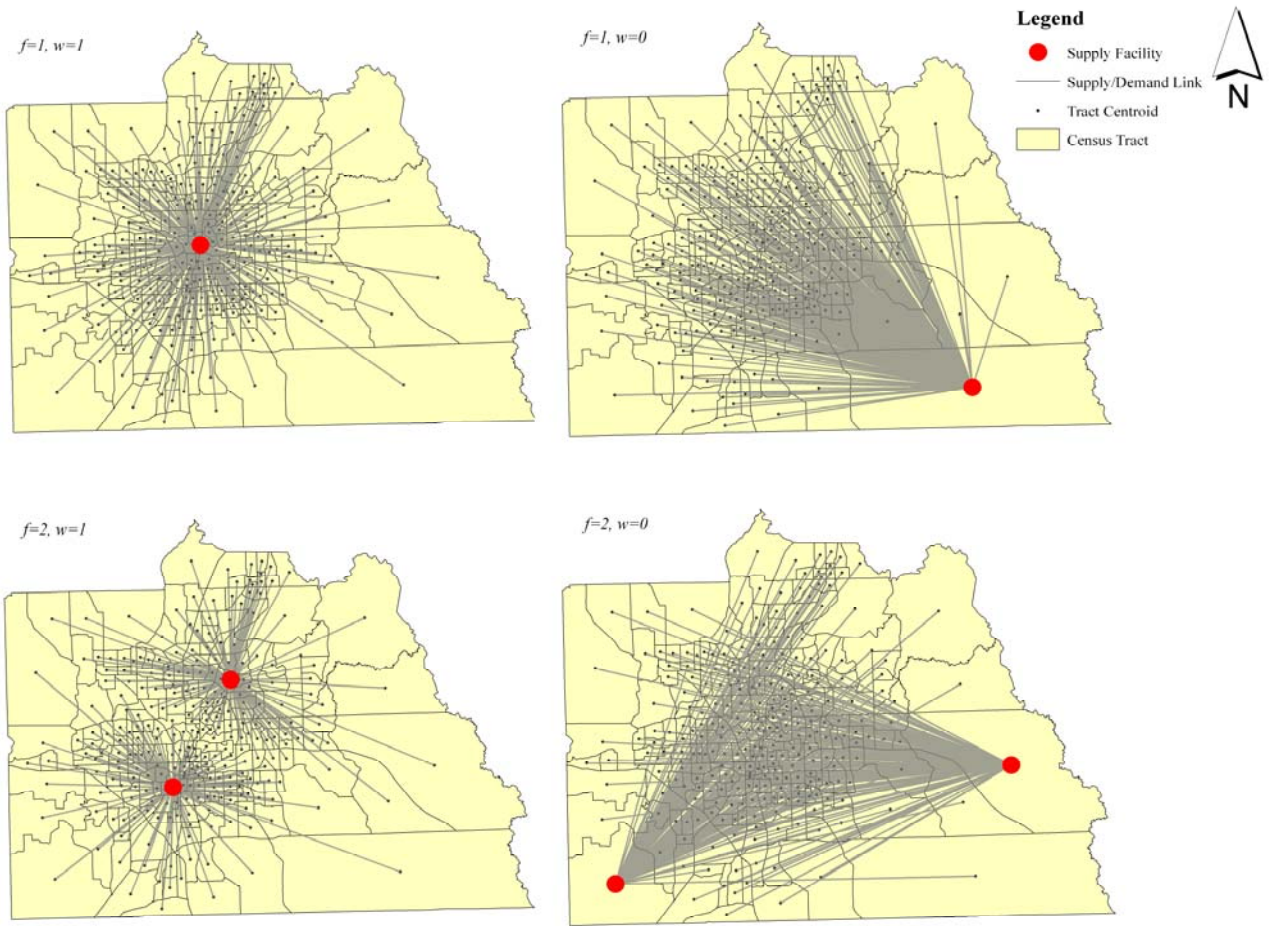
Figure 16. Facility Locations/Allocations (*f* = 1, 2) in the Orlando Metropolitan Area.
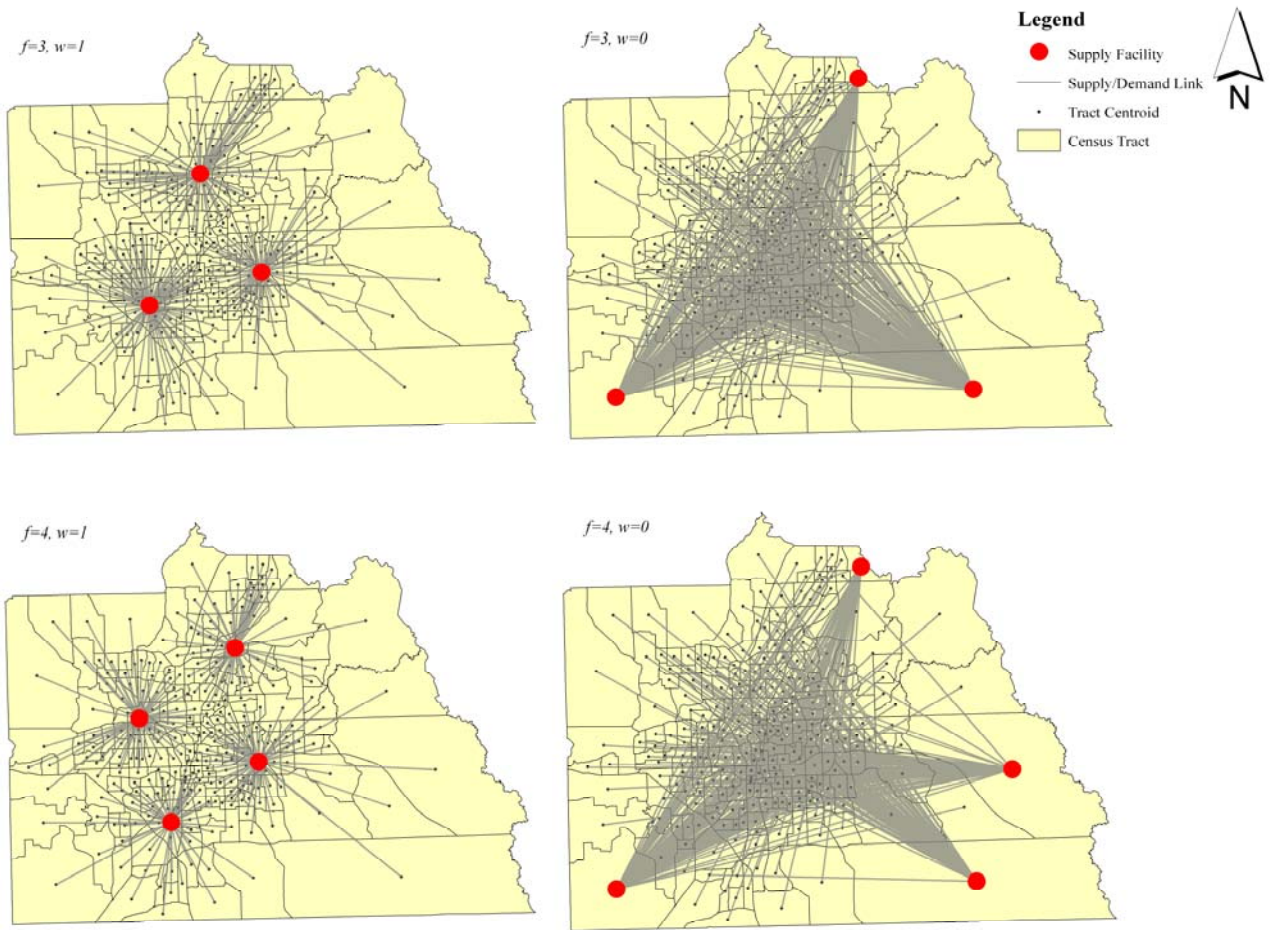
Figure 17. Maps of Facility Locations/Allocations (*f* = 3, 4) in the Orlando Metropolitan Area.
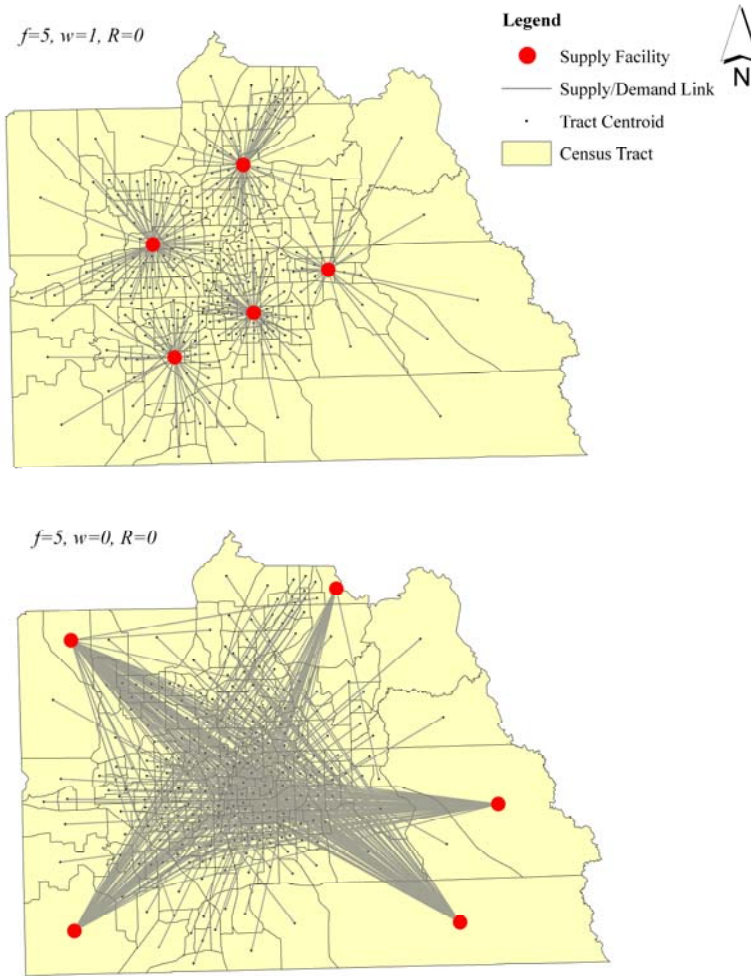
Figure 18. Maps of Facility Locations/Allocations (*f* = 5) in the Orlando Metropolitan Area.

5.5 Results of the Bi-objective Critical Supply Facility Location Model with Neighborhood Adjacency Constraints in the Orlando Metropolitan Area

This section shows the results of the Bi-objective Critical Supply Facility Location Model subject to Neighborhood Adjacency Constraints in the Orlando metropolitan area. The model was run at R = 10 miles and R = 20 miles. All solutions are solved optimally. The graphical trends are very similar to what was previously reported (See Figures 19 and 20). The important thing to mention in this section, is that no solutions were reported at f = 5 where R = 20 miles. This is because, as shown in the following section, the maximum interfacility distance where f = 5 is 19.03 miles, thus resulting in infeasibility. Figures 21 and 22 give some visualizations of the influence of Neighborhood Adjacency Constraints on optimal facility locations.

Table 11. Results of the Bi-objective Critical Supply Facility Location Model with Neighborhood Adjacency Constraints in Orlando Metropolitan Area (R = 10 miles).

Number of Facilities (f)	Weight (w)	Z1	Z2	Node(s) Chosen	Time (seconds)	Gap (%)
2	0.0	1301.44	449.85	215, 246	10.72	0.00
2	0.1	1206.48	444.31	215, 246	24.25	0.00
2	0.2	796.79	369.51	196, 215	17.20	0.00
2	0.3	611.22	309.75	115, 215	18.97	0.00
2	0.4	466.88	228.35	26, 85	140.97	0.00
2	0.5	358.14	149.46	70, 149	29.59	0.00
2	0.6	348.57	138.60	73, 149	27.09	0.00
2	0.7	342.07	126.60	73, 149	29.70	0.00
2	0.8	338.69	117.12	73, 149	30.83	0.00
2	0.9	337.44	111.20	73, 95	30.22	0.00
2	1.0	337.40	109.54	68, 93	25.08	0.00
3	0.0	1329.85	461.25	26, 217, 246	8.84	0.00
3	0.1	1191.55	453.73	26, 217, 246	72.95	0.00
3	0.2	825.56	393.60	26, 115, 217	13.86	0.00
3	0.3	538.65	297.31	66, 146, 215	21.13	0.00
3	0.4	414.97	231.72	66, 145, 215	120.34	0.00
3	0.5	299.88	142.27	43, 148, 221	25.78	0.00
3	0.6	288.92	128.91	42, 148, 221	21.67	0.00
3	0.7	280.67	113.87	42, 148, 221	21.16	0.00
3	0.8	276.33	101.57	42, 148, 221	31.22	0.00
3	0.9	275.06	95.85	42, 148, 221	33.48	0.00
3	1.0	275.06	95.85	42, 148, 221	31.00	0.00
4	0.0	1343.77	465.53	26, 215, 217, 246	6.03	0.00
4	0.1	1106.91	450.30	26, 196, 217, 246	11.05	0.00
4	0.2	787.50	390.71	26, 105, 120, 217	16.02	0.00
4	0.3	535.00	309.47	9, 100, 205, 217	123.41	0.00
4	0.4	363.54	222.81	52, 148, 215, 221	20.78	0.00
4	0.5	298.71	175.14	9, 178, 206, 236	20.55	0.00
4	0.6	257.36	126.72	37, 178, 222, 236	20.63	0.00
4	0.7	257.36	126.72	37, 178, 222, 236	20.36	0.00
4	0.8	241.01	90.82	37, 178, 222, 236	19.89	0.00
4	0.9	239.32	83.19	37, 178, 222, 236	19.42	0.00
4	1.0	239.32	83.19	37, 178, 222, 236	19.42	0.00
5	0.0	1344.82	467.22	26, 215, 217, 246, 268	5.73	0.00
5	0.1	1115.33	454.91	26, 196, 215, 217, 246	9.38	0.00
5	0.2	772.47	392.58	26, 178, 205, 217, 240	11.26	0.00
5	0.3	492.22	302.88	9, 178, 205, 217, 236	13.56	0.00
5	0.4	330.82	215.48	37, 177, 215, 221, 235	20.83	0.00
5	0.5	283.19	178.96	37, 177, 215, 221, 235	29.14	0.00
5	0.6	243.34	128.62	41, 105, 131, 212, 239	1042.30	0.00
5	0.7	230.59	105.23	41, 105, 131, 212, 239	114.55	0.00
5	0.8	222.28	79.44	34, 41, 105, 124, 238	141.55	0.00
5	0.9	222.28	79.44	34, 41, 105, 124, 238	72.91	0.00
5	1.0	222.28	79.44	34, 41, 105, 124, 238	94.75	0.00

Table 12. Results of the Bi-objective Critical Supply Facility Location Model with Neighborhood Adjacency Constraints in Orlando Metropolitan Area (R = 20 miles).
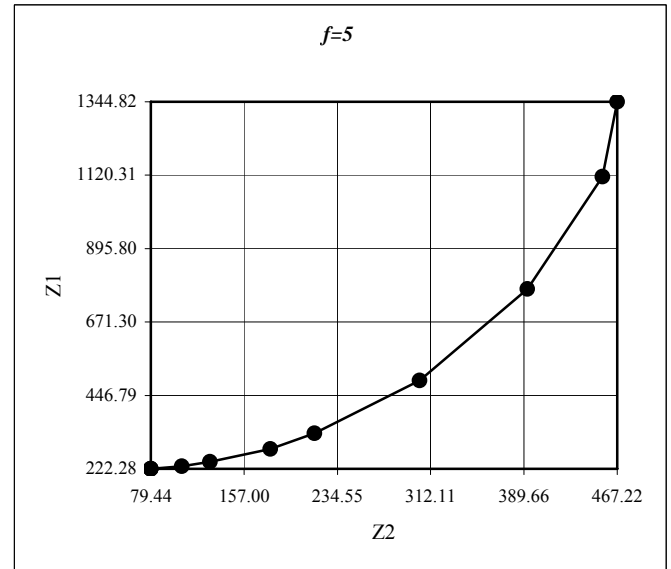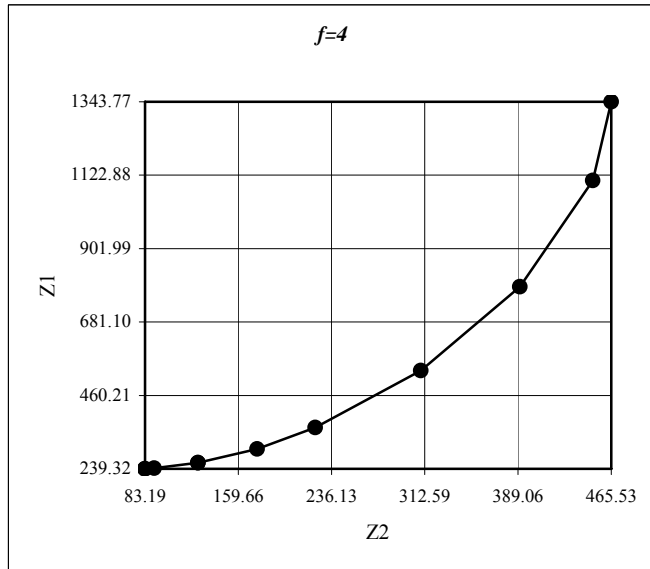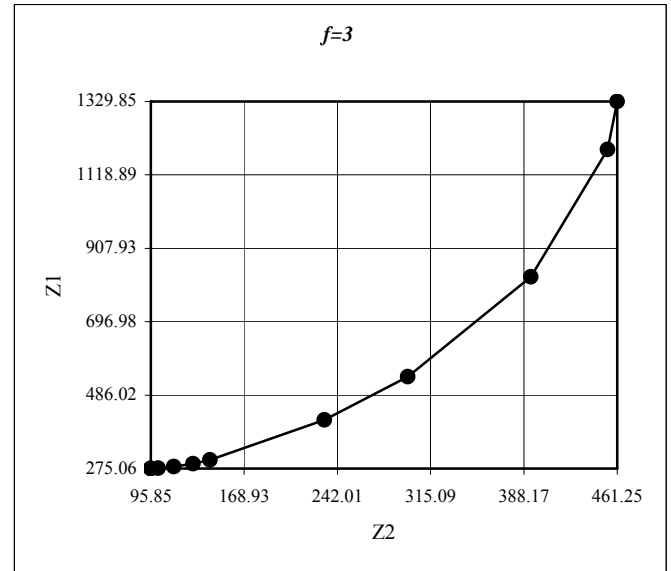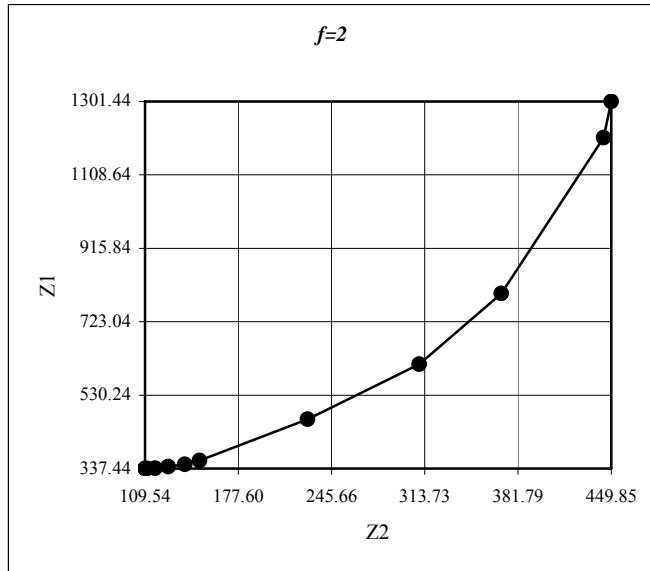
Number of Facilities (f)	Weight (w)	$Z1$	$Z2$	Node(s) Chosen	Time (seconds)	Gap (%)
2	0.0	1309.23	449.85	215, 246	21.61	0.00
2	0.1	1206.47	444.31	215, 246	26.72	0.00
2	0.2	796.79	369.51	196, 215	14.83	0.00
2	0.3	611.22	309.75	115, 215	14.77	0.00
2	0.4	503.69	252.71	113, 215	94.91	0.00
2	0.5	436.88	204.92	1, 77	72.88	0.00
2	0.6	419.72	185.19	4, 79	133.95	0.00
2	0.7	405.48	158.66	4, 79	155.77	0.00
2	0.8	396.01	131.06	4, 79	135.69	0.00
2	0.9	394.01	122.09	4, 79	136.97	0.00
2	1.0	394.01	121.69	4, 79	125.50	0.00
3	0.0	1334.92	461.25	26, 217, 246	8.25	0.00
3	0.1	1191.55	453.73	26, 217, 246	54.06	0.00
3	0.2	826.78	393.08	26, 77, 217	31.42	0.00
3	0.3	608.03	322.60	26, 77, 217	26.41	0.00
3	0.4	471.45	248.96	9, 80, 215	296.53	0.00
3	0.5	392.75	183.40	12, 162, 228	488.97	0.00
3	0.6	381.82	170.55	12, 162, 228	156.06	0.00
3	0.7	371.55	151.83	12, 162, 228	166.55	0.00
3	0.8	365.91	135.92	12, 162, 228	151.44	0.00
3	0.9	364.11	127.84	12, 162, 228	162.99	0.00
3	1.0	364.11	127.84	12, 162, 228	155.49	0.00
4	0.0	1339.97	463.53	27, 217, 246, 268	6.03	0.00
4	0.1	1091.65	447.17	27, 90, 217, 268	24.09	0.01
4	0.2	849.60	403.68	26, 90, 217, 268	15.66	0.00
4	0.3	603.66	324.91	26, 90, 217, 268	52.61	0.00
4	0.4	458.44	247.84	4, 90, 215, 268	150.88	0.00
4	0.5	413.83	213.72	4, 90, 215, 268	136.66	0.00
4	0.6	393.83	189.50	8, 136, 215, 267	183.42	0.00
4	0.7	375.89	156.42	8, 136, 215, 267	120.56	0.00
4	0.8	365.06	124.79	4, 91, 215, 268	130.22	0.00
4	0.9	363.00	115.53	4, 91, 215, 268	117.05	0.00
4	1.0	363.00	115.53	4, 91, 215, 268	111.83	0.00
5	0.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.1	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.2	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.3	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.4	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.5	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.6	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.7	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.8	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	0.9	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
5	1.0	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible

Figure 19. Pareto-optimal Results of the Bi-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area (R = 10 miles).
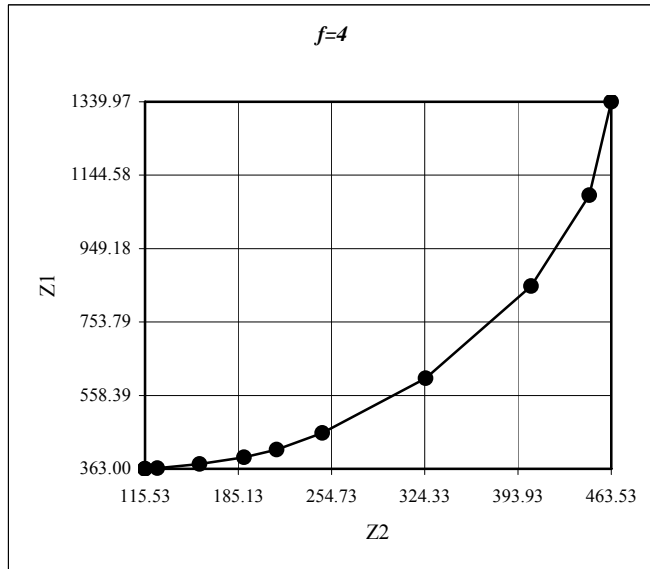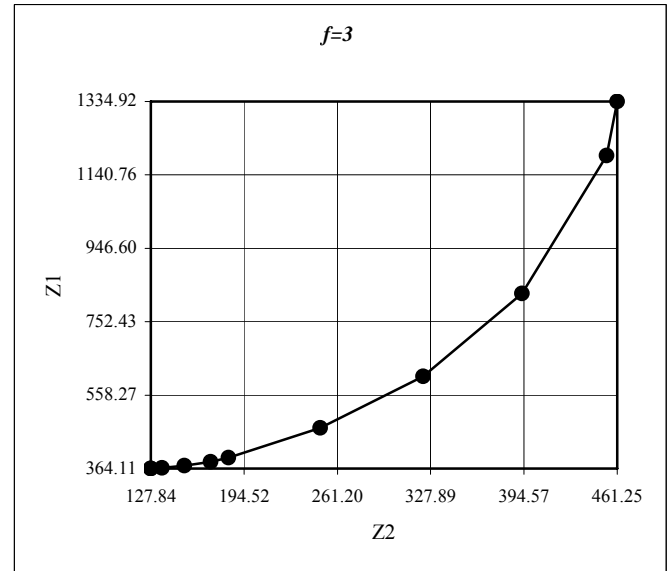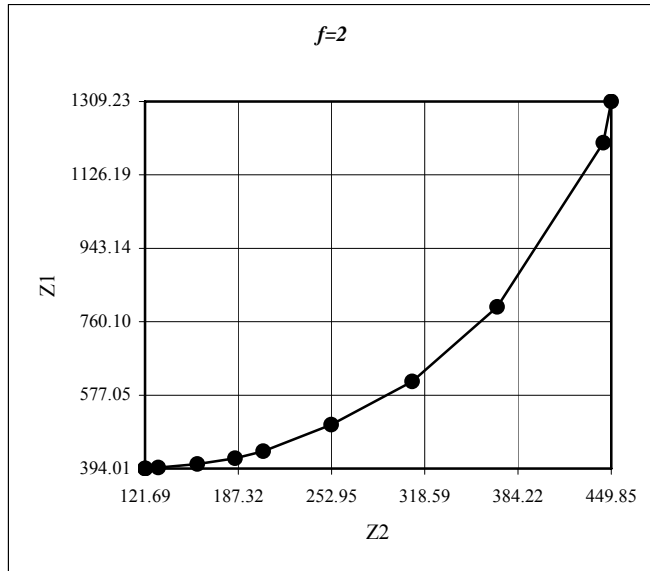
Figure 20. Pareto-optimal Results of the Bi-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area ($R = 20$ miles). Solutions at $f=5$ are infeasible, because the maximum interfacility distance is 19.03 miles.
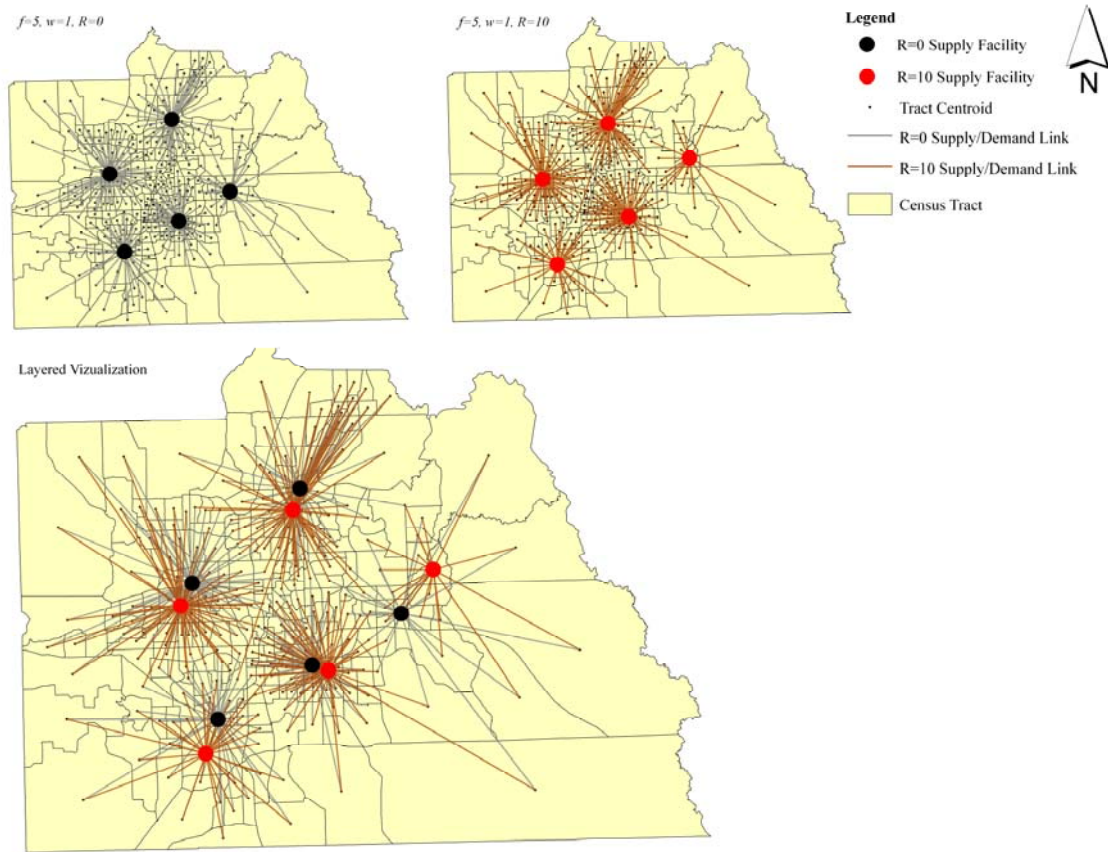
Figure 21. Layered Visualization of Facility Location/Allocations with Neighborhood Adjacency Constraints ($f = 5$, $R = 10$) in the Orlando Metropolitan Area.
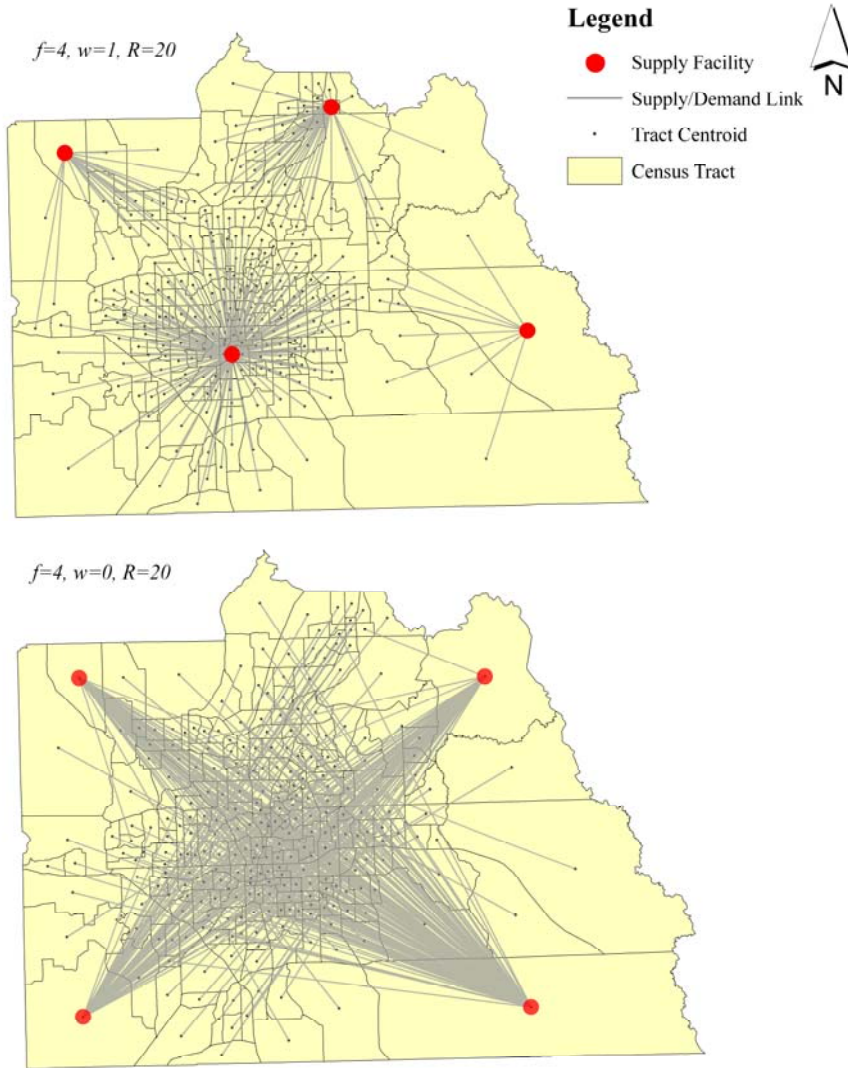
Figure 22. Maps of Facility Locations/Allocations with Neighborhood Adjacency Constraints (*R* = 20) in the Orlando Metropolitan Area.

5.6 Results of the Tri-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area

This section describes the Tri-objective Critical Supply Facility Location Model in the Orlando metropolitan area. As mentioned before, having three or more objectives can be difficult to present due to the number of permutations of weights. As a result, trade-offs among Z_1, Z_2, and Q are run separately for the ease of transmitting results. First, I will show trade-off results for Z_1 and Q, and then trade-offs among Z_2 and Q.

The *p*-dispersion problem is notoriously difficult to solve (Erkut 1990), especially among large data sets. As a result, some knacks were developed to help obtain faster solution times. Solutions were solved at either optimally or near optimality with no more than a gap of 1%. One stratagem that was used is to set a lower bound constraint where Q is greater than or equal to some number that is a known acceptable interfacility distance. With this approach, w was initially set at 1 with a lower bound constraint set at 0. As solution values become known and weight increases on Q, the lower bound constraint becomes whatever solution value was reported for Q in the previous run. This cuts back much of the pruning necessary to find an optimal answer, thus eliminating several hours of run-time.

Table 13 gives results of the two objectives, Z_1 and Q. Table 14 gives results of the two objectives Z_2 and Q. Results are organized by the number of facilities and weight increments of 0.1. As a special note, where $w_1 = 0$, objective values for Z_1 and Z_2 are inaccurate; this is because the *p*-dispersion objective is not concerned with allocations to demands. As a result, w was run at 0.000001 so that allocations to demands would be considered and to help illustrate accurate objective value results for Z_1 and Z_2 in the pareto-optimal graphs.

Figures 23 and 24 show the pareto-optimal trade-off curves among the three objectives. Interesting to mention here is that the curve tends to become more kinked with more facilities that are being placed. The curves are steepest at $f = 5$ for both Z_1/Q and Z_2/Q suggesting that a decision maker can have substantial gains in dispersing their facilities while still either being accessible to populations or maintaining distance from other critical facilities. For example, among Z_1 and Q where $f = 5$, $w_1 = 0.2$, and $w_2 = 0$, 20% of dispersion is gained while only 1% of access is lost. Among Z_2 and Q where $f = 5$, $w_1 = 0$, $w_2 = 1$, 87% of dispersion is gained while only 15% of protection is lost. However, an important thing to note on the trade-offs between Z_2 and Q is that the range in objective values for Z_2 is very small relative to the range in the previous models discussed. As a result, whatever values are lost among Z_2 may be insignificant since that range is very small and dispersion would be a more significant compromise to consider. In other words, the facilities can be maximally dispersed but that does not imply that the facilities are not protected in a spatial sense.

Table 13. Results of the Tri-objective Critical Supply Facility Location Model in Orlando Metropolitan Area (Z_1 and Q).

| Number of Facilities (f)	Weight ($w1$)	($w2$)	Lower Bound Constraint	$Z1$	$Z2$	Q	Node(s) Chosen	Time (seconds)	Gap (%)
2	0.000000	0	0.00	1032.23	350.87	39.85	217, 268	46061.63	0.00
2	0.000001	0	39.85	826.07	289.71	39.85	217, 268	1.63	0.00
2	0.100000	0	13.03	439.89	147.82	25.74	110, 215	9266.81	0.00
2	0.200000	0	13.03	340.07	110.70	13.03	68, 145	7691.94	0.00
2	0.300000	0	0.00	340.07	110.70	13.03	68, 145	5793.52	0.74
2	0.400000	0	0.00	337.59	112.15	11.67	73, 149	3288.23	0.00
2	0.500000	0	0.00	337.59	112.15	11.67	73, 149	1913.41	0.00
2	0.600000	0	0.00	337.40	109.54	11.41	68, 93	913.06	0.92
2	0.700000	0	0.00	337.40	109.54	11.41	68, 93	5330.02	0.01
2	0.800000	0	0.00	337.40	109.54	11.41	68, 93	2269.73	0.00
2	0.900000	0	0.00	337.40	109.54	11.41	68, 93	1349.88	0.00
2	1.000000	0	0.00	337.40	109.54	NA	68, 93	20.33	0.00
3	0.000000	0	31.81	1324.41	457.70	31.84	11, 217, 246	6.48	0.00
3	0.000001	0	31.84	635.26	213.78	31.84	10, 217, 246	5.22	0.00
3	0.100000	0	13.27	292.52	102.75	14.75	51, 211, 235	27762.33	0.00
3	0.200000	0	11.88	280.38	97.90	13.27	43, 148, 227	16934.06	0.00
3	0.300000	0	11.88	276.18	96.38	11.88	47, 150, 222	10935.11	0.00
3	0.400000	0	11.56	276.18	96.38	11.88	47, 150, 222	6650.20	0.46
3	0.500000	0	0.00	275.80	96.06	11.56	42, 148, 222	4778.72	0.00
3	0.600000	0	0.00	275.06	95.66	10.74	42, 148, 221	3079.38	0.91
3	0.700000	0	0.00	275.06	95.66	10.74	42, 148, 221	991.36	0.97
3	0.800000	0	0.00	275.06	95.66	10.74	42, 148, 221	364.14	0.94
3	0.900000	0	0.00	275.06	95.66	10.74	42, 148, 221	1958.61	0.01
3	0.990000	0	0.00	275.06	95.66	10.74	42, 148, 221	275.78	0.00
3	1.000000	0	0.00	275.06	95.66	NA	42, 148, 206	31.42	0.01
4	0.000000	0	23.93	1326.70	463.53	23.93	27, 217, 246, 268	10.45	0.00
4	0.000001	0	23.93	550.28	189.93	23.93	27, 217, 240, 262	20.11	0.00
4	0.100000	0	10.82	256.31	89.84	13.55	15, 103, 222, 243	51312.92	0.00
4	0.200000	0	10.82	241.10	84.18	10.82	37, 177, 222, 236	25295.66	0.00
4	0.300000	0	10.01	241.10	84.18	10.82	37, 177, 222, 236	16450.30	0.00
4	0.400000	0	10.01	239.32	83.14	10.01	37, 178, 222, 236	11168.94	0.60
4	0.500000	0	10.01	239.32	83.14	10.01	37, 178, 222, 236	7078.77	0.79
4	0.600000	0	10.01	239.32	83.14	10.01	37, 178, 222, 236	3636.47	0.00
4	0.700000	0	9.81	239.32	83.14	10.01	37, 178, 222, 236	1353.42	0.99
4	0.800000	0	9.81	239.24	82.90	9.81	37, 178, 221, 236	406.26	0.99
4	0.900000	0	0.00	239.24	82.73	9.81	37, 178, 221, 236	110.91	0.83
4	0.990000	0	0.00	239.24	82.73	9.81	37, 178, 221, 236	99.64	0.12
4	1.000000	0	0.00	239.24	82.73	NA	37, 178, 221, 236	11.30	0.00
5	0.000000	0	18.88	921.29	313.42	19.03	26, 215, 230, 248, 262	31.72	0.00
5	0.000001	0	19.03	468.39	159.37	19.03	26, 215, 230, 248, 262	47.31	0.00
5	0.100000	0	10.00	240.75	84.95	12.67	15, 28, 177, 221, 238	135088.78	0.00
5	0.200000	0	9.64	219.65	77.23	9.64	41, 105, 121, 212, 238	31467.70	0.00
5	0.300000	0	9.64	219.65	77.23	9.64	41, 105, 121, 212, 238	21633.06	0.00
5	0.400000	0	9.64	219.65	77.23	9.64	41, 105, 121, 212, 238	31109.06	0.38
5	0.500000	0	7.65	217.22	77.16	7.65	40, 121, 178, 208, 234	17276.13	0.62
5	0.600000	0	7.65	217.22	77.16	7.65	40, 121, 178, 208, 235	13434.16	0.79
5	0.700000	0	7.65	217.22	77.16	7.65	40, 121, 178, 208, 235	7047.39	0.93
5	0.800000	0	7.65	217.22	77.16	7.65	40, 121, 178, 208, 235	421.00	0.86
5	0.900000	0	0.00	217.22	77.16	7.65	40, 121, 178, 208, 235	421.00	0.86
5	0.990000	0	0.00	217.20	76.94	7.26	40, 121, 178, 211, 235	117.03	0.05
5	1.000000	0	0.00	217.20	76.94	NA	40, 121, 178, 211, 235	12.45	0.00

Table 14. Results of the Tri-objective Critical Supply Facility Location Model in Orlando Metropolitan Area (Z_2 and Q).

Number of Facilities (f)	Weight ($w1$)	($w2$)	Lower Bound Constraint	Z1	Z2	Q	Node(s) Chosen	Time (seconds)	Gap (%)
2	0	0.000000	0.00	1032.23	350.87	39.85	217, 268	46061.63	0.00
2	0	0.000002	39.85	1322.91	448.72	39.85	217, 268	1.63	0.00
2	0	0.200000	0.00	1296.11	448.72	39.85	217, 268	90.56	0.01
2	0	0.400000	0.00	1296.11	448.72	39.85	217, 268	20.23	0.00
2	0	0.600000	0.00	1298.04	448.72	39.85	217, 268	21.25	0.00
2	0	0.800000	0.00	1298.04	448.72	39.85	217, 268	19.72	0.00
2	0	1.000000	0.00	1298.04	448.72	39.85	217, 268	19.52	0.00
2	0	1.200000	0.00	1298.04	448.72	39.85	217, 268	19.27	0.00
2	0	1.400000	0.00	1298.04	448.72	39.85	217, 268	19.39	0.00
2	0	1.600000	0.00	1304.09	449.85	36.55	215, 246	64.61	0.00
2	0	1.800000	0.00	1304.09	449.85	36.55	215, 246	25.11	0.00
2	0	2.000000	0.00	1304.09	449.85	NA	215, 246	6.25	0.00
3	0	0.000000	31.84	1324.41	457.70	31.84	11, 217, 246	6.48	0.00
3	0	0.000002	31.84	1322.46	457.70	31.84	11, 217, 246	4.61	0.00
3	0	0.020000	31.84	1324.41	457.70	31.84	11, 217, 246	5.28	0.00
3	0	0.100000	0.00	1328.33	459.26	31.81	9, 217, 246	569.25	0.00
3	0	0.200000	0.00	1328.33	459.26	31.81	9, 217, 246	107.59	0.87
3	0	0.400000	0.00	1328.33	459.26	31.81	9, 217, 246	48.69	0.54
3	0	0.600000	0.00	1328.33	459.26	31.81	9, 217, 246	57.47	0.92
3	0	0.800000	0.00	1328.33	459.26	31.81	9, 217, 246	42.27	0.91
3	0	1.000000	0.00	1328.33	459.26	31.81	9, 217, 246	63.03	0.98
3	0	1.200000	0.00	1343.52	461.25	29.75	26, 217, 246	24.30	0.91
3	0	1.400000	0.00	1343.52	461.25	29.75	26, 217, 246	12.81	0.62
3	0	1.600000	0.00	1343.52	461.25	29.75	26, 217, 246	15.91	0.24
3	0	1.800000	0.00	1343.52	461.25	29.75	26, 217, 246	18.00	0.01
3	0	2.000000	0.00	1343.52	461.25	NA	26, 217, 246	4.95	0.00
4	0	0.000000	23.93	1326.70	463.53	23.93	27, 217, 246, 268	10.45	0.00
4	0	0.000002	23.93	1318.26	462.26	23.93	27, 217, 246, 268	9.58	0.00
4	0	0.020000	23.93	1326.70	463.53	23.93	27, 217, 246, 268	8.02	0.00
4	0	0.200000	23.93	1326.70	463.53	23.93	27, 217, 246, 268	7.97	0.00
4	0	0.400000	23.93	1326.70	463.53	23.93	27, 217, 246, 268	7.98	0.00
4	0	0.600000	23.93	1326.70	463.53	23.93	27, 217, 246, 268	7.50	0.00
4	0	0.800000	23.93	1326.70	463.53	23.93	27, 217, 246, 268	7.50	0.00
4	0	1.000000	0.00	1327.29	463.53	23.93	27, 217, 246, 268	330.30	0.95
4	0	1.200000	0.00	1327.29	463.53	23.93	27, 217, 246, 268	89.51	0.96
4	0	1.400000	0.00	1331.42	463.53	23.93	27, 217, 246, 268	943.83	0.01
4	0	1.600000	0.00	1354.14	465.53	10.38	26, 215, 217, 246	13.41	0.76
4	0	1.800000	0.00	1354.14	465.53	10.38	26, 215, 217, 246	85.91	0.00
4	0	1.980000	0.00	1354.14	465.53	10.38	26, 215, 217, 246	16.16	0.00
4	0	2.000000	0.00	1354.14	465.53	NA	26, 215, 217, 246	4.77	0.00
5	0	0.000000	18.88	921.29	313.42	19.03	26, 215, 230, 248, 262	31.72	0.00
5	0	0.000002	19.03	1270.44	443.21	19.03	26, 215, 230, 248, 262	13.83	0.00
5	0	0.020000	18.88	1325.48	462.44	18.88	27, 119, 217, 246, 268	27.48	0.00
5	0	0.200000	18.88	1326.19	462.44	18.88	27, 119, 217, 246, 268	516.14	0.00
5	0	0.400000	18.88	1326.19	462.44	18.88	27, 119, 217, 246, 268	438.48	0.33
5	0	0.600000	18.88	1326.19	462.44	18.88	27, 119, 217, 246, 268	211.95	0.00
5	0	0.800000	17.88	1326.19	462.44	18.88	27, 119, 217, 246, 268	123.52	0.00
5	0	1.000000	17.88	1324.43	463.53	17.88	27, 196, 217, 246, 268	97.80	1.00
5	0	1.200000	0.00	1316.99	463.53	17.88	27, 196, 217, 246, 268	619.23	1.00
5	0	1.400000	0.00	1327.41	467.22	10.38	26, 215, 217, 246, 268	311.30	0.81
5	0	1.600000	0.00	1327.41	467.22	10.38	26, 215, 217, 246, 268	13.44	0.43
5	0	1.800000	0.00	1327.41	467.22	10.38	26, 215, 217, 246, 268	11.91	0.00
5	0	2.000000	0.00	1327.41	467.22	NA	26, 215, 217, 246, 268	4.52	0.00
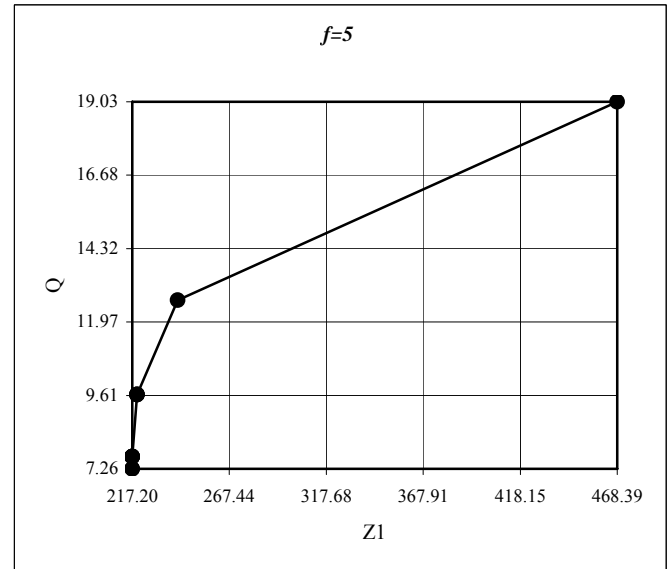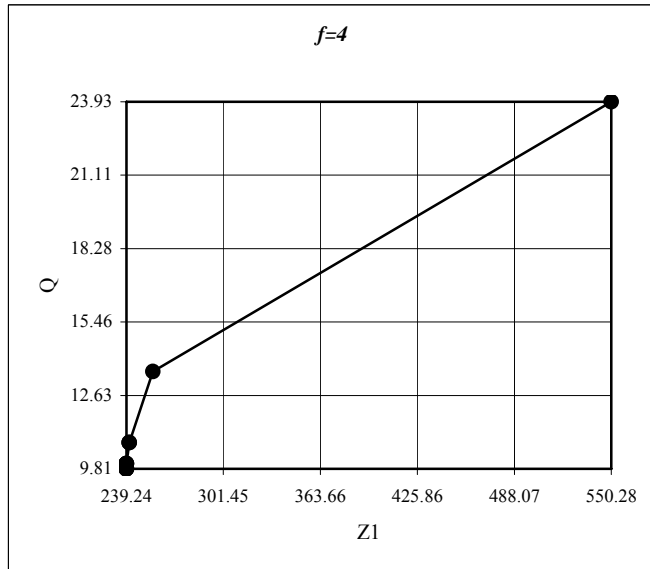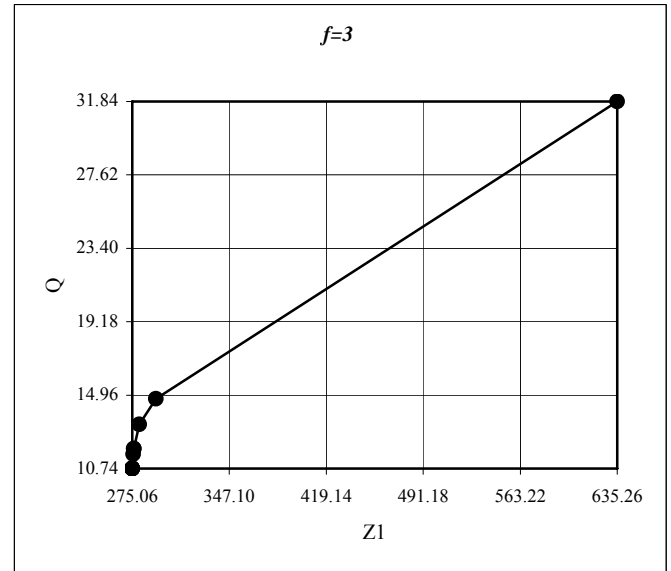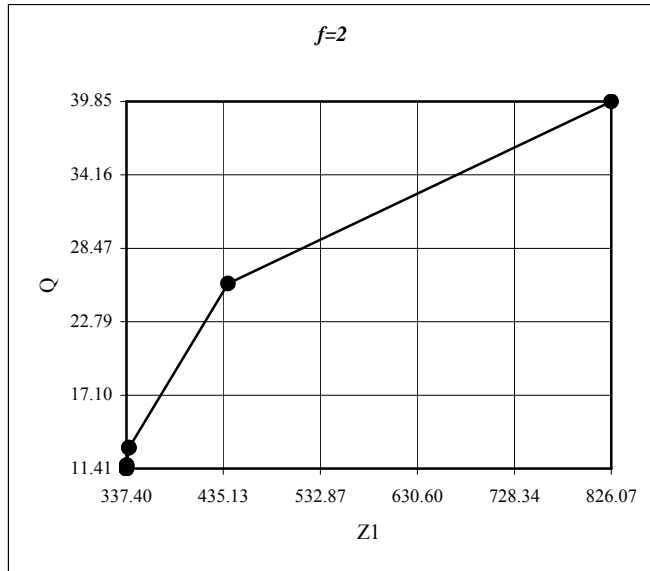
Figure 23. Pareto-optimal Results of the Tri-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area (Z_1 and Q).
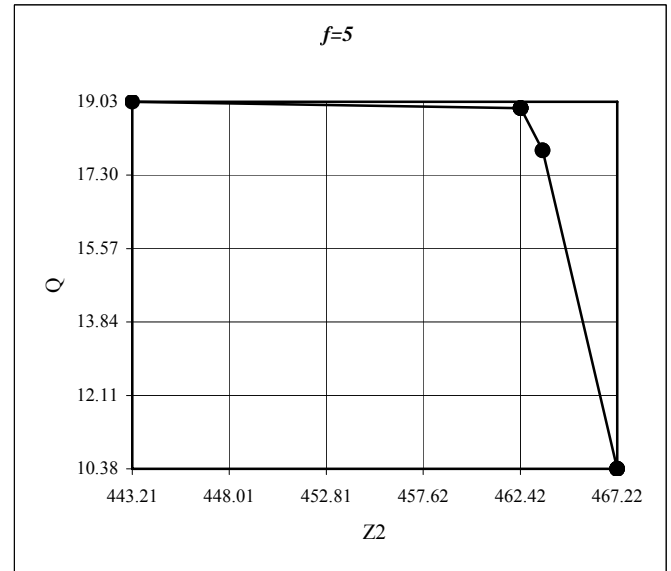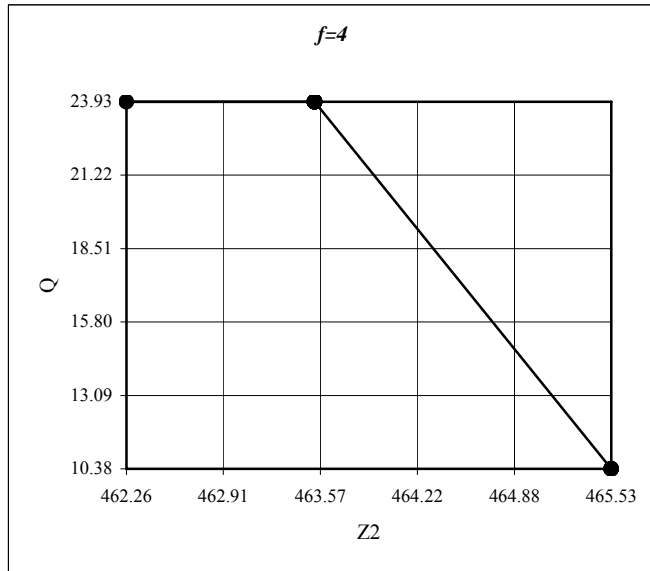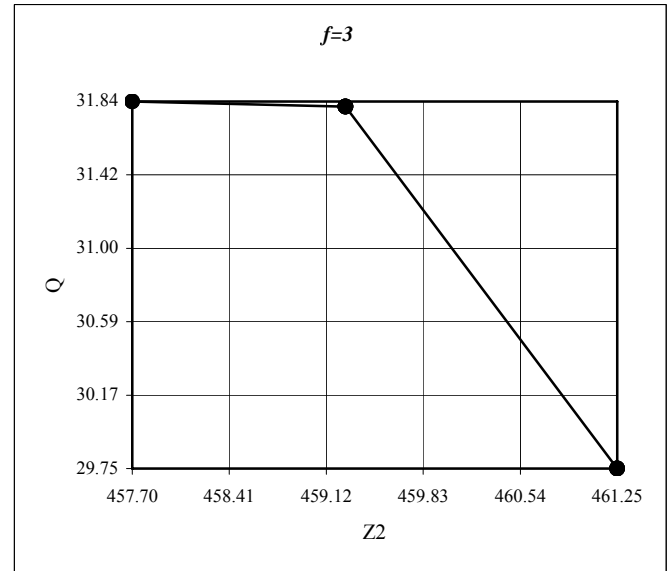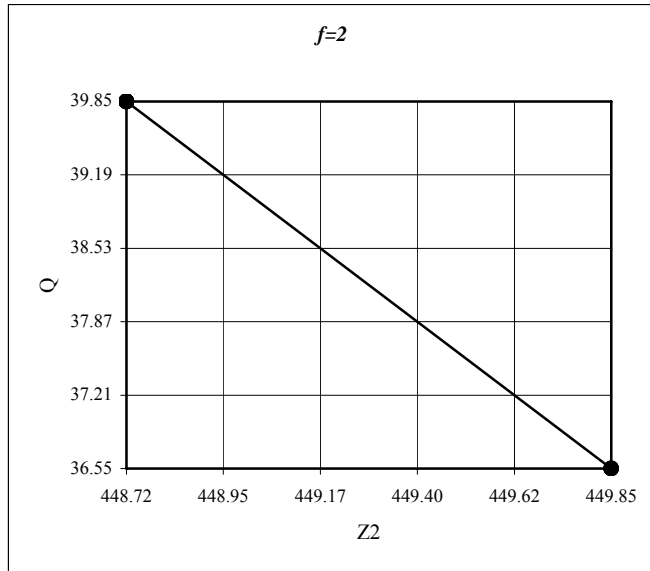
Figure 24. Pareto-optimal Results of the Tri-objective Critical Supply Facility Location Model in the Orlando Metropolitan Area (Z_2 and Q).
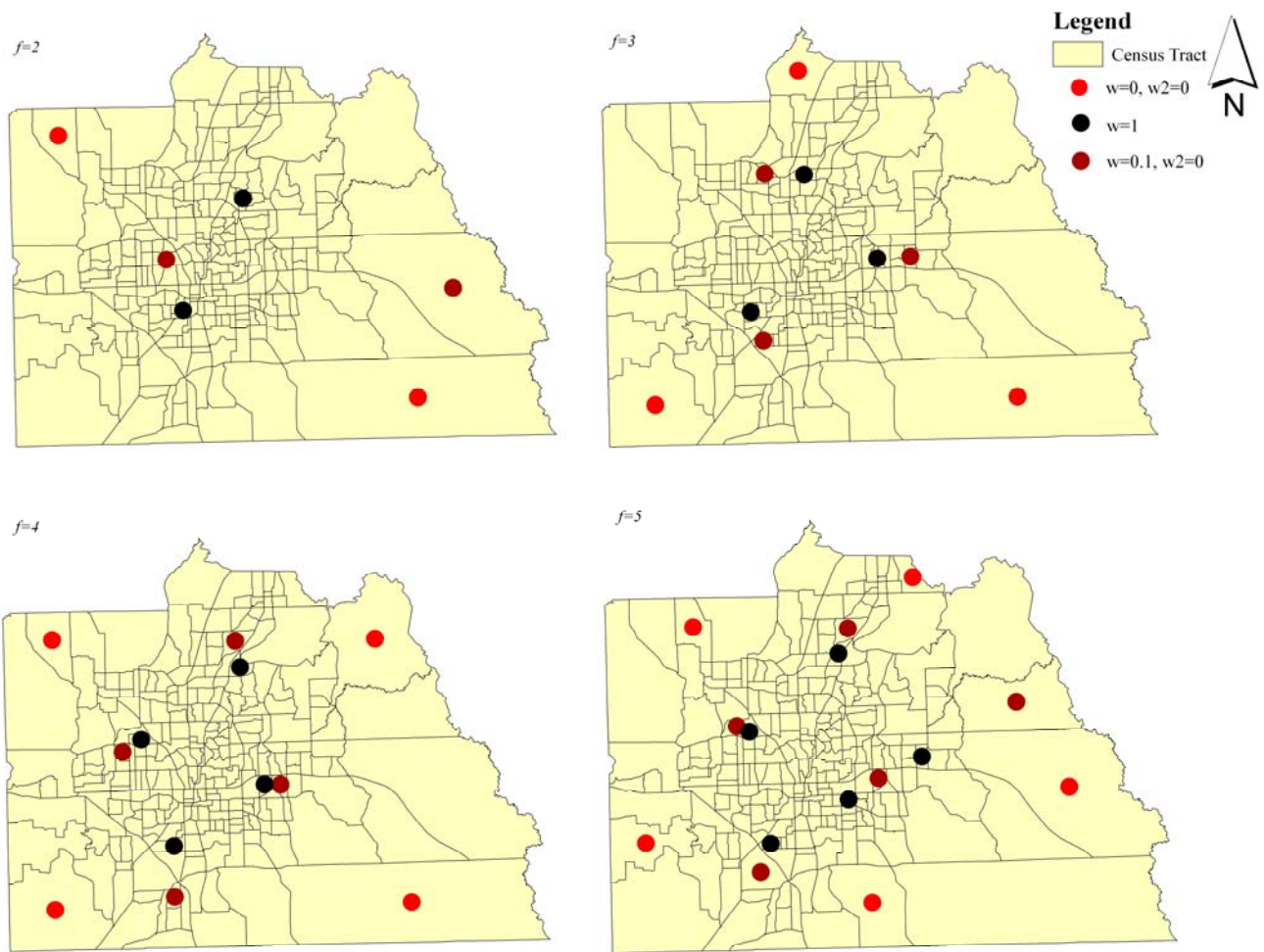
Figure 25. Visualization of Facility Locations with Various Dispersion Weights.
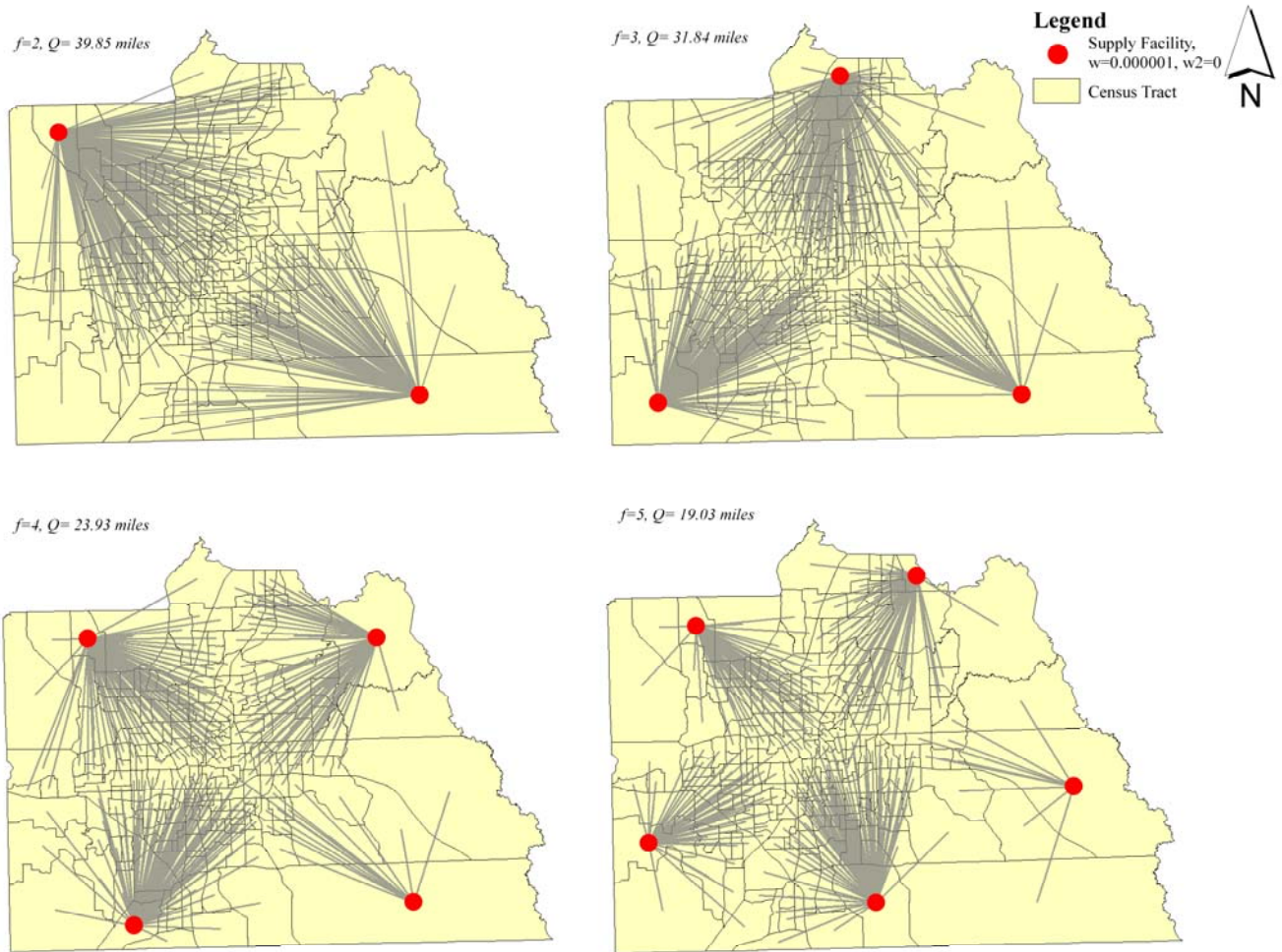
Figure 26. Maps of Facility Location/Allocations with Emphasis on Dispersion.

5.7 Conclusion

In review, the trade-offs of access and security among a single facility are fairly direct, meaning a compromise in access is nearly equal the gain in protection. However, for multiple facilities, the trade-offs in this model show more substantial gains. This indicates that locating multiple facilities for emergency supplies will not only allow for redundant supply, but will also allow for some protection to be gained for a fractional loss in access. Although the trade-offs may not be great among one facility, given the actual size of a facility in relation to a census tract, having a 1% gain in protection could have a considerable influence on the distance to other critical facilities. For example, a 1% gain in protection might possibly place a facility in one

census tract at a sufficient enough distance from a vulnerable area, thus allowing for a potentially satisfactory solution.

In addition, scaling does not seem to have much influence on the objective function values. However, since the larger study area was not as uniform in area, facility locations did not necessarily behave in a predictable manner. In fact, facilities happened to cluster as a result of the uneven shape of the larger study area.

As explained previously, these results are not intended to be actual policy decisions. The model explored in this thesis may need further refinement and fine-tuning for actual courses of action. Other constraints about cost or supply limitations were ignored here; these are genuine components that would need to be taken into consideration.

In regards to guidance for choosing distance constraints or facility dispersion, it is difficult to say which is 'better', because each have advantages. From a computational standpoint, Neighborhood Adjacency Constraints allow the model to solve much faster in comparison with incorporating the p-dispersion objective. However, as seen in the pareto-optimal graphs in Figures 23 and 24, facility dispersion can have substantial gains amongst competing objectives. So in this sense, it may be beneficial to incorporate the p-dispersion objective. However, large datasets would necessitate the use of heuristics for solving the p-dispersion problem. If willing to deal with computational and permutational barriers, the p-dispersion is recommended because of their pareto-optimal gains from being an objective. However, Neighborhood Adjacency Constraints are a recommended substitute.

CHAPTER VI: CONCLUSIONS

6.1 Discussion

Critical infrastructure protection has been deemed an important research area for the 21st Century. As a budding field of research, new dimensions are needed to give alternatives to protection measures that may be unavailable, or even unacceptable. Alternative avenues of thought and methods can lead to better and more-rounded problem solutions and this thesis was intended to accomplish that. In addition to critical infrastructure protection, disaster preparedness for human-made attacks has been made pertinent as a result of recent terrorist actions. Bio-warfare, in particular, has been an increasing concern and proposing a multi-hazards approach to siting emergency supplies can help alleviate any casualties or disruptions that could occur.

The modeling approach presented in this thesis illustrates the key elements incorporated in locating future critical facilities. In result, linear programming for critical infrastructure protection and disaster preparedness can have conflicting objectives (i.e. access vs. security). However, multi-objective optimization can help illustrate possible non-inferior locations for facilities of this nature and can enable best compromise solutions subject to objective parameters.

According to the literature review, urban concentrations are more spatially vulnerable compared with more dispersed networks. Based on the previous assumption, this thesis gives some theoretical normative insight into critical supply facility location with regards to access and protection. In particular, I present a new model that incorporates critical facility clustering as a modeling parameter to act as a repellant for future critical facilities. Further, I incorporate the human settlement structure of an urban area to act as an attractor for emergency supply facilities. In addition, I incorporate facility dispersion to help facilitate protection amongst multiple facilities being placed. This approach has given some insight into the spatial structure of critical facilities and urban populations (and their subsequent spatial dimension of vulnerability) with how they interact as being interdependent parts of an emergency infrastructure network. In conclusion, the model this thesis introduces presents a multi-hazard approach for strategically siting future critical supply facilities and incorporates new techniques for planning critical infrastructures.

6.2 Project Significance

Planning for preparedness in locating critical facilities for protection is highly contingent on what scale is being used. In this case, the scale (magnitude) of an attack should correlate with the scale (extent) of a population or area. The larger the anticipated attack, the larger the area the model should be applied to. For example, if a planner were to go about locating a critical supply facility for protection, he/she would make a decision about which size attack to prepare for. If they were concerned about a nuclear bomb, they would want to locate their facility further away from an entire city, whereas if they were concerned with a smaller type of bomb, they might decide to locate in a particular block within a city that is less vulnerable to attack. This is ultimately a problem that a decision-maker or planner will have to deal with. In addition, they should be aware of the issue and how it applies to their solution approach.

For the case stated above, put yourself in the attacker's shoes for a second. Your goal is to wipe out as many people or critical facilities as possible, probably even both. Since facilities do not move at different times of the day, this problem should focus on people. Where could an attacker find the largest amount of people clustered together at what time of day? People tend to cluster together during the day time (working hours) where they all meet together to do business. So an attacker would target any place that has several critical facilities and large amounts of people. If the attacker was a rational being, which they probably are considering the long-term planning done by those committed to the attacks on 9/11, they should have reason to believe the most effective time of day, and place of attack would be during working hours and at a centralized place. With this thought in mind, the most rational place to locate critical facilities for vulnerability reduction and attack mitigation would be away from this (centralized) area.

For instance, in the context of deconcentrating key facilities, it would not be wise to rebuild the World Trade Center into another large skyscraper, let alone two. Buildings 1 and 2 of the World Trade Center were the two tallest buildings in New York City, and were probably the most vulnerable to attack as a result. In order to mitigate a potential large disaster, having these offices decentralized would have not only reduced their vulnerability, but would have also reduced the number of casualties if a large attack were to happen.

This research is useful for a wide variety of people and organizations. It is useful for government officials seeking to implement a public policy on certain types of critical infrastructure that is deemed to be necessary to protect. This model is especially useful for

planners, whether they are involved in land-use, engineering, disaster preparedness planning, or transportation. In addition to those in the public sector, private industry can also find this model useful if they plan to solve location problems for facilities they deem to be important and require protection. This research is especially useful for academics and researchers who are working in the same area of location modeling, critical infrastructure protection, or disaster preparedness.

An important aspect to note about location modeling and formulating these optimization models is that these problems, such as the *p*-median, can be extended, modified, or applied to different study areas. This makes it important to be familiar with other models that are used in the literature, and highlights the need to see connections between scholarly research in the spatial optimization field and current real world problems. My approach is original and will hopefully inspire additional original research or improvements on future models built in a similar fashion.

A main concern for the security of our nation is not only that our enemies are irrational beings, but that fact that our enemies *are* rational beings. This was proven by those that planned and carried out the attacks on September 11, 2001. This is the most terrifying part, and the part we must pay most attention to, because these are the ones who have the most potential to inflict cataclysmic damage.

6.3 Future Work

This thesis introduces select techniques for siting critical infrastructures. Since access to populations and distance protection from other critical facilities are the only objectives concerned with here, other objectives may have been left out. For instance, the two factors of access to populations and protection from other critical facilities may not be the only objectives that planners base their decisions on for an actual critical facility placement. Preparedness for natural hazards may also be an important objective to consider. In addition, constraints such as a fixed facility charge or a facility's supply limitations to demands might be incorporated. In turn, there are other possible objectives or constraints that could be considered for placing a future critical supply facility.

Part of this thesis looks at the non-inferior objective values displayed on a pareto-optimal graph curve. It is known in the multi-objective optimization literature that a steeply kinked trade-off curve can result in larger gains amongst conflicting objectives. However, most analyses of

pareto-optimal curves are conveyed through qualitative measurements. More accurate analyses of pareto-optimal trade-off curves should include quantitative descriptors, which give a numerical value of how ideal the trade-offs 'behave'. The Gini-coefficient may give a simple estimate of the value of a trade-off curve; however, more intricate analysis in the rate of change amongst the weights should accurately portray how ideal the Lorenz curve is in a multi-objective analysis.

Other areas of future research for incorporating protection and access of emergency supplies may include spatio-temporal modeling of the Strategic National Stockpile for security purposes and designating points of dispensing (PODs) or break of bulk (BOB) sites for enabling access to demand populations (See Horner and Downs 2007). In a protection sense, the bulk stockpile's location can change as function of time to strategically site the stock in other places for security purposes, thus creating a sense of uncertainty of where a critical supply may be located to an enemy. From an accessibility standpoint, BOB sites can be designated in case of an emergency, thus enabling better logistical dispensing of resources to demand populations.

One essential geographical problem address earlier is a problem of scale. Although noted that scale does not appear to have any influence over objective values, it certainly can affect the placements of facilities relative to other vulnerable areas. For example, in the larger study area with emphasis on protection, facilities are being placed in a dense urban area in southern Pinellas County. A potential solution to this problem is to run an auxiliary model which incorporates a smaller network (e.g. Pinellas County) to find a subscale optimal location within this smaller area. This would help mitigate against scaling issues with placing semi-desirable facilities in irregular conurbations like the one along the I-4 corridor.

APPENDIX A: STANDARD INDUSTRIAL CLASSIFICATION CODES

Table 15. Critical Standard Industrial Classification (SIC) codes.

Standard Induatrial Classifications (SIC) Codes	
Adult Care Facilities	City Government-Economic Program Adm
Aerospace Industries (Mfrs)	City Government-Education Programs
Air Ambulance Service	City Government-Environmental Programs
Air Cargo Service	City Government-Executive Offices
Air Courier Services	City Government-Finance & Taxation
Aircraft Brokers (Whol)	City Government-General Offices
Aircraft Charter Rental & Leasing Svc	City Government-Housing Programs
Aircraft Ferrying & Transporting Svc	City Government-Legal Counsel
Aircraft Ground Support & Service Equip	City Government-Licensing & Inspection
Aircraft Schools	City Government-Social & Human Resources
Aircraft Servicing & Maintenance	City Government-Transportation Programs
Aircraft-Dealers	City Government-Urban Planning & Dev
Aircraft-Manufacturers	City Government-Veterans Affairs Admin
Airline Companies	City Govt-Regulation/Adm-Comms/Utilities
Airline Training Schools	Cleaners-Wholesale
Airport Authority & Terminal Svcs	Cleaning Compounds (Wholesale)
Airport Equipment & Supplies (Mfrs)	Cleaning Compounds-Manufacturers
Airport Transportation Service	Cleaning Services-Commercial/Residential
Airports	Cleaning Services-Industrial
Ambulance Service	Cleaning Systems-Pressure Chemical-Mfrs
Ambulances & Hearses (Wholesale)	Cleaning Systs-Pressure Chem/Etc (Whol)
Amusement Places	Clinics
Animal Hospitals	Communications
Armored Car Service	Communications Consultants
Assisted Living Facilities	Communications Equipment NEC (Mfrs)
Banks	Communications Services NEC
Baseball Clubs	Communications Services-Common Carriers
Batteries-Dry Cell-Manufacturers	Containerized Freight & Cargo Service
Batteries-Dry Cell-Wholesale	County Government-Conservation Depts
Batteries-Storage-Retail	County Government-Courts
Batteries-Storage-Wholesale	County Government-Economic Program Adm
Battery Supplies	County Government-Environmental Programs
Biological Products (Manufacturers)	County Government-Executive Offices
Biotechnology Products & Services	County Government-Finance & Taxation
Blood Banks & Centers	County Government-Fire Protection
Broadcasting Companies	County Government-General Offices
Bus Lines	County Government-Housing Programs
Buses-Charter & Rental	County Government-Legal Counsel
Buses-Distributors (Whol)	County Government-Licensing & Inspection
Buses-Manufacturers	County Government-Public Health Programs
Buses-New & Used (Wholesale)	County Government-Public Order & Safety
Buses-School Transportation Service	County Government-Social/Human Resources
Carnivals	County Government-Urban Planning & Dev
Chemical Cleaning-Industrial	County Govt-Correctional Institutions
Chemical Plant-Equipment & Supls (Whol)	County Govt-Reg & Adm-Comms/Utilities
Chemicals (Wholesale)	County Govt-Transportation Programs
Chemicals-Manufacturers	Courier Services
Chemicals-Reclaiming	Cruises
Chemicals-Retail	Delivery Service
Chemists-Manufacturing	Department of Motor Vehicles
City Government-Courts	Diesel Fuel (Wholesale)

Table 15-Continued.

Standard Induatrial Classifications (SIC) Codes	
Distributing Service-Circular & Sample	Financing Consultants
Distribution Centers (Whol)	Financing-Automobile
Distribution Services	Financing-Business
Distributor-Groceries (Whol)	Financing-Insurance Premium
Drug Millers (Mfrs)	Fire Department Equipment & Supls (Whol)
Electric Companies	Fire Departments
Electric Contractors	Fireworks (Wholesale)
Electric Contractors-Marine	Fireworks-Manufacturers
Emergency Medical & Surgical Service	First Aid Instruction
Emergency Notification Service	First Aid Service
Explosives (Wholesale)	First Aid Supplies
Explosives-Manufacturers	Food Banks
Fairgrounds	Food Brokers (Whol)
Farm Equipment (Wholesale)	Food Facilities (Wholesale)
Farm Equipment-Manufacturers	Food Facilities-Consultants
Farm Equipment-Renting (Wholesale)	Food Markets
Farm Equipment-Repairing & Parts	Food Plans
Farm Management Service	Food Preparations NEC (Manufacturers)
Farm Markets	Food Processing Consultants
Farm Supplies (Wholesale)	Food Processing Equipment & Supls (Whol)
Farming Service	Food Products & Manufacturers
Farms	Food Products (Wholesale)
Federal Government-Agricultural Programs	Food Products-Machinery (Manufacturers)
Federal Government-Conservation Depts	Food Products-Manufacturers Equip (Whol)
Federal Government-Courts	Food Products-Retail
Federal Government-Economic Program Adm	Food Service-Distributors (Whol)
Federal Government-Finance & Taxation	Food Service-Management
Federal Government-General Offices	Foods-Carry Out
Federal Government-Housing Programs	Foods-Dehydrated (Wholesale)
Federal Government-International Affairs	Football Clubs
Federal Government-Legal Counsel	Freight Brokers & Agents
Federal Government-Libraries	Freight-Consolidating
Federal Government-Licensing/Inspection	Freight-Forwarding
Federal Government-National Security	Freight-Traffic Consultants
Federal Government-Police	Fuel-Retail
Federal Government-Social & Human Rsrcs	Gas (Lpg) Bottled Bulk Equip/Supl (Whol)
Federal Government-Transportation Prgrms	Gas Companies
Federal Government-Urban Planning & Dev	Gas-Ind & Medical-Cylinder & Bulk-Mfrs
Federal Govt-Correctional Institutions	Gas-Indstrl/Med-Cylinder & Bulk (Whol)
Federal Govt-Environmental Programs	Gas-Liquefied Petro-Bttld/Bulk (Whol)
Federal Govt-Veterans Affairs Admin	Gas-Liquid Petro-Carburetion Syst (Mfr)
Ferries	Gas-Natural
Fertilizer Mixing Only (Manufacturers)	Gasoline & Oil Bulk Stations (Whol)
Fertilizers (Wholesale)	Gasoline & Oil-Wholesale
Fertilizers-Manufacturers	Gasoline Additive-Distributors (Whol)
Fertilizers-Retail	Generators-Diesel (Mfrs)
Financial Advisory Services	Generators-Electric (Wholesale)
Financial Document Information Services	Generators-Electric-Manufacturers
Financial Planners-Certified	Government Offices-City, Village & Twp
Financial Planning Consultants	Government Offices-County
Financing	Government Offices-State

Table 15-Continued.

Standard Industrial Classifications (SIC) Codes	
Government Offices-US	Oil Field Service
Government-Contract Consultants	Oil Marketers & Distributors (Whol)
Government-Contractors	Oil Recovery-Enhanced (Mfrs)
Government-Forestry Services	Oil Refiners (Manufacturers)
Government-Individual/Family Social Svcs	Oils-Essential (Wholesale)
Government-Job Training/Voc Rehab Svcs	Oils-Fuel (Wholesale)
Government-Relations Consultants	Oils-Lubricating-Retail
Government-Specialty Hosp Ex Psychiatric	Oils-Lubricating-Wholesale
Government-Trusts Except Educational	Oils-Petroleum (Wholesale)
Government-Weather Agencies	Oils-Petroleum-Manufacturers
Health Care Products	Oils-Synthetic (Wholesale)
Hospital Consultants	Organ & Tissue Banks
Hospital Equip-Repairing & Refinishing	Paramedical Services
Hospitals	Paramedics
Industrial Inorganic Chmcls NEC (Mfrs)	Pesticides & AG Chemicals NEC (Mfrs)
Industrial Organic Chemicals NEC (Mfrs)	Petroleum Bulk Stations-Terminals (Whol)
Laboratories	Petroleum Consultants
Laboratories-Analytical	Petroleum Equipment (Manufacturers)
Laboratories-Biological	Petroleum Products (Wholesale)
Laboratories-Clinical	Petroleum Products-Manufacturers
Laboratories-Medical	Pharmaceutical Cntnrs Equip/Supls (Mfrs)
Laboratories-Petroleum	Pharmaceutical Consultants
Laboratories-Pharmaceutical (Mfrs)	Pharmaceutical Information
Laboratories-Research & Development	Pharmaceutical Preparation (Mfrs)
Laboratories-Testing	Pharmaceutical Products-Wholesale
Laboratory Equipment & Supplies (Whol)	Pharmacies
Laboratory Equipment & Supplies-Mfrs	Phosphatic Fertilizers (Manufacturers)
Lubricating Oils & Greases (Mfrs)	Physicians & Surgeons
Mail Receiving Service	Physicians & Surgeons Equip & Supls-Mfrs
Mail Sorting Service	Physicians & Surgeons Equip & Supls-Whol
Mailing & Shipping Services	Physicians & Surgeons Information Bureau
Medical & Surgical Svc Organizations	Pipe Line Companies
Medical Centers	Pipe Line Contractors
Medical Groups	Pipe-Joint Compounds (Manufacturers)
Medical Research	Piping Contractors
Medical Transportation	Piping-Process & Industrial
Medicinal Chem/Botanical Prods (Mfrs)	Poison Control Centers
Monuments	Police Departments
Monuments-Manufacturers	Ports
Museums	Post Offices
Natural Gas Transmission	Power Distr/Specialty Transformer (Mfrs)
Natural Gas Transmission & Distribution	Power Plant Consultants
Nursing Homes	Power Transmission Equip-Manufacturers
Ocean-Freight	Power Transmission Equipment (Wholesale)
Office & Desk Space-Rental	Propane (LP) Gas
Office Buildings & Parks	Radio Stations & Broadcasting Companies
Oil & Gas Consultant	Railroad Contractors
Oil & Gas Exploration & Development	Railroads
Oil & Gas Producers	Schools
Oil Additives-Manufacturers	Schools & Educational Services NEC
Oil Field Equipment-Manufacturers	Schools for the Deaf

Table 15-Continued.

| Standard Industrial Classifications (SIC) Codes	
Schools With Special Academic Education	Transportation Services
Schools-Business & Secretarial	Trucking
Schools-Business & Vocational	Trucking-Contract Hauling
Schools-Cooking	Trucking-Heavy Hauling
Schools-General Interest	Trucking-Liquid & Dry Bulk
Schools-Industrial Technical & Trade	Trucking-Local Cartage
Schools-Medical & Dental-Assistants/Tech	Trucking-Motor Freight
Schools-Nursery & Kindergarten Academic	Trucking-Refrigerated
Schools-Universities & Colleges Academic	Trucking-Transportation Brokers
Sheriff	Truck-Transporting
Shipping Agents	Utilities
Shipping Masters	Utilities-Underground-Cable Locating Svc
Shopping Centers & Malls	Utilities-Undrgrnd-Cbl Pipe/Wire (Whol)
Stadiums Arenas & Athletic Fields	Utility Bill Consultants
State Government-Agricultural Programs	Utility Contractors
State Government-Conservation Depts	Utility Management
State Government-Courts	Warehouses-Cold Storage
State Government-Education Programs	Water & Sewage Companies-Utility
State Government-Environmental Programs	Water Companies-Bottled, Bulk, Etc
State Government-Executive Offices	Water Supply Systems
State Government-Finance & Taxation	Water-Distilled (Wholesale)
State Government-Fire Protection	Zoos
State Government-General Offices	
State Government-Housing Programs	
State Government-Legal Counsel	
State Government-Libraries	
State Government-Licensing & Inspection	
State Government-National Security	
State Government-Police	
State Government-Public Health Programs	
State Government-Social/Human Resources	
State Government-Transportation Programs	
State Govt-Correctional Institutions	
State Govt-Reg & Adm-Comms & Utilities	
Storage-Batteries (Manufacturers)	
Surgical Centers	
Surgical Instruments-Manufacturers	
Telecommunications Consultants	
Telecommunications Contractors	
Telecommunications Services	
Telephone & Television Cable Contractors	
Telephone Companies	
Telephone Consultants	
Television Stations & Broadcasting Co	
Television Systs/Eqpt-Clsd Crct (Whol)	
Television-Cable & CATV	
Tourist Attractions	
Towers (Manufacturers)	
Transportation	
Transportation Consultants	
Transportation Lines	

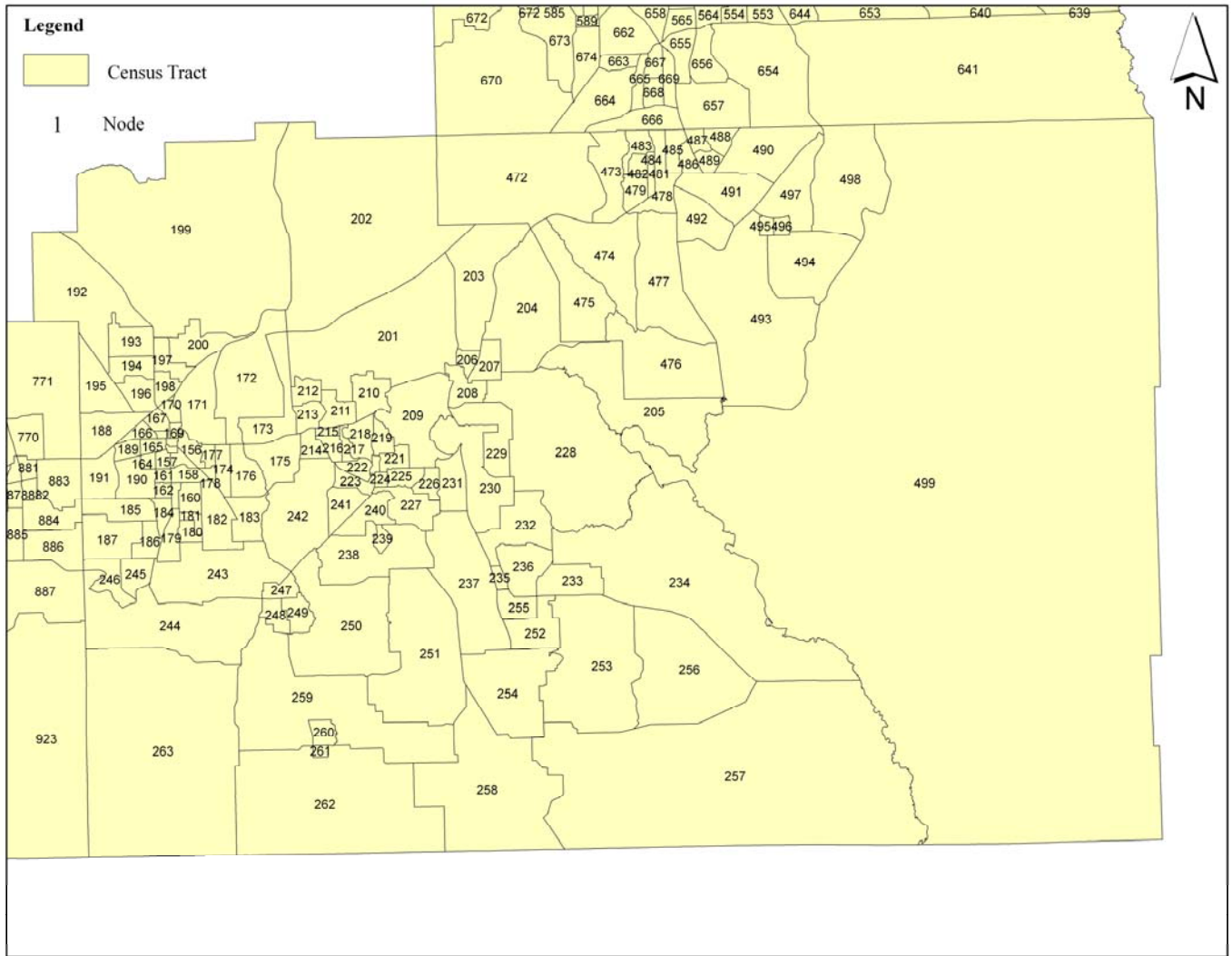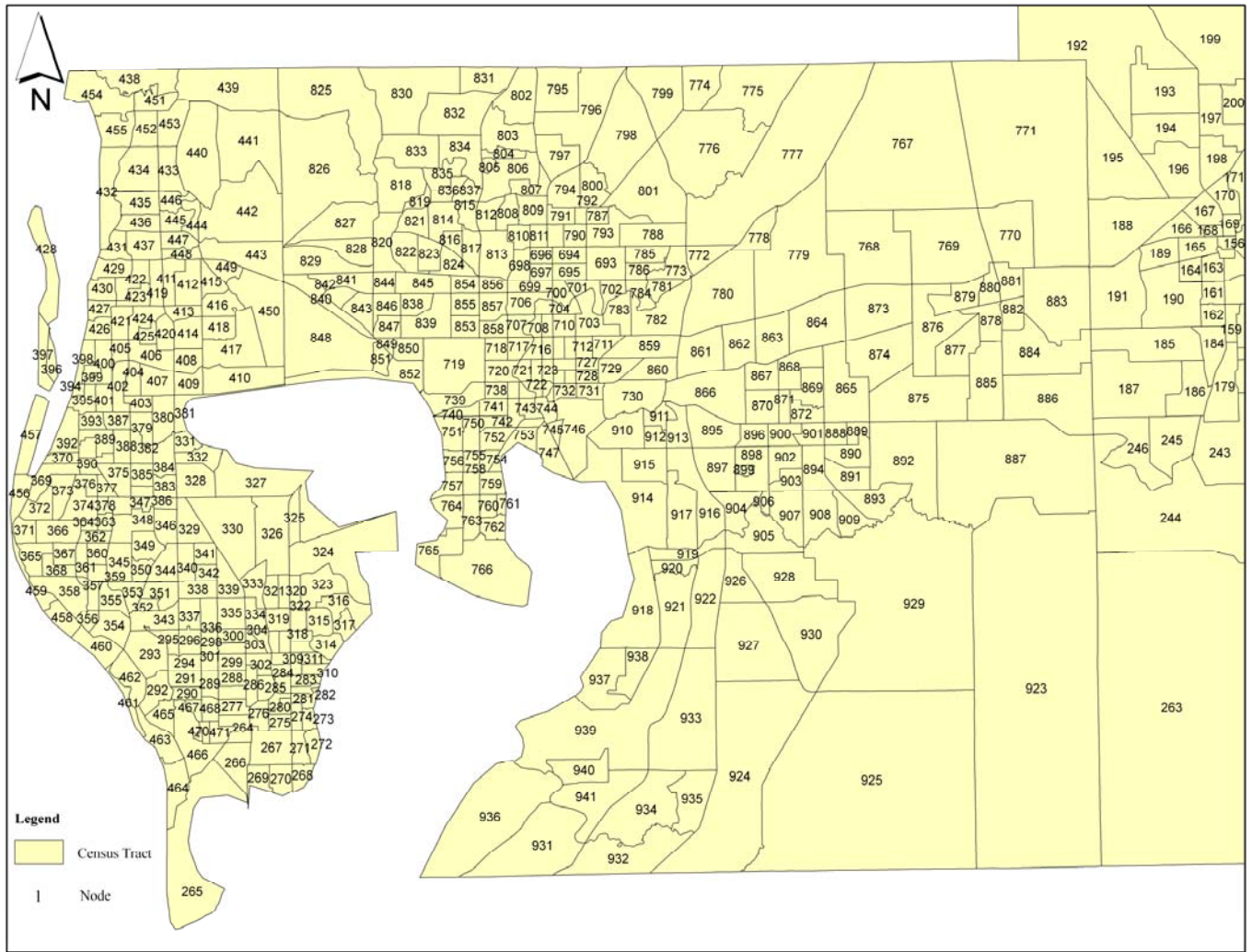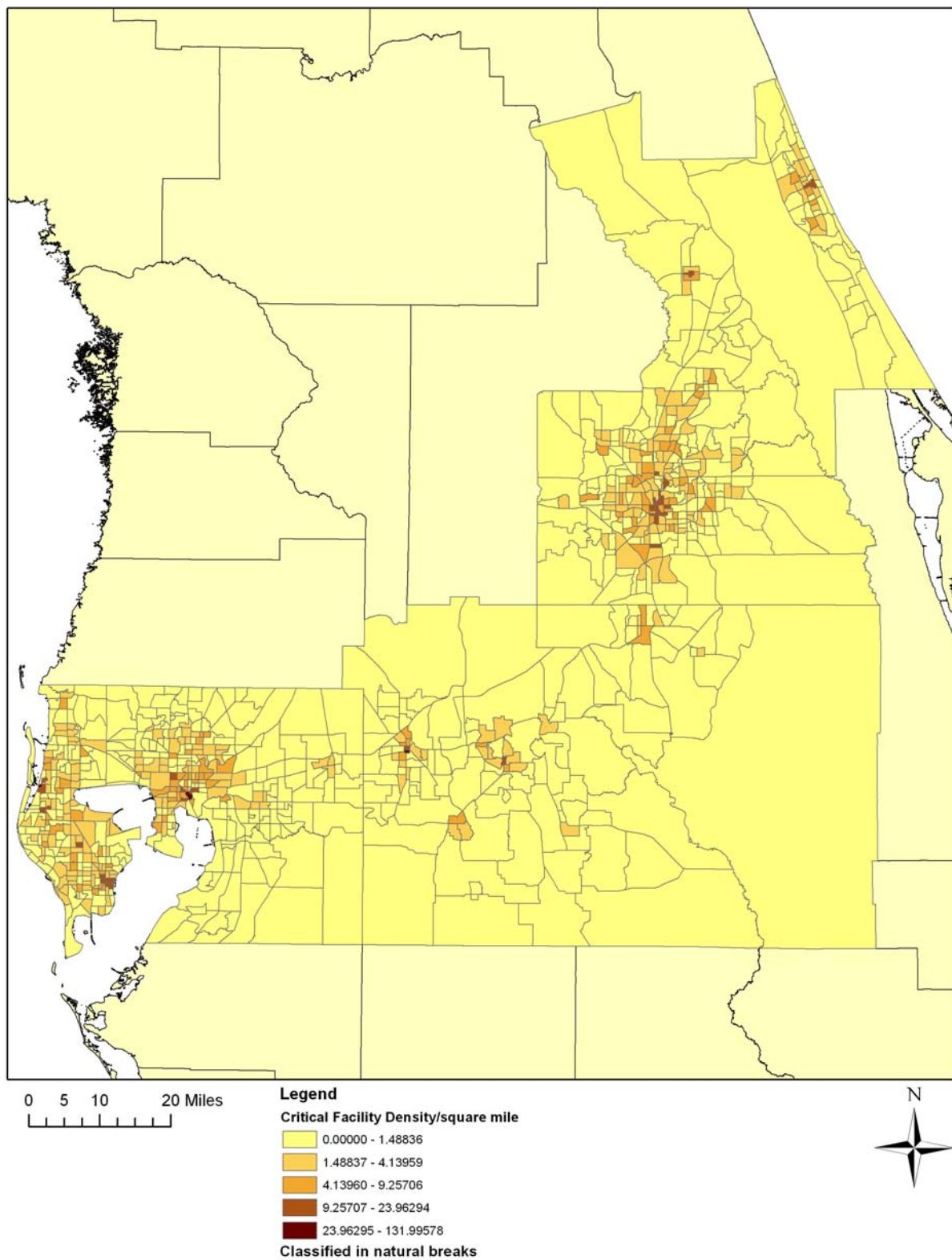# APPENDIX B: TAMPA-ORLANDO CONURBATION MAPS
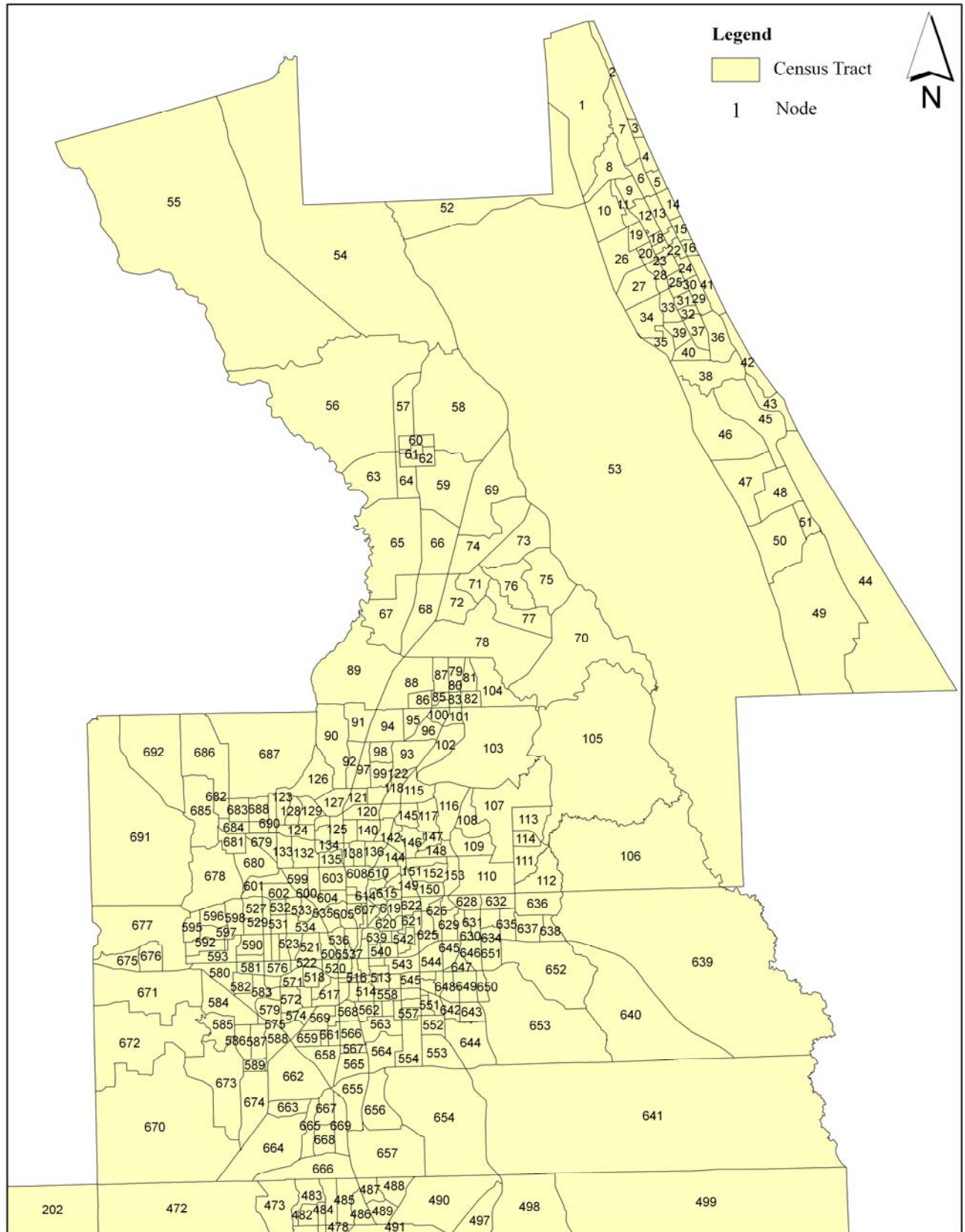
Figure 27. Map of nodes in Orange, Seminole, and Volusia County.
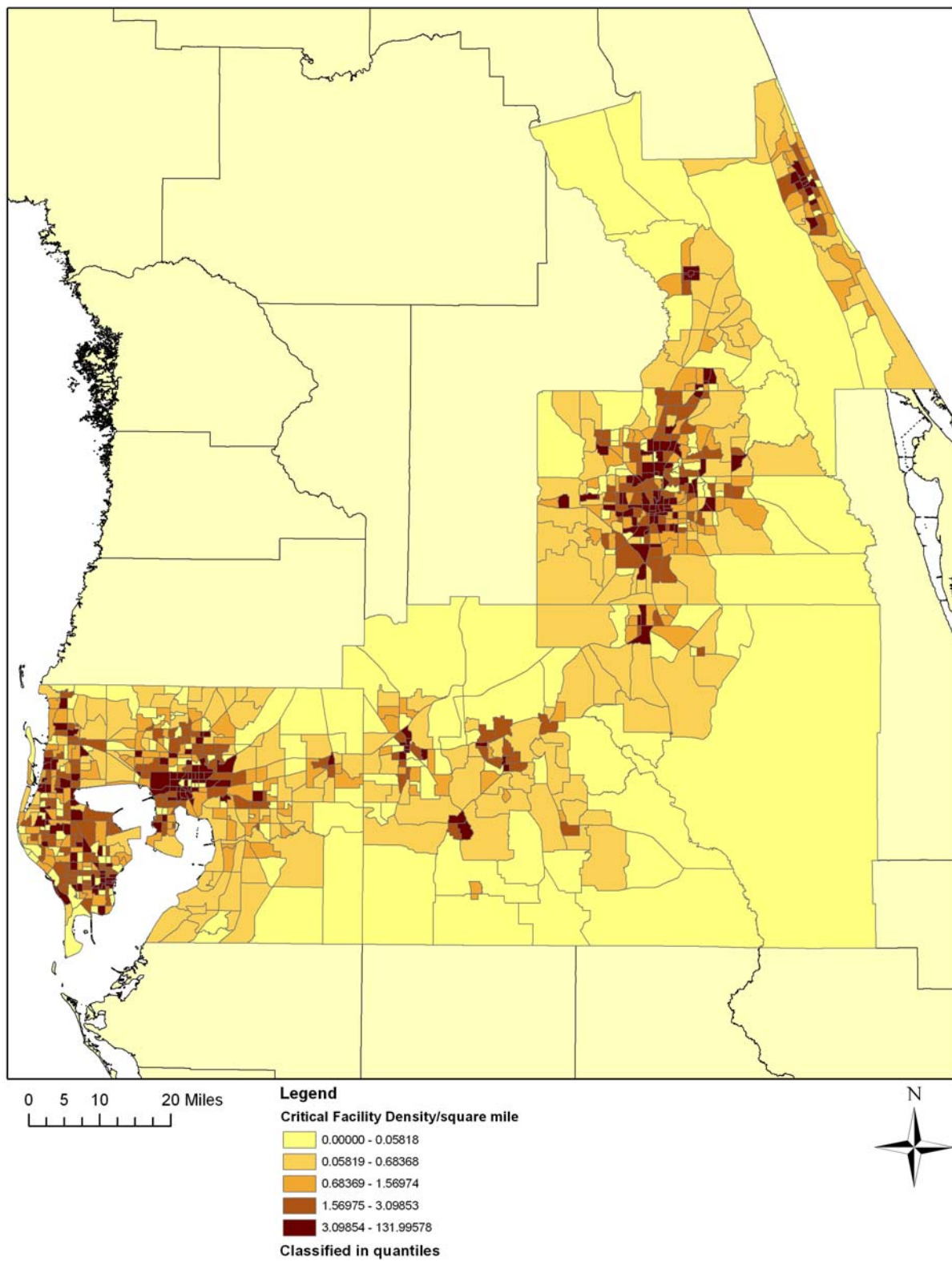
84

**Figure 28. Map of nodes in Polk and Osceola County.**

Figure 29. Map of nodes in Hillsborough and Pinellas County.

Figure 30. Critical Facility Density/Square Mile in the Tampa-Orlando Conurbation (Classified in Natural Breaks). *Source:* InfoUSA (2007).
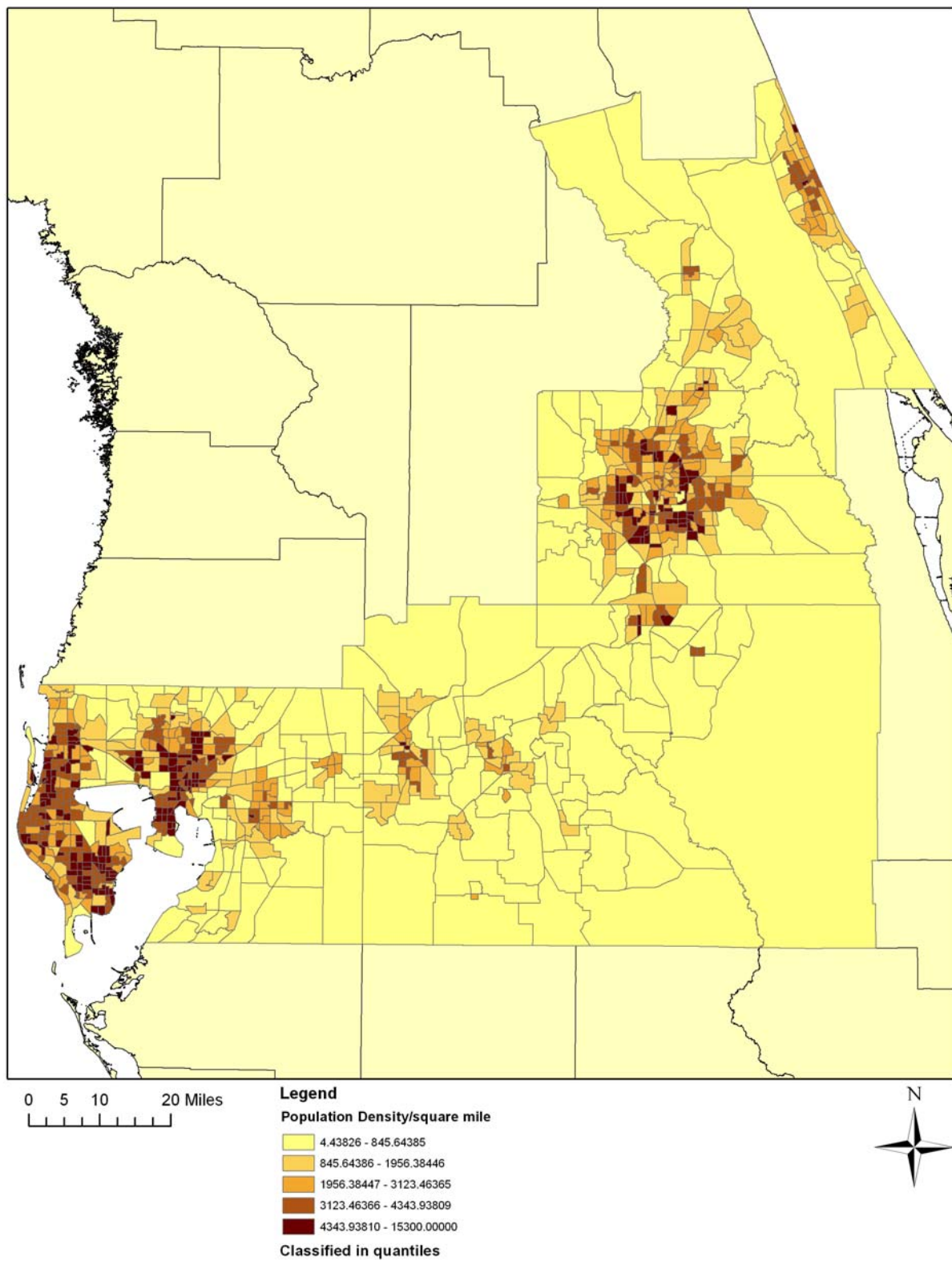
Figure 31. Critical Facility Density/Square Mile in the Tampa-Orlando Conurbation (Classified in Quantiles). *Source:* InfoUSA (2007).
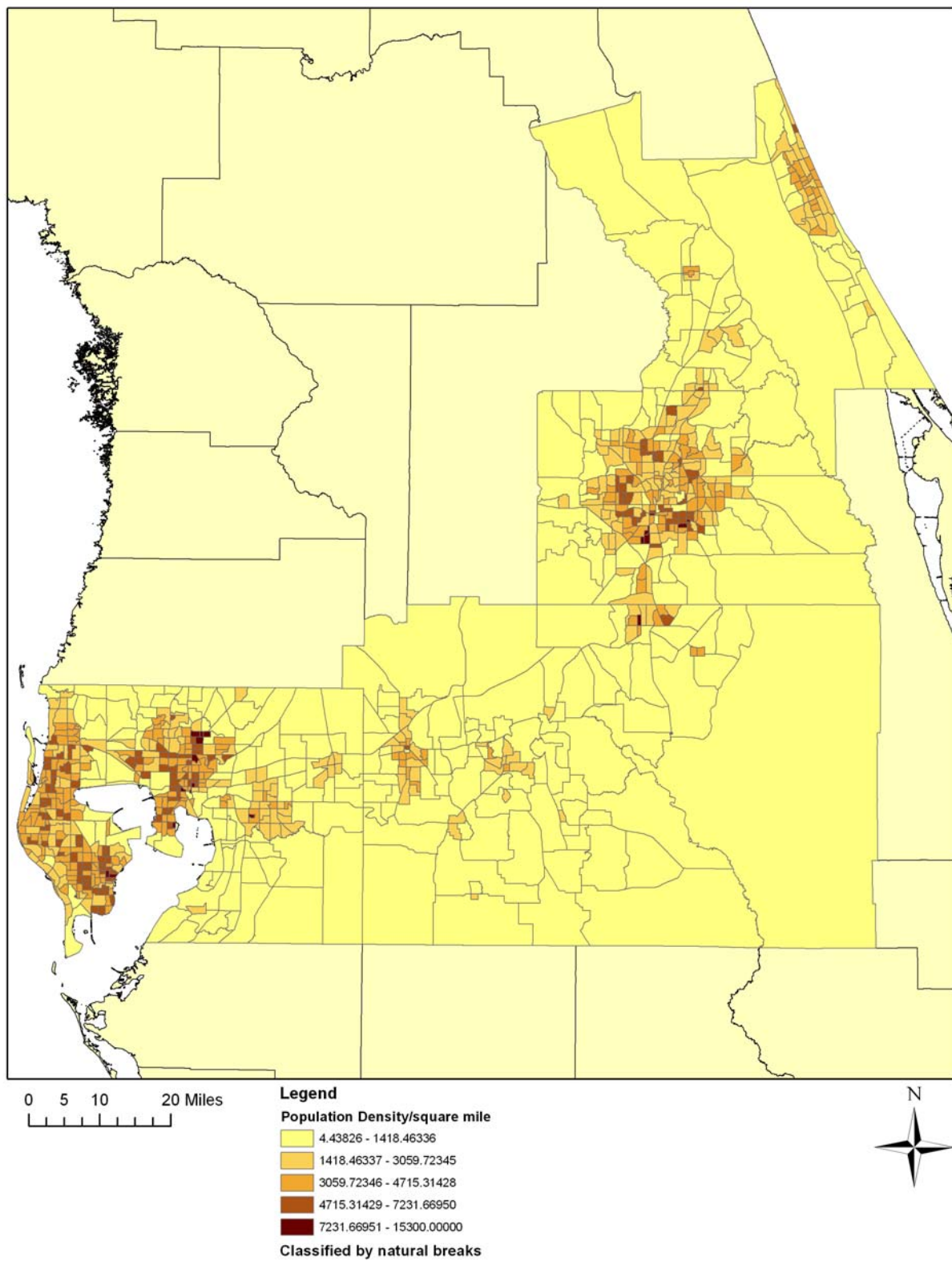
Figure 32. Population Density/Square Mile in the Tampa-Orlando Conurbation (Classified in Natural Breaks). *Source:* U.S. Census Bureau (2006).

Figure 33. Population Density/Square Mile in the Tampa-Orlando Conurbation (Classified in Quantiles). *Source:* U.S. Census Bureau (2006).

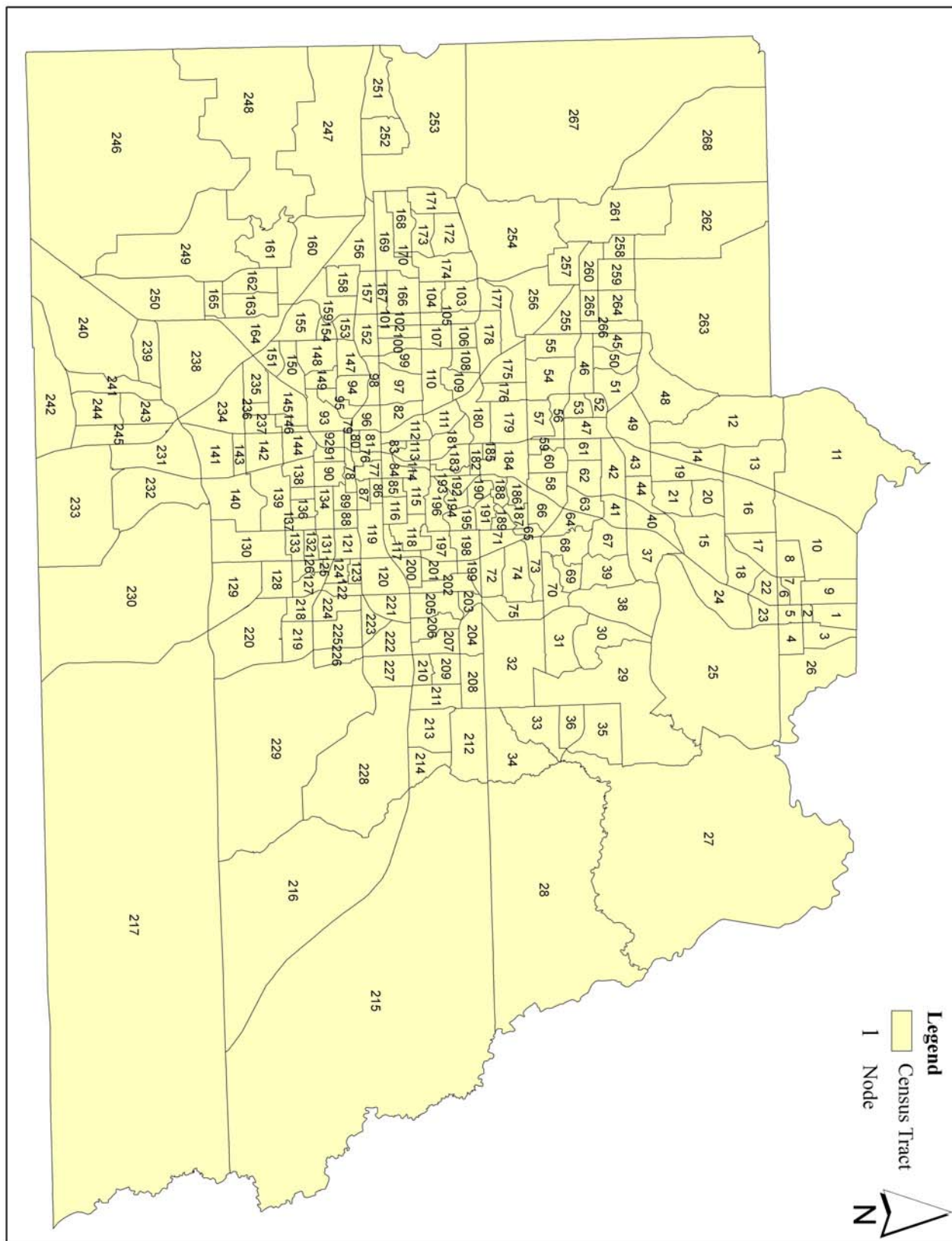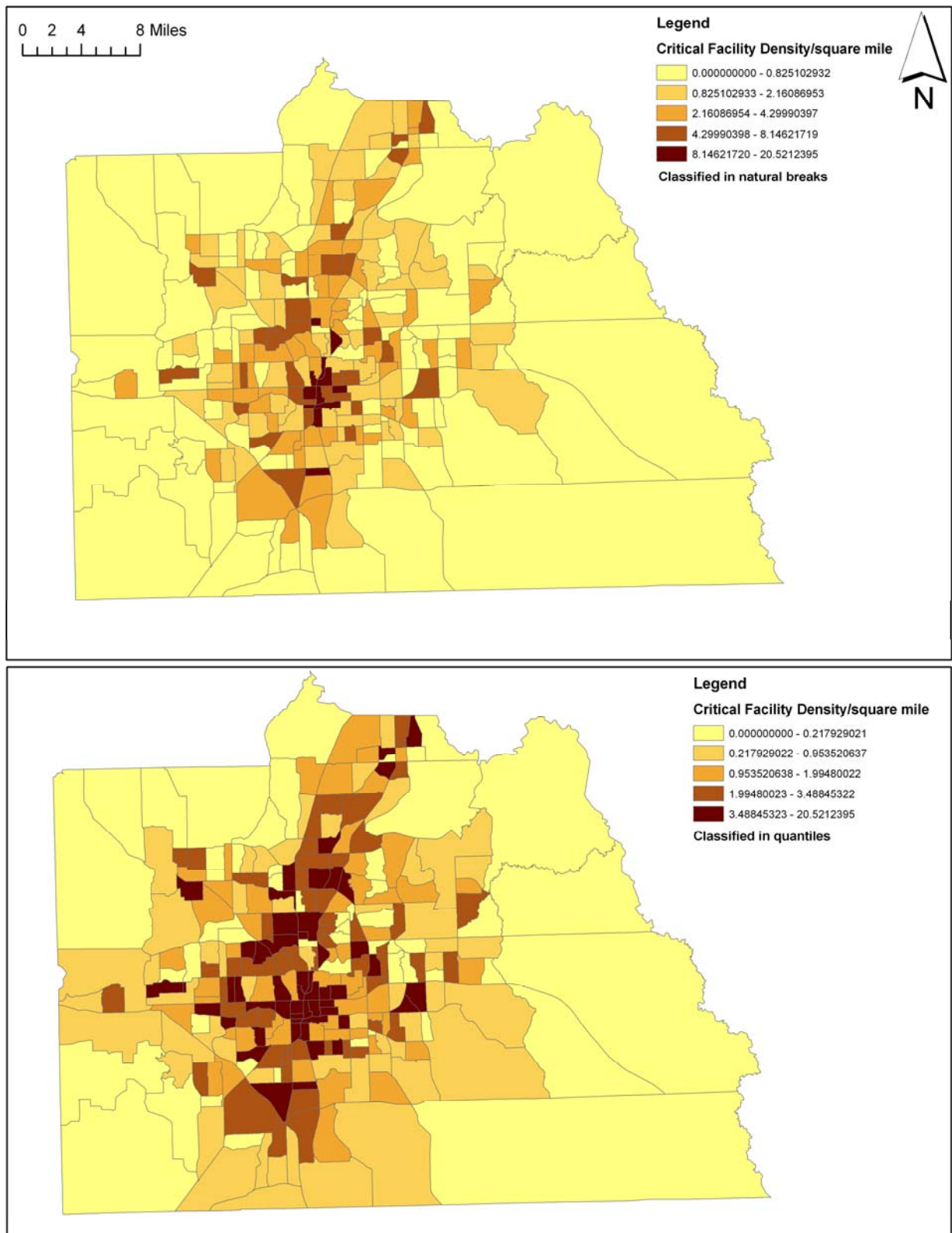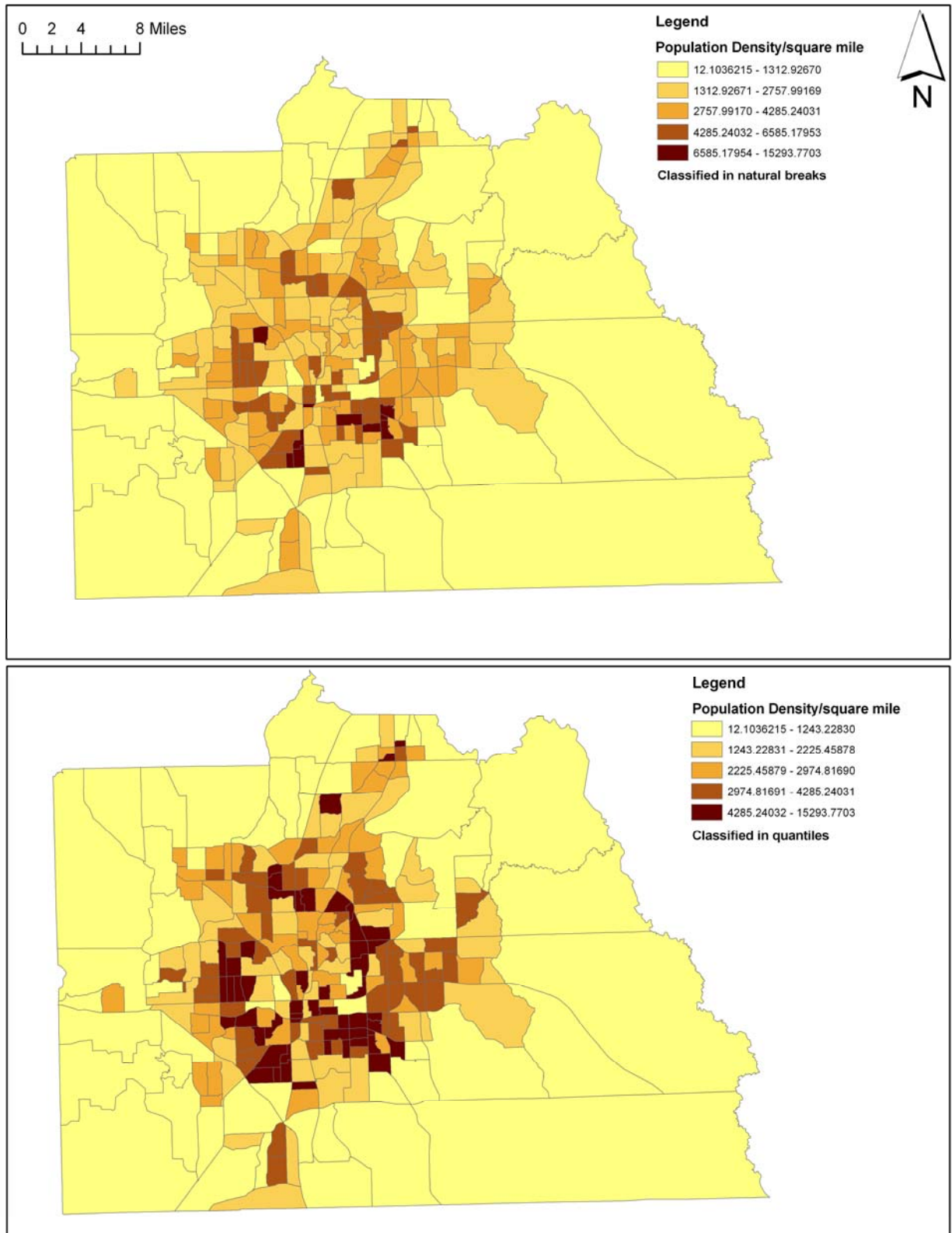# APPENDIX C: ORLANDO METROPOLITAN AREA MAPS

Figure 34. Map of nodes in Orange and Seminole County.

Figure 35. Maps of Critical Facility Density/Square Mile in the Orlando Metropolitan Area (Natural Breaks and Quantiles). *Source:* InfoUSA (2007).

Figure 36. Maps of Population Density/Square Mile in the Orlando Metropolitan Area (Natural Breaks and Quantiles). *Source:* U.S. Census Bureau (2006).

94

REFERENCES

Amin, M. (2005). Energy Infrastructure Defense Systems. *Proceedings of the IEEE*, Vol. 93, 5, pp. 861-875.

Apostolakis, G. E., Lemon, D. M. (2005). A Screening Methodology for the Identification and Ranking of Infrastructure Vulnerabilities Due to Terrorism. *Risk Analysis*, Vol. 25, 2, pp. 361-376.

Asbjornslett, B. J., Rausand, M. (1999). Assess the vulnerability of your production system. *Production Planning & Control*, Vol. 10, 3, pp. 219-229.

Baker, G. H., Little, R. G. (2006). Enhancing Homeland Security: Development of a Course on Critical Infrastructure Systems. *Journal of Homeland Security and Emergency Management*, Vol. 3, 4, Article 4.

Berman, O., Gavious, A. (2007). Location of terror response facilities: A game between state and terrorist. *European Journal of Operations Research*, Vol. 117, 2, pp. 1113-1133.

Brand, M., Kerby, D., Elledge, B., Johnson, D., Magas, O. (2006). A Model for Assessing Public Health Preparedness Competencies and Evaluating Training Based on the Local Preparedness Plan. *Journal of Homeland Security and Emergency Management*, Vol. 3, 2, Article 3.

Brandeau, M. L., Chiu, S. S. (1989). An Overview of Representative Problems in Location Research. *Management Science*, Vol. 35, 6, pp. 645-674.

Bravata, D. M., Zaric, G. S., Holty, J. C., Brandeau, M. L., Wilhelm, E. R., McDonald, K. M., Owens, D. K. (2006). Reducing Mortality from Anthrax Bioterrorism: Strategies for Stockpiling and Dispensing Medical and Pharmaceutical Supplies. *Biosecurity and Bioterrorism: Biodefense Strategy, Practice, and Science*, Vol. 4, 3, pp. 244-262.

Brown, G., Carlyle, M., Salmerón, J., Wood, K. (2006). Defending Critical Infrastructure. *Interfaces*, Vol. 36, 6, pp. 530-544.

Caruson, K., MacManus, S. A., Kohen, M., Watson, T. A. (2005). Homeland Security Preparedness: The Rebirth of Regionalism. *Publius—The Journal of Federalism*, Vol. 35, 1, pp. 143-168.

Caruson, K., MacManus, S. A. (2006). Mandates and Management Challenges in the Trenches: An Intergovernmental Perspective on Homeland Security. *Public Administration Review*, Vol. 66, 4, pp. 522-536.

Caruson, K., MacManus, S. A. (2007). Designing Homeland Security Policy within a Regional Structure: A Needs Assessment of Local Security Concerns. *Journal of Homeland Security and Emergency Management*, Vol. 4, 2, Article 7.

Centers for Disease Control and Prevention. (2007). *Cities Readiness Initiative Fact Sheet*. Received from http://www.bt.cdc.gov/cri/facts.asp on July 11, 2007.

Charney, I. (2005). Reflections on the Post-WTC Skyline: Manhattan and Elsewhere. *International Journal of Urban and Regional Research*, Vol. 29, 1, pp. 172-179.

Chopra, S., Sodhi, M. S. (2004). Managing Risk to Avoid Supply Chain Breakdown. *MIT Sloan Management Review*, Vol. 46, 1, pp. 53-61.

Church, R. L., Garfinkle, R. (1978). Locating an Obnoxious Facility on a Network. *Transportation Science*, Vol. 12, pp. 107-118.

Church, R. L., Scaparra, M. P., Middleton, R. S. (2004). Identifying Critical Infrastructure: The Median and Covering Facility Interdiction Problems. *Annals of the Association of American Geographers*, Vol. 94, 3, pp. 491-502.

Church, R. L., Scaparra, M. P. (2007). Protecting Critical Assets: The r-Interdiction Median Problem with Fortification. *Geographical Analysis*, Vol. 39, 2, pp. 129-146.

Cohon, J. L. (1978). *Multiobjective Programming and Planning*. Academic Press, New York.

Conrad, S. H., LeClaire, R. J., O'Reilly, G. P., Uzunalioglu, H. (2006). Critical National Infrastructure Reliability Modeling and Analysis. *Bell Labs Technical Journal*, Vol. 11, 3, pp. 51-71.

Critical Infrastructure Protection Program. (2006). *What is CIP?* Retrieved from http://cipp.gmu.edu/cip/ on April 25, 2007.

Cutter, S. L., Richardson, D. B., Wilbanks, T. J. (2003). *The Geographical Dimensions of Terrorism*. Routledge, New York and London.

Daschle, T. (2006, October 15). The Unsolved Case of Anthrax. *The Washington Post*, p. B07.

Daskin, M. (1995). *Network and Discrete Location: Models, Algorithms, and Applications*. John Wiley and Sons, Inc., New York.

Drezner, Z., Wesolowsky, G. O. (1985). Location of Multiple Obnoxious Facilities. *Transportation Science*, Vol. 19, 3, pp. 193-202.

Dunbobbin, B. R., Medovich, T. J., Murphy, M. C., Ramsey, A. L. (2004). Security Vulnerability Assessment in the Chemical Industry. *Process Safety Progress*, Vol. 23, 3, pp. 214-220.

Eisinger, P. (2004). The American City in the Age of Terror: A Preliminary Assessment of the Effects of September 11. *Urban Affairs Review*, Vol. 40, 1, pp. 115-130.

Erkut, E., Neuman, S. (1989). Analytical models for locating undesirable facilities. *European Journal of Operational Research*, Vol. 40, 3, pp. 275-291.

Erkut, E. (1990). The discrete *p*-dispersion problem. *European Journal of Operational Research*, Vol. 46, 1, pp. 48-60.

Ezell, B. C. (2007). Infrastructure Vulnerability Assessment Model (I-VAM). *Risk Assessment*, Vol. 27, 3, pp. 571-583.

Falkenrath, R. A. (2001). Problems of Preparedness: U.S. Readiness for a Domestic Terrorist Attack. *International Security*, Vol. 25, 4, pp. 147-186.

Farahani, R. Z., Asgari, N. (2006). Combination of MCDM and covering techniques in a hierarchical model for facility location: A case study. *European Journal of Operation Research*, Vol. 176, 3, pp. 1839-1858.

Farrell, A. E., Zerriffi, H., Dowlatabadi, H. (2004). Energy Infrastructure and Security. *Annual Review of Environment and Resources*, Vol. 29, pp. 421-469.

Federal Bureau of Investigation. (1999). *Terrorism in the United States 1999*. Retrieved from http://www.fbi.gov/publications.html on October 2, 2007.

Federal Emergency Management Agency. (2005). *Risk Assessment: A How-To Guide to Mitigate Potential Terrorist Attacks Against Buildings*. Retrieved from http://www.fema.gov/plan/prevent/rms/ on September 5, 2007.

Florida Department of Health. (2007). *Florida Public Health and Medical Preparedness Strategic Plan: A Road-Map to Public Health Preparedness and Response in Florida.* Retrieved from http://www.doh.state.fl.us/DEMO/php/index.html on December 19, 2007.

Garb J. L., Cromley, R. G., Wait, R. B. (2007). Estimating populations at risk for disaster preparedness and response. *Journal of Homeland Security and Emergency Management*. Vol. 4, 1, Article 3.

Gazmararian, J. A., Oster, N. V., Green, D. C., Schuessler, L. Howell, K., Davis, J., Krovisky, M., Warburton, S. W. (2002). Vaccine Storage Practices in Primary Care Physician Offices: Assessment and Intervention. *American Journal of Preventive Medicine*, Vol. 23, 4, pp. 246-253.

Gerber, B. J., Cohen, D. B., Cannon, B., Patterson, D., Stewart, K. (2005). On the Front Line: American Cities and the Challenge of Homeland Security Preparedness. *Urban Affairs Review*, Vol. 41, 2, pp. 182-210.

Ghosh, A., Rushton, G. (1987). *Spatial Analysis and Location-Allocation Models*. Van Nostrand Reinhold Company, New York.

Giovachino, M., Calhoun, T., Carey, N., Coleman, B., Gonzalez, G., Hardeman, B., McCrue, B. (2005). Optimizing a District of Columbia Strategic National Stockpile Dispensing Center. *Journal of Public Health Management and Practice*, Vol. 11, 4, pp. 282-290.

Goodman, S. E., Kirk, J. C., Kirk, M. H. (2007). Cyberspace as a medium for terrorists. *Technological Forecasting and Social Change*, Vol. 74, 2, pp. 193-210.

Greenberg, M., Mantell, N., Lahr, M., Felder, F., Zimmerman, R. (2007). Short and intermediate economic impacts of a terrorist-initiated loss of electric power: Case study of New Jersey. *Energy Policy*, Vol. 35, 1, pp. 722-733.

Griebel, M., Phillips, T. S. (2001). Architectural Design for Security in Courthouse Facilities. *Annals of the American Academy of Political and Social Science*, Vol. 576, Courthouse Violence: Protecting the Judicial Workplace, pp. 118-131.

Grubesic T. H., Horner M. W. (2006). Deconstructing the divide: extending broadband xDSL services to the periphery. *Environment and Planning B: Planning and Design*, Vol. 33, 5, pp. 685-704.

Hakimi, S. L. (1965). Optimum Distribution of Switching Centers in a Communication Network and Some Related Graph Theoretic Problems. *Operations Research*, Vol. 13, 3, pp. 462-475.

Harrald, J. R., Stephens, H. W., van Dorp, J. R. (2004). A Framework for Sustainable Port Security. *Journal of Homeland Security and Emergency Management*, Vol. 1, 2, Article 12.

Harvey, M. E., Hung, M. S., Brown, J. R. (1974). The Application of a p-Median Algorithm to the Identification of Nodal Hierarchies and Growth Centers. *Economic Geography*, Vol. 50, 3, pp. 187-202.

Havlak, R., Gorman, S. E., Adams, S. A. (2002). Challenges associated with creating a pharmaceutical stockpile to respond to a terrorist event. *Clinical Microbiology and Infection*, Vol. 8, 8, pp. 529-533.

Horner, M. W., Downs, J. A. (2007). Testing a Flexible GIS-Based Network Flow Model for Routing Hurricane Disaster Relief Goods. *Transportation Research Record*, Vol. 2022, 1, pp. 47-54.

Jaiswal, N. K. (1997). *Military Operations Research: Quantitative Decision Making*. Kluwer, London.

Jia, H., Ordóñez, F., Dessouky, M. M. (2007). Solution approaches for facility location of medical supplies for large-scale emergencies. *Computers & Industrial Engineering*, Vol. 52, 2, pp. 257-276.

Klein, J. O., Helms, C. M. (2006). Strengthening the Supply of Routinely Administered Vaccines in the United States: Progress and Problems—2005. *Clinical Infectious Diseases*, Vol. 42, pp. S145-S150.

Kosal, M. E. (2007). Terrorism Targeting Industrial Chemical Facilities: Strategic Motivations and the Implications for U.S. Security. *Studies in Conflict & Terrorism*, Vol. 30, 1, pp. 41-73.

Krieger, D. (1977). What Happens If…? Terrorists, Revolutionaries, and Nuclear Weapons. *Annals of the American Academy of Political and Social Science*, Vol. 430, Nuclear Proliferation: Prospects, Problems, and Proposals, pp. 44-57.

Kuby, M. J., Fagan, W. F., ReVelle, C. S., Graf, W. L. (2005). A multiobjective optimization model for dam removal: an example of trading of salmon passage with hydropower and water storage in the Willamette basin. *Advances in Water Resources*, Vol. 28, 8, 845-855.

Lane, K. S., Chu, S. Y., Santoli, J. M. (2006). The United States Pediatric Vaccine Stockpile Program. *Clinical Infectious Diseases*, Vol. 42, 3, pp. 125-129.

Larson, R. C. (2005). *Decision Models for Emergency Response Planning*, a chapter in *The McGraw-Hill Handbook of Homeland Security*, David Kamien, editor.

Lee, E. K., Maheshwary, S., Mason, J., Glisson, W. (2006). Decision support system for mass dispensing of medications for infectious disease outbreaks and bioterrorist attacks. *Annals of Operations Research*, Vol. 148, 1, pp. 25-53.

Li, H., Rosenwald, G. W., Jung, J., Liu, C. (2005). Strategic Power Infrastructure Defense. *Proceedings of the IEEE,* Vol. 93, 5, pp. 918-933.

Liu, C., Jung, J., Heytd, G. T., Vittal, V., Phadke, A. G. (2000). The Strategic Power Infrastructure Defense (SPID) System. *IEEE Control Systems Magazine,* Vol. 20, 4, pp. 40-52.

Loukaitou-Sideris A., Taylor, B. D., Fink, C. N. Y. (2006). Rail Transit Security in an International Context: Lessons from Four Cities. *Urban Affairs Review*, Vol. 41, 6, pp. 727-748.

Lovins, A. B., Lovins, L. H. (1982). *Brittle Power*. Brick House Publishing Company, Andover, MA.

Malczewski, J. (1999). *GIS and Multicriteria Decision Analysis*. John Wiley and Sons, Inc., New York.

Malczewski, J. (2000). On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches. *Transactions in GIS*, Vol. 4, 1, pp. 5-22.

Malczewski, J., Chapman, T., Flegel, C., Walters, D., Shrubsole, D., Healy, M. A. (2003). GIS—multicriteria evaluation with ordered weighted averaging (OWA): case study of developing watershed management strategies. *Environmental Planning A*, Vol. 35, 10, pp. 1769-1784.

McGuire, M. C. (2006). Uncertainty, Risk Aversion, and Optimal Defense Against Interruptions in Supply. *Defence and Peace Economics*, Vol. 17, 4, pp. 287-309.

Melachrinoudis, E. (1999). Bi-criteria location of a semi-obnoxious facility. *Computers & Industrial Engineering*, Vol. 37, 3, pp. 581-593.

Melachrinoudis, E., Xanthopulos, Z. (2003). Semi-obnoxious single facility location in Euclidean Space. *Computers and Operations Research*, Vol. 30, 14, pp. 2191-2209.

Mills, E. S. (2002). Terrorism and U.S. Real Estate. *Journal of Urban Economics*, Vol. 51, 2, pp. 198-204.

Min, H. J., Beyeler, W., Brown, T., Son, Y. J., Jones, A. T. (2007). Toward modeling and simulation of critical national infrastructure interdependencies. *IIE Transactions*, Vol. 39, 1, pp. 57-71.

Mirchandani, P. B., Francis, R. L. (1990). *Discrete Location Theory*. John Wiley and Sons, Inc., New York.

Monath, T. P., Gordon, L. K. (1998). Strengthening the Biological Weapons Convention. *Science*, New Series, Vol. 282, 5393, pp. 1423-1423.

Murray, A. T., Church, R. L. (1997). Solving the anti-covering location problem using Langrangian relaxation. *Computers and Operations Research*, Vol. 24, 2, pp. 127-140.

National Security Telecommunications Advisory Committee (NSTAC). (1997). *Information Assurance Task Force Risk Assessment*. Available at http://www.ncs.gov/n5 hp/reports/EPRA.html. In Ezell, B. C. (2007). Infrastructure Vulnerability Assessment Model (I-VAM). *Risk Assessment*, Vol. 27, 3, pp. 571-583.

National Vaccine Advisory Committee. (2003). Strengthening the Supply of Routinely Recommended Vaccines in the United States: Recommendations from the National Vaccine Advisory Committee. *Journal of the American Medical Association*, Vol. 290, 23, pp. 3122-3128.

Need, J. T., Mothershead, J. L. (2006). Strategic National Stockpile Program: Implications for Military Medicine. *Military Medicine*, Vol. 171, 8, pp. 698-702.

Oppong, J. R., Hodgson M. J. (1994). Spatial Accessibility to Health Care Facilities in Suhum District, Ghana. *Professional Geographer*, Vol. 46, 2, pp. 199-209.

Pirkul, H., Gupta, R., Rolland, E. (1999). VisOpt: a visual interactive optimization tool for P-median problems. *Decision Support Systems*, Vol. 26, 3, pp. 209-223.

President's Commission on Critical Infrastructure Protection (1997). *Critical Foundations: Protecting America's Infrastructures*.

Raas, W., Long, A. (2007). Assessing Israeli Capabilities to Destroy Iranian Nuclear Facilities. *International Security*, Vol. 31, 4, pp. 7-33.

Rakas, J., Teodorović, D., Kim, T. (2004). Multi-objective modeling for determining location of undesirable facilities. *Transportation Research Part D*, Vol. 9, 2, pp. 125-138.

Ramberg, B. (1982). Attacks on Nuclear Reactors: The Implications of Israel's Strike on Osiraq. *Political Science Quarterly*, Vol. 97, 4, pp. 653-669.

ReVelle, C., Swain, R. (1970). Central Facilities Location. *Geographical Analysis*, Vol. 2, 1, pp. 30-42.

Salmeron, J., Wood, K., Baldick, R. (2004). Analysis of Electric Grid Security Under Terrorist Threat. *IEEE Transactions on Power Systems*, Vol. 19, 2, pp. 905-912.

Sathe, A., Miller-Hooks, E. (2005). Optimizing Location and Relocation of Response Units in Guarding Critical Facilities. *Transportation Research Record*, 1923, pp. 127-136.

Savitch, H. V. (2003). Does 9-11 Portend a New Paradigm for Cities? *Urban Affairs Review*, Vol. 39, 1, pp. 103-127.

Savitch, H. V., Ardashev, G. (2001). Does Terror have an Urban Future? *Urban Studies*, Vol. 38, 13, pp. 2515-2533.

Smelser, N. J., Baltes, P. B. (2001). *International Encyclopedia of the Social and Behavioral Sciences.* Pergamon Press, Oxford.

Sternberg, E., Lee, G. C. (2006). Meeting the Challenge of Facility Protection for Homeland Security. *Journal of Homeland Security and Emergency Management*, Vol. 3, 1, Article 11.

Sule, D. R. (2001). *Logistics of Facility Location and Allocation*. Marcel Dekker, Inc., New York and Basel.

Swanstrom, T. (2002). Are Fear and Urbanism at War? *Urban Affairs Review*, Vol. 38, 1, pp. 135-140.

Tegnell, A., Van Loock, F., Baka, A., Wallyn, S., Hendrikis, J., Werner, A., Gouvras, G. (2006). Development of a matrix to evaluate the threat of biological agents used for bioterrorism. *Cellular and Molecular Life Sciences*, Vol. 63, 19-20, pp. 2223-2228.

Torgerson, R. (2004). Force protection: today's reality. *Journal of Hazardous Materials*, Vol. 115, 1-3, pp. 193-196.

U.S. Census Bureau. (2006). *Annual Estimates of the Population for the United States, Regions, States, and for Puerto Rico: April 1, 2000 to July 1, 2006.* Retrieved from www.census.gov/popest/states on July 12, 2007.

U.S. Department of Homeland Security. (2007). *Target Capabilities List: A Companion to the National Preparedness Guidelines.* Retrieved from http://www.doh.state.fl.us/DEMO/php/index.html on December 19, 2007.

Wald, M. L. (2002, January 6). Student Pilot, 15, Crashes Plane Into Tower in Florida. *The New York Times*, p. 18.

Wallace, W. A., De Balogh, F. (1985). Decision Support Systems for Disaster Management. *Public Administration Review*, Vol. 45, Special Issue: Emergency Management: A Challenge for Public Administration, pp. 134-146.

White House, The. (2001). *Executive Order on Critical Infrastructure Protection.* Retrieved from http://www.whitehouse.gov/news/releases/2001/10/20011016-12.html on April 25, 2007.

White House, The. (2003). *The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets.* Retrieved from http://www.whitehouse.gov/pcipb/physical.html on July 29, 2007.

Willis, H. H., Morral, A. R., Kelly, T. K., Medby, J. J. (2005). *Estimating Terrorism Risk*. Center for Terrorism Risk Management Policy. In Ezell, B. C. (2007). Infrastructure Vulnerability Assessment Model (I-VAM). *Risk Assessment*, Vol. 27, 3, pp. 571-583.

Wright, P. D., Liberatore, M. J., Nydick, R. L. (2006). A Survey of Operations Research Models and Applications in Homeland Security. *Interfaces*, Vol. 36, 6, pp. 514-529.

Zhan, F. B., Noon, C. E. (1998). Shortest Path Algorithms: An Evaluation using Real Road Networks. *Transportation Science*, Vol. 32, 1, pp. 65-73.

BIOGRAPHICAL SKETCH

Paul Maliszewski was born in Titusville, Florida on April 16, 1984. He graduated with distinction from Clearwater High School in 2002. Upon moving to Tallahassee to study geography, he graduated in 2006 with a Bachelor of Science. He anticipates a Master of Science in Geography in the summer of 2008. During his studies, Paul worked as a teaching assistant for courses in World Geography and Map Analysis. In addition, he assisted in geocoding and maintaining a database of invasive exotic plant species in Florida for the Department of Biological Sciences. Also, he helped gather data and prepare a Wilbur Smith Associate's report on an origin-destination study of truck movement in North Florida for the Florida Department of Transportation. Aside from research, his favorite hobbies include listening to, playing, writing, and recording music. He is continuing his doctoral studies in Geography at Arizona State University where he was awarded a University Graduate Fellowship for the 2008-2009 school year.