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Extending interdiction and median models to identify critical hurricane shelters

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ABSTRACT

Shelters serve as critical facilities where people gather during and after hurricanes. A basic requirement of 'operation' for a shelter is being functional and available to help. However, what happens when shelters themselves are damaged and unable to serve those people? An open question with key policy implications is: How can we identify the most critical shelter(s) as a part of broader emergency evacuation operations and how can we respond to an interdiction? This paper develops a two-step modeling framework consisting of enhanced *r*-interdiction median models (RIM) to identify the most significant shelter(s) and revised *p*-median models to identify shelters to repurpose during such an interdiction where shelters are rendered off-line. Proposed models are applied on a Southeast Florida case study with respect to scenarios based on varying hurricane strength and shelter demand. Findings indicate that models are susceptible to travel cost variation based on the demand-weighted objectives, and that shelter selections vary due to different demand scenarios created which focus on different population segments. As hurricane strength increases, critical shelter identification is driven by flooding and storm surge risks. These findings can inform efforts to harden those critical shelters so that they can better serve populations in need.

1. Introduction

Shelters serve as critical facilities where people receive help before, during and after hurricanes. Therefore, the primary goal of shelter management is to protect the affected population from the possible dangers associated with these storms [1]. This requires emergency officials to ensure that these shelters remain open to help meet people's needs. One problem of shelter management in the planning process is to identify the most critical shelter(s) that would be most undesirable to lose due to storm damage. This issue has become especially pressing during recent hurricanes such as Hurricane Irma (2017) and Hurricane Michael (2018), where the weaknesses with respect to shelter operations, especially while serving at-risk populations such as seniors or minors, have been widely documented [2]. As such, planning for better shelter management is a crucial part of emergency logistics and disaster operations.

There is a growing literature on disaster operations and management proposing solutions to the problems encountered during, before and after disasters [3]. There are several modeling approaches for different aspects of this growing branch of logistics planning. Some studies have focused on the inventory planning for disaster relief operations (e.g., Refs. [4–6]) whereas others focused on determining the optimal facility locations along with the quantity of relief items needed (e.g., Refs. [7,8]). There are also studies that focus on determining the optimum strategies to protect critical facilities in case of attacks [9,10]. Within those solution approaches, spatial optimization models integrated with geographical information systems (GIS) are widely used [11,12]. Specifically, *p*-median-based models were frequently employed as spatial optimization techniques, with some variations in large-scale implementations [13–16]. Optimal shelter location selection is one of the

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problems that can be solved using these models [17–19]. For example, a mathematical model was developed in Ref. [20] in order to study a cross-county collaboration initiative using a *p*-median optimization model for optimal shelter assignment, originally developed in Refs. [21, 22]. The objective function of *p*-median models mathematically searches for the minimum total cost while assigning the population demand to *p* selected shelters in the affected region. The *r*-interdiction median models, on the other hand, maximize the total cost of travel or assignment associated with the interdiction (elimination) of one or more facilities [23]. These models aim to identify the most critical facility or facilities among those that are available. This model, to the authors' knowledge, has not been applied in the context of hurricane shelter management [24]. In the case of emergency operations, an *r*-interdiction model would select the shelter(s) whose removal would most adversely affect emergency operations since it would require more time to evacuate the victims of the hurricane to other available shelters. This would especially be critical for populations-at-risk such as seniors and children since any extra time required can be vital for these population groups.

With a specific focus on interdiction and median problems, there are both stochastic [25,26] and deterministic [10,15] formulations in the literature. In Refs. [25,26], deterministic versions of the proposed stochastic models were created. Several researchers have seen the need to focus on multiple levels while incorporating different actors (e.g., attackers to critical facilities and defenders of those facilities) into their models. That is, they developed decision processes in order to decide which shelters are under attack, and therefore which shelters should be fortified (please refer to [10, 15. 25, 27, 28] for two-level problems and [29,30] for three-level problems). Several studies [10,28,31] make use of both *r*-interdiction median and *p*-median models, where the aim is to protect critical facilities under possible attack; however, the employment of these two models varies. In Ref. [10], the defender decided on *p* facilities to open and given this input, the attacker decided on the facilities to interdict. On the other hand, in Refs. [28,31], *p*-median models were used to determine optimal conditions for interdiction problem settings. In Ref. [28], a *p*-median model was used to determine the initial conditions for interdiction settings, where, it is assumed that *p* facilities were at optimal sites initially. In Ref. [31], *p*-median model objective for each interdiction pattern was used to solve an interdiction problem to decide on the facilities to fortify. However, our study has a different setting. Following the decision of the most critical *r* facilities by an *r*-interdiction setting, best repurposing alternatives were identified from the remaining shelter group by employing *p*-median models.

This paper develops a two-step modeling framework that utilizes both interdiction and median models. In the first step, enhanced *r*-interdiction median models are formulated to identify the most important shelter(s) with respect to travel cost (travel time between population block group centroids and shelter locations), and the spatial distributions of different population segments representing the demand patterns. Although there are shelter registries, it is almost impossible to know the exact shelter demand given many factors driving evacuation decisions. Moreover, demand estimation is even more challenging considering some specific population segments having needs for access and functional assistance. Older adults (65+, 85+) are likely to be in that category during an emergency situation since their health conditions may easily deteriorate [32–38]. Note that the terminology "special needs populations" is only used in the states of Florida, Louisiana, South Carolina and North Carolina to specify those people in need of access and functional assistance. Accordingly, a shelter that is dedicated for the special needs populations is referred as "special needs shelter" (SpNS), where their special needs could be met [39,40]. The terminology is also used in this study since the case studies are derived from the State of Florida; however, we do not only focus on special needs shelters (SpNSs) and regular shelters but we also study all the shelters without this differentiation. Moreover, while simulating the demand and supply data, the hurricane categories are also considered according to their severity.

In the second step, subsequent *p*-median models are used along with the aforementioned shelter typology to select which regular shelter(s) can be repurposed as special needs shelters (SpNSs) in the case of the interdiction of one or more of the special needs shelters. The proposed approach is applied on a case study developed for two highly populated areas in the Southeast Florida, namely Miami-Dade and Broward Counties. In the models, origins (demand points) are the centroids of the U.S. census block groups and the destinations (accessible facilities) are the regular or special needs shelters (SpNSs). Travel times between the origins and destinations are estimated from the Florida Statewide Network Model (FSUTMS). Five different population segments are used as the bases for shelter demand and are selected for the analyses as follows: total population, 65 + population, 85 + population, 5- population, and 18- population. Moreover, this paper focuses on the following two distinct cases created based on the hurricane strength: (a) those hurricanes that have a strength of Category 3 and less, and (b) those Category 4 and 5 hurricanes.

The main contributions of this paper are as follows: This paper utilizes a novel two-step methodology composed of *r*-interdiction and *p*-median models in order to identify the most critical shelters and the best options for repurposing existing shelters in the case of their interdiction. No previous work has combined these optimization approaches in this way, with the intent of improving hurricane shelter planning and response, which would make our work new to the literature. The viability of our approach is demonstrated in a case study application in Southeast Florida based on real-world data and distinct demand figures based on different population segments and shelter availabilities. Hurricane strengths are accounted for in addition to the possibility of serving special needs populations.

2. Methodology

This paper develops a two-step modeling framework consisting of enhanced *r*-interdiction median models (RIM) to identify the most significant shelter(s) and revised *p*-median models to identify shelters to repurpose during such an interdiction where shelters are rendered offline. Thus, a two-step deterministic spatial mathematical model is proposed. Since the first step is to identify the critical shelters, *r*-interdiction median (RIM) models are utilized. In the second step, on the other hand, given the problem of identification of critical shelters, alternative shelters are determined by *p*-median models. A conceptual representation of this two-step model is given in Fig. 1. In the following sections, descriptions of the proposed *r*-interdiction and *p*-median models are presented in detail.

2.1. First step: the r-interdiction median (RIM) problem

In the literature, *p*-median models have frequently been used as spatial optimization techniques. The *p*-median formulation, when applied in the sheltering context, would involve selection of *p* uncapacitated shelters from a set of available shelters, in such a manner that the total demand-weighted travel cost (i.e., travel distance or travel time) of supplying each demand point from those *p* shelters is the minimum. Therefore, the idea is to find the set of *p* shelters that can serve all the population demand most efficiently based on the weighted travel cost, which represents the sum of all population demand and shelter interactions. At the optimum solution of the *p*-median model, each population block group may or may not be assigned to its closest shelter alternative in the whole network (but assigned to the closest one in the solution set); however, the system-wide summation is the minimum of all alternative solutions. If *p* is equal to the number of all available shelters in the network, the problem simply becomes finding the closest shelter to each demand point. Moreover, it is possible to revise the *p*-median formulation for cases where shelters are capacitated [21].

While the *p*-median problem focuses on minimization of the demand weighted travel cost, the *r*-interdiction median problem (RIM) aims to select the most important *r* facilities among the existing ones such that

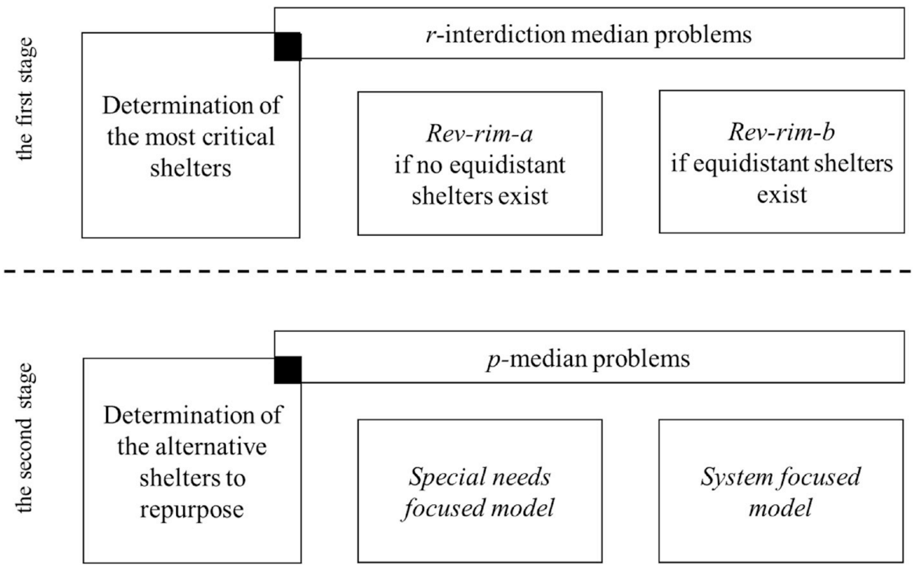


Fig. 1. Conceptual representation of the proposed two-step modeling framework.

the system will be affected most negatively when those r shelters are interdicted [23]. In the shelter management context, the r-interdiction median problem is based on the assignment of the population demand to the available shelters. Each shelter with an assigned demand is subject to interdiction (elimination). Population demand assigned to an interdicted shelter must be assigned to a farther shelter, which will increase the total demand-weighted distance. Since there is no capacity constraint, each demand point is assigned to the closest shelter based on the travel time. The r-interdiction median model can be mathematically expressed as follows [41]:

$$Maximize \sum_{i\in N}\sum_{j\in F} P_i d_{ij} x_{ij} \tag{1a}$$

subject to

$$\sum_{j\in F} x_{ij} = 1 \qquad \forall \ i \in N \tag{1b}$$

$$\sum_{j\in F} y_j = r \tag{1c}$$

$$\sum_{k\in T_{ij}} x_{ik} \le y_j \qquad \forall i \in N, \forall j \in F \tag{1d}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in N, \forall j \in F \tag{1e}$$

$$y_j \in \{0,1\} \qquad \forall j \in F \tag{1f}$$

where the notation is as follows:

Indices:

i for demand points
j, k for existing shelters

Sets:

N for demand points i
F for existing shelters j, k
$T_{ij} = \{k \in F | k \neq j \ \ and \ \ d_{ik} > d_{ij}\}$, for the set of existing shelters (excluding j) that are located farther than j is from demand point i

Parameters:

P_i = demand at the demand point i
d_{ij} = the minimum travel cost between demand point i and shelter j
r = the number of shelters to be interdicted

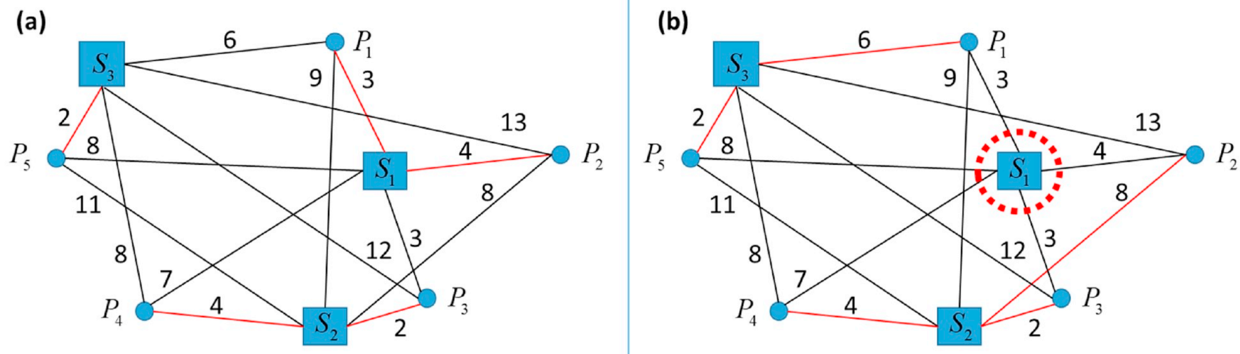
Decision variables:

$$x_{ij} = \begin{cases} 1, & \text{if demand point } i \text{ is assigned to shelter } j \\ 0, & \text{otherwise} \end{cases}$$

$$y_j = \begin{cases} 1, & \text{if shelter } j \text{ is interdicted} \\ 0, & \text{otherwise} \end{cases}$$

In this model, the objective function (1a) maximizes the overall weighted travel cost between demand points and remaining shelter locations after the interdiction of r shelters. Equation (1b) guarantees that each demand point is assigned to a single shelter whereas Equation (1c) ensures the number of interdicted shelters is equal to r. The most important change within the RIM formulation with respect to a regular p-median formulation is due to Equation (1d). According to the p-median formulation, each demand point i must be assigned to the closest shelter j considering a given solution set of p shelters. In the RIM model, demand points should be assigned to the farthest available shelters due to the objective function based on the maximization. However, due to Equation (1d), we ensure that a demand point i is assigned to the closest shelter j if shelter j is not interdicted, or to the next closest shelter, k if the closest shelter j is interdicted. Equation (1d) simply prevents any assignment of the demand point i to a shelter farther than the distance between shelter j is and demand point i unless shelter j is interdicted. Hence, demand point i has to be assigned to the closest non-interdicted shelter. Equation (1e) and Equation (1f) are integrality restrictions on the decision variables.

To clarify the model, a hypothetical network is given in Fig. 2. In this network, there are 3 uncapacitated shelters and 5 demand points. For simplicity, it is assumed that the demand of each demand point is equal to 1. Therefore, the distance between a demand point and a shelter (the numbers on the arcs) is the cost of assigning that demand point to this specific shelter. Another assumption is that only one shelter will be interdicted ($r = 1$). In part (a), no interdiction case is depicted. Therefore, each demand point is assigned to the closest shelter (the assignments are shown in red). For example, demand point 1 (P_1) is assigned to the shelter 1 (S_1) with a cost of 3 distance units. The total assignment cost of this initial case is 15 distance units. Moreover, the individual assignment costs of each demand point and the total cost of assignment



(a)

Interdicted Shelter	Demand Points					Total Cost
	P1	P2	P3	P4	P5	
None	3	4	2	4	2	15
S1	6	8	2	4	2	22
S2	3	4	3	7	2	19
S3	3	4	2	4	8	21

(b)

Interdicted Shelter	Demand Points					Total Cost
	P1	P2	P3	P4	P5	
None	3	4	2	4	2	15
S1	6	8	2	4	2	22
S2	3	4	3	7	2	19
S3	3	4	2	4	8	21

Fig. 2. A hypothetical network depicting the *r*-interdiction problem (when $r = 1$).

under each interdiction case are given. Accordingly, the maximum cost (22 distance units) is incurred when S_1 is interdicted, which is depicted in part (b). In this case, since S_1 is interdicted, P_1 and P_2 are assigned to farther shelters than those that were initially assigned. The increase in total assignment cost is the largest of all possible interdiction alternatives (S_1, S_2, and S_3). Since the maximum cost is due when S_1 is interdicted, it is the most critical shelter in the network based only on the cost.

2.1.1. Revised r-interdiction median models

Since the *r*-interdiction median model presented above is an NP-hard integer problem, it may not be possible to solve larger problems in reasonable computation times. Moreover, the original formulation is valid for the cases where travel costs between a specific demand point and the respective destination shelters are different. To elaborate on the latter issue, given the generalized and aggregate nature of demand points as they are represented in GIS, it is possible that there could be multiple shelter buildings at the same demand point. In this way, one could imagine one building on a particular site being interdicted and no longer functioning as a shelter, while other buildings on the site remained on-line and operational. Moreover, due to the aggregation inherent to the demand points, the traditional model would see these buildings at the same location and would not be able to account for this subtle reality. Some of these related issues are discussed in Ref. [42]. Moreover, although not being at close proximity, some shelters would be almost at the same distance to a demand point. In order to overcome these limitations and in turn better represent the reality of a possible modeling scenario, this paper proposes two revised formulations based on the original RIM problem.

2.1.1.1. Rev-rim-a. Through this revised formulation, the number of constraints and variables are decreased without changing the main structure of the original formulation presented as (1a)-(1f), where the indices, parameters and decision variables are the same. However, there are new sets as follows:

$$Maximize \sum_{i \in N} \sum_{j \in F_i^{+1}} P_i d_{ij} x_{ij} \tag{2a}$$

subject to

$$\sum_{j \in F_i^{+1}} x_{ij} = 1 \qquad \forall \ i \in N \tag{2b}$$

$$\sum_{j \in F} y_j = r \tag{2c}$$

$$\sum_{k \in T_{ij}} x_{ik} \le y_j \qquad \forall i \in N, \forall j \in F_i \tag{2d}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in N, \forall j \in F_i^{+1} \tag{2e}$$

$$y_j \in \{0,1\} \qquad \forall j \in F \tag{2f}$$

where the revised notation of sets is as follows:

Sets:

F_i for the set of *r* closest shelters to population block *i*

F_i^{+1} for the set of $r+1$ closest shelters to population block *i*

Equations (2a)-(2f) are the same as (1a)-(1f) in concept; however, the domains are different. This formulation depends on the structure of the model. Since the objective function is of maximization type and there are no imposed shelter capacities, the model should assign each demand point to the farthest shelter; however, Equation (1d) imposes those assignments to be done to the closest non-interdicted shelters. As such, it is for sure that at most $r+1$ shelter alternatives are required for each demand point. This is since, for some demand points, all of the *r* interdicted shelters could be the closest shelters to them in the worst-case scenario. Thus, rather than considering all shelters as alternatives for each demand point, it is sufficient to use a subset for each demand point. Although this requires a preprocessing (sorting shelter distances/travel times for each demand point), this is also required for the original formulation for obtaining the set T_{ij} for each demand point *i* and shelter *j* in Equation (1d). In Equations (2a), (2b) and (2e), F_i^{+1} is used as the domain because this set has all the required alternatives for each demand point i. In Equation (2d), rather than formulating for all shelter alternatives, formulating for r closest alternatives (F_i) is sufficient. This is since the model will automatically assign that demand point to the r+1st alternative, when considered with other sets of equations, if all r closest shelters for a demand point i are interdicted.

2.1.1.2. Rev-rim-b. Through the second revised formulation, the model could handle the cases where some shelters are equally distanced from some demand points. This may happen due to the co-location and iso-distance issues described above where a given demand point contains multiple physical shelters that can be defined differently. We refer to these as 'equal distance' cases because one building on a particular site can be interdicted and no longer function as a shelter, while other buildings on the site remained on-line and operational. In this formulation, the same indices, parameters and decision variables are used along with the introduction of a new set of constraints as well as several changes in set definitions. The formulation is as follows:

$$Maximize \sum_{i \in N} \sum_{j \in F_i^{+1}} P_i d_{ij} x_{ij} \tag{2g}$$

subject to

(2b), (2c), (2e), (2f) and

$$x_{ij} + y_j \leq 1 \quad \forall i \in N, \forall j \in F_i^{+1} \tag{2h}$$

$$\sum_{k \in T'_{ij}} x_{ik} \leq y_j \quad \forall i \in N, \forall j \in F_i \tag{2i}$$

Sets:

$T'_{ij} = \{k \in F | k \neq j \text{ and } d_{ik} \geq d_{ij}\}$, for the set of existing shelters (excluding j) that are as far as or farther than j is from demand point i

In order to come up with solutions for those equal-distance cases, Equation (2h) is introduced to the formulation. Equation (2h) ensures that, if a shelter is interdicted, there should be no assignments to that specific shelter. In the original model, this is intuitively done by the objective function (1a) and Equation (1d) by equating all alternative assignments to zero if the closest shelter is not interdicted. However, it is required that the shelters are distanced differently for each demand point (this is also the case in rev-rim-a). When equally distanced shelters exist, the original model may not be able to make the least cost assignment (when $r > 1$). Therefore, it is a must to construct the direct relationship between the specific assignment variables and interdiction variables (x_{ij} and y_j). In addition to the introduction of Equation (2h), preferences for equal-distance cases should be specified a priori since they are required for sorting the shelters in an ascending distance order for each demand point and are also used to construct Equation (2i).

Revised models improve the original formulation in two aspects: (a) revised formulations rev-rim-a and rev-rim-b require a smaller number of variables and constraints than the original formulation (Note: Revised formulations require heuristic algorithms for larger problems similar to the original formulation. For a complete enumeration, $\binom{F}{r}$ problems should be solved, which will be impossible to perform for larger sets), and (b) rev-rim-b model could provide solutions for the cases in which there are equally distanced shelters for some demand points, which is not the case in the original formulation.

After identifying the most critical shelters in the first step, it is of utmost importance to determine those alternative regular shelters that could be repurposed as SpNS in case those critical shelters are interdicted. For this purpose, in the next section, p-median models are presented in order to select the best alternative shelters to repurpose as SpNS considering both special needs populations and the whole population.

2.2. Second step: the p-median problem and a case of shelter repurposing

The previous section presented r-interdiction median models to identify the most critical shelter(s). Emergency agencies can use the result of these types of analyses to fortify these critical shelters since their efficient functioning during a hurricane is vital. However, the proposed RIM models have the following simplifying assumptions: (a) the selection is just based on demand-weighted cost (e.g., travel distance, travel time), (b) the whole roadway network is assumed to be available for evacuation, and (c) no-partial assignments are available which is meaningful in a system consisting of shelters with unlimited capacities. Although this uncapacitated shelter assumption is arguably limiting, capacity-based implementations for r-interdiction median model are beyond the scope of this paper. Rather, this study focuses on identifying those critical shelters based on the travel cost.

On the other hand, an important question that this paper addresses is as follows: What will happen if one of these critical shelters is interdicted for any reason? Expert interviews with Bay County Emergency Operations personnel in Panama City Florida indicated that some shelters have become inhabitable due to disruptions such as roof failures and lack of generators [43]. As such, it was extremely critical to identify those shelters that could be utilized once particular shelters failed. The experiences in Bay County during Hurricane Michael showed that emergency managers should address this issue by having contingency plans in terms of utilizing and/or repurposing existing shelters. Another possibility is that the demand for shelter space and service would be more than expected, and some shelters would operate at full capacity and may not accept last minute victims. Further complicating the issue in the special needs shelters, unregistered evacuees and people who do not require special needs (e.g., elderly populations that may function without assistance in their daily lives) may also require special assistance in addition to the already registered people. This indicates the need to have sufficient special needs shelters to serve the needs of these at-risk populations [13]. Repurposing a regular shelter as special needs or pet-friendly shelter, therefore, would have been a necessary response in those circumstances as per Hurricane Irma [44].

For this purpose, a modified version of the p-median model is utilized in this paper. The aim is to optimally locate that shelter whose conversion to a special needs shelter would be the most beneficial for people when a special needs shelter is interdicted. In this way, we can think of this model as a means of adding back into the system, the best possible shelter location given a previous interdiction. The optimum solution is simply the least cost conversion alternative as opposed to the maximum cost one in the r-interdiction median model, and there are two alternative optimality definitions in this paper: i) Special needs-focused optimum, and ii) System-focused optimum.

2.2.1. Shelter repurposing alternative 1: special needs focused optimum

Under this alternative, the minimization of special needs-wide costs is the main consideration for the conversion of regular shelters into SpNS. That is, if one or more SpNS interdictions happen, n regular shelters are repurposed as SpNS, which minimizes the weighted travel cost of assignments of special needs demand to the new set of SpNSs. The mathematical formulation is as follows:

$$Minimize \sum_{i \in N} \sum_{j \in K \cup M} P_i d_{ij} x_{ij} \tag{3a}$$

subject to

$$\sum_{j \in K \cup M} x_{ij} = 1 \quad \forall \; i \in N \tag{3b}$$

$$x_{ij} \leq Y_j \quad \forall \; i \in N, \forall j \in K \cup M \tag{3c}$$

$$\sum_{j\in M} Y_j = m \tag{3d}$$

$$\sum_{j\in K} Y_j = n \tag{3e}$$

$$x_{ij} \in \{0,1\} \qquad \forall i\in N, \forall j \in K\cup M \tag{3f}$$

$$Y_j \in \{0,1\} \qquad \forall j \in K\cup M \tag{3g}$$

where the notation is as follows:

Indices:

i for demand points
j for existing shelters

Sets:

N for demand points *i*
K for existing regular shelters
M for remaining SpNSs after interdiction

Parameters:

P_i = SpNS demand at demand point *i*
d_{ij} = the minimum travel cost between demand point *i* and shelter *j*
m = number of remaining SpNSs
n = number of regular shelters to be repurposed as SpNS

Decision variables:

$$x_{ij} = \begin{cases} 1, & \text{if demand point } i \text{ is assigned to shelter } j \\ 0, & \text{otherwise} \end{cases}$$

$$Y_j = \begin{cases} 1, & \text{if shelter } j \text{ is an open SpNS} \\ 0, & \text{otherwise} \end{cases}$$

In this setting, it is assumed that there are *p* SpNSs and *k* regular shelters initially. When *r* of those *p* SpNSs are interdicted, there remains *m* shelters (*m* = *p*-*r*). Thus, the formulation tries to find those *n* regular shelters to be repurposed as SpNS. The objective function (3a) minimizes the demand-weighted travel cost for the assignments of SpNS demand. Equation (3b) ensures that each demand point is assigned to a single shelter within the extended set of all shelters whereas Equation (3c) ensures that there will not be any assignments to a shelter if that shelter is not dedicated to special needs populations (including the ones to be repurposed). Equation (3d) guarantees that the total number of SpNSs remaining from their initial set is equal to *m* while Equation (3e) guarantees the total number of shelters to be repurposed is *n*. Equations (3f) and (3g) are the integrality restrictions.

This alternative could be considered myopic since the focus is optimizing special needs populations' sheltering. Therefore, an extended version is presented in the next section.

2.2.2. Shelter repurposing alternative 2: system-focused optimum

Under this alternative, the minimization of system-wide costs is the main consideration for the conversion of regular shelters into SpNS. Therefore, this model tries to minimize the cost of overall assignments (both the regular and special needs assignments). The mathematical formulation of this extended shelter-repurposing problem is as follows:

$$\textit{Minimize} \quad \sum_{i\in N}\sum_{j\in K\cup M} P_i^S d_{ij} x_{ij}^S + \sum_{i\in N}\sum_{j\in K} P_i^R d_{ij} x_{ij}^R \tag{3h}$$

subject to

$$\sum_{j\in K\cup M} x_{ij}^S = 1 \qquad \forall \; i\in N \tag{3i}$$

$$\sum_{j\in K} x_{ij}^R = 1 \qquad \forall \; i\in N \tag{3j}$$

$$x_{ij}^S \le Y_j^S \quad \forall \; i\in N, \forall j\in K\cup M \tag{3k}$$

$$x_{ij}^R \le Y_j^R \quad \forall \; i\in N, \forall j\in K \tag{3l}$$

$$Y_j^S + Y_j^R = 1 \quad \forall \; j\in K \tag{3 m}$$

$$\sum_{j\in M} Y_j^S = m \tag{3n}$$

$$\sum_{j\in K} Y_j^S = n \tag{3o}$$

$$\sum_{j\in K} Y_j^R = k - n \tag{3p}$$

$$x_{ij}^S \in \{0,1\} \qquad \forall i\in N, \forall j\in K\cup M \tag{3q}$$

$$x_{ij}^R \in \{0,1\} \qquad \forall i\in N, \forall j\in K \tag{3r}$$

$$Y_j^S \in \{0,1\} \qquad \forall j\in K\cup M \tag{3s}$$

$$Y_j^R \in \{0,1\} \qquad \forall j\in K \tag{3t}$$

where the notation is as follows:

Indices:

S for special needs
R for regular needs

Parameters:

P_i^S = SpNS demand at demand point *i*
P_i^R = regular shelter demand at demand point *i*
k = number of regular shelters before conversion

Decision variables:

$$x_{ij}^S = \begin{cases} 1, & \text{if demand point } i \text{ is assigned to SpNS } j \\ 0, & \text{otherwise} \end{cases}$$

$$x_{ij}^R = \begin{cases} 1, & \text{if demand point } i \text{ is assigned to regular shelter } j \\ 0, & \text{otherwise} \end{cases}$$

$$Y_j^S = \begin{cases} 1, & \text{if shelter } j \text{ is an open SpNS} \\ 0, & \text{otherwise} \end{cases}$$

$$Y_j^R = \begin{cases} 1, & \text{if shelter } j \text{ is an open regular shelter} \\ 0, & \text{otherwise} \end{cases}$$

Here, the objective function (3h) minimizes the total demand weighted travel cost. It is comprised of two parts. The first part is the summation of regular demand assignment costs, and the second part is the summation of special needs demand assignment costs. Equations (3i) and (3j) ensure that each demand point will be assigned to a single shelter, SpNS and regular shelter, respectively. Equation (3k) and (3l) ensure that a demand point could only be assigned to a shelter if that shelter is open. Equation (3 m) ensures that a shelter could only serve either as a regular shelter or as an SpNS. This is included for the regular shelters only since only regular shelters are subject to conversion. Equations (3n) and (3p) control the number of shelters kept open as SpNS and regular, respectively whereas Equation (3°) represents the number of regular shelters to be repurposed. Equation (3q)-(3t) are the integrality restrictions on decision variables.

3. Study area, data, and assumptions

3.1. Study area

Developed models are demonstrated for their efficacy via a case study application including two counties located in southeastern Florida –Broward and Miami-Dade- where approximately 4.65 million (Broward with 1,91 million and Miami-Dade with 2.74 million) residents are spread over the counties based on the 2016 American Community Survey estimations (Fig. 3a). Hurricane Irma seriously affected these two counties, and shelter management emerged as an issue of concern, especially for the special needs and other vulnerable populations such as seniors and minors [2]. However, not all the areas within those two counties are used in the numerical analyses, and the focus is rather on the most vulnerable areas. Therefore, storm surge zones are used to identify those hurricane-prone areas (Fig. 3b and c). Note also that there are five strength categories for hurricanes, ranging from 1 to 5, 5 being the highest level. According to this hurricane severity, hurricane prone areas (those areas that need to be evacuated) and the shelters that can withstand that severity also change. That is, for each scenario we develop below, the shelter set is different since some shelters cannot be utilized due to the flooding, storm surge and wind risk that may affect them at higher hurricane intensities.

3.2. Data

In order to capture the impact of hurricane strength on the identification of the most critical shelter(s) (the first-step) and identify those regular shelters to be repurposed as SpNS (the second-step), two general cases are generated (Table 1): Case 1 and Case 2. Note that we also include the base case, Case 0, which considers all population block groups and shelters without paying attention to hurricane categories. In both steps and cases, the cost of assignment of a population block group to a shelter is the demand weighted travel cost, such that the number of people in that population block group is multiplied by the travel time from that population block group to the specified shelter. This means that there are two factors determining the assignment cost: the demand to be assigned, and the travel cost.

For the first factor, demand, it is not possible to estimate the exact number of people who will need sheltering. Registries may fall in short, some unregistered people may require sheltering and health conditions of elder people could easily deteriorate so that they may require special assistance. As such, the distribution of five different population segments are used as proxies for demand estimates: total population, population over the age of 85 (85+), over the age of 65 (65+), under the age of 5 (5-), and under the age of 18 (18-). Although the exact demand figures would not be the same, the aim here is to identify the most critical shelters under the studied demand scenarios to examine the changes in the model results. Rather than trying to grasp the exact numbers, the idea is to use the distribution of population segments as approximations for purposes of demonstrating our approach. For example, the oldest-old (85+) population is the group that would most probably require sheltering. Therefore, the distribution of the people over 85 can be used to approximate the SpNS demand during the analyses. In Case 1, hurricanes of up to category 3 are considered whereas hurricanes of category 4 and category 5 are considered in Case 2. The worst-case scenario assumed for the severity under Case 1 is of category 3, and in Case 2 it is of category 5. Thus, the storm surge zone of Case 1 contains the storm surge zone of category 3 (which includes both category 1 and category 2 surge zones) whereas Case 2 contains the storm surge zone of category 5 (which covers all other lower category surge zones). Then, the population block groups that remain under respective surge zones are distributed into these two cases (Fig. 3b and c). Moreover, shelters are also classified according to their stated endurance (category 3 or category 5) and designation (regular shelter or SpNS) (Fig. 4a and Fig. 4b).

For the second factor, travel cost, each demand point and shelter pair has a specific unit travel cost for all settings; however, there could be differences in the minimum travel cost for each population block between Case 1 and Case 2 since there are different number of shelters. Since the assignments are performed to the closest available shelter, the travel cost variation among cases is very important for the results. For the travel cost estimates, the free flow travel times between the origins (population block group centroids) and destinations (shelters) have been

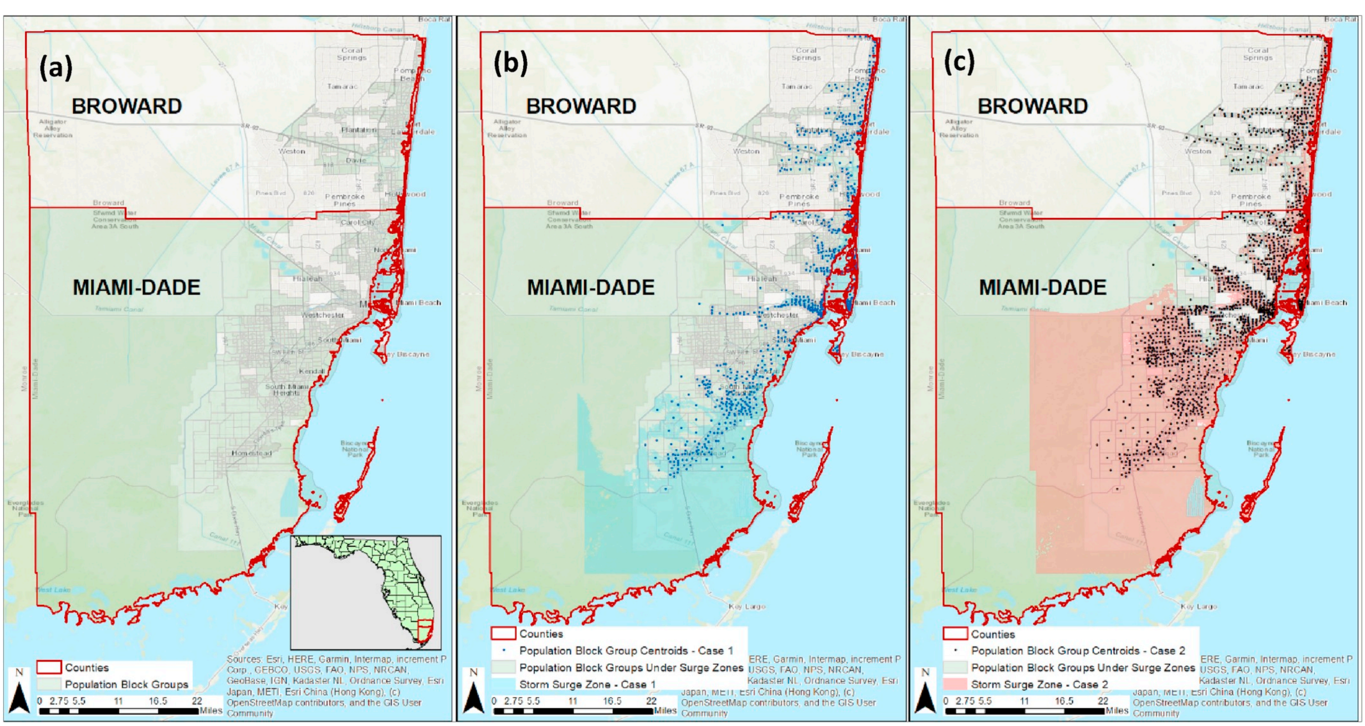


Fig. 3. Study area: (a) Counties, (b) Population block groups in Case 1 (c) Population block groups in Case 2.

Table 1
Distribution of population block groups and shelters under different cases.

	Broward			Miami-Dade			Total (Broward + Miami-Dade)		
	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2	Case 0	Case 1	Case 2
# of pop. block groups	940	217	327	1594	651	1197	2534	868	1524
Total pop.	1,917,122	342,245	529,163	2,736,543	1,019,168	1,966,776	4,653,665	1,361,413	2,495,939
85 + pop.	44,135	11,481	15,984	58,572	21,542	43,759	102,707	33,023	59,743
65 + pop.	286,498	72,656	101,217	406,136	147,521	298,292	692,634	220,177	399,509
5- pop.	108,879	15,769	27,708	154,857	62,384	115,465	263,736	78,153	143,173
18- pop.	402,548	54,045	92,753	548,990	218,325	402,522	951,538	272,370	495,275
# of shelters	47	47	40	103	103	46	150	150	86
All	47	47	40	103	103	46	150	150	86
Regular	42	42	35	95	95	41	137	137	76
SpNS	5	5	5	8	8	5	13	13	10

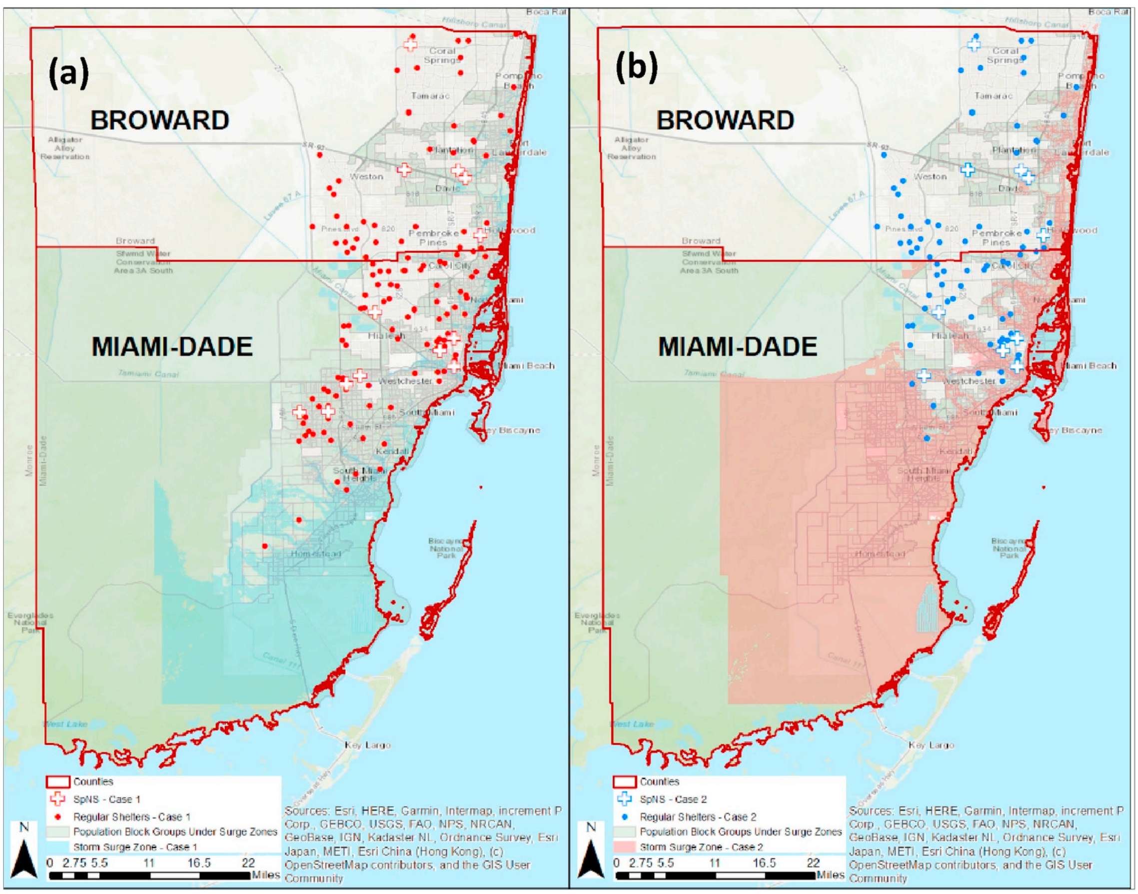


Fig. 4. Distribution of regular shelters and SpNSs in (a) Case 1, and (b) Case 2.

used. In order to obtain those travel times, the Florida Statewide Network model (FSUTMS) is used by generating an OD (origin-destination) cost matrix in ArcGIS network analyst tool [45]. The data for storm surge zones is gathered from the Florida Geographical Data Portal, data for shelters is gathered from the Department of Homeland Security, and demographics data for population block groups is gathered from the Florida Geographic Data Library [46–48]. For solving the optimization problems created, CPLEX 12.6 commercial solver is used on a computer with an Intel i5-2320 (3.00 GHz) processor and 8 gigabytes RAM. In the following section, the assumptions of the problem settings are stated.

3.3. Assumptions

The following list presents the assumptions related to the data preparation and problem solving stages:

i. Each population block group can be assigned to any shelter. For example, a population block group in Miami-Dade County can be assigned to a shelter in Broward County, thus there are no limitations on cross-county assignments, which was a formerly studied topic [21].
ii. Regular and special needs shelter demands are assumed to be of the population block groups under specified surge zones. For the *r*-interdiction problems, the assumed demand distribution has a specific meaning under each problem set. For example, when the demand distribution of total population is used for determining *r*-critical regular shelters, it is assumed that the demand for regular shelters is approximated by the distribution of the total population. Moreover, for the shelter repurposing problems, each population block group may have both regular and special needs shelter demand.

iii. Population block groups with no population are not considered even if they are within the surge zones.
iv. There are no capacity limitations for the shelters in both *r*-interdiction and shelter repurposing problems.
v. Shelters with an evacuation capacity of less than or equal to 1 person are not considered (although there are no capacity restraints, those shelters are assumed to be unavailable).
vi. For the general case scenarios (demand = "ALL"), it is assumed that there is not a shelter categorization of regular or SpNS and the demand amount of each demand point is assumed to be the total of regular and SpNS demand ($P_i = P_i^R + P_i^S$).
vii. For shelter repurposing, it is assumed that any regular shelter could be transformed into SpNS; however, hurricane endurance is considered, so they are different from the Case 1 and Case 2.
viii. Worst case scenarios are considered for both population block groups and shelters as follows:
   a. Block groups are selected by intersecting population block group polygons (not the centroids) with storms surge zone polygons, so even a minimal intersection can cause the selection of that population block.
   b. Category information is assigned with respect to the most severe category of a given population block (i.e., if it is partially under both second and third category storm surge zones, third category is assigned to that population block).
   c. Shelters listed as available for category 1, 2, and 3 are only considered for Case 1 and not considered for category 4 and 5 hurricane strengths, and thus those shelters are not available in Case 2.

4. Results

Results are first presented based on utilizing the *r*-interdiction median models to identify the most critical *r* shelter(s), and second, based on having SpNS interdictions utilizing revised *p*-median models to identify the regular shelters to repurpose as SpNS. Both of these test cases are performed for two distinct hurricane strengths (Case 1 and Case 2).

Results obtained by the *r*-interdiction median models are given in Table 2 when the parameter *r* (the number of shelters to be interdicted) is changed from 1 to 5. For example, when all shelters are assumed to serve all population segments (All pairs), the most important shelter ($r = 1$) is S_{98}. When the two most critical shelters ($r = 2$) are sought, S_{98} and S_{109} are the ones, and the five most important shelters ($r = 5$) for this distribution and shelter setting are S_{98}, S_{109}, S_{39}, S_{45} and S_{110}, respectively (Note: This pattern may not necessarily be in this manner since the most important r+1 shelters may not include the same shelters selected while solving for *r* shelters. For example, for 65 + population for both all and regular scenarios under Case 1, the most critical shelter S_2 ($r = 1$) is not in the list of the most critical two ($r = 2$) shelters).

According to the Case 1 results (when disaster severity is low), those scenarios including all shelters and those that focus on the regular shelters only led to the same critical shelter selection patterns. In other words, the results when SpNSs are dedicated and undedicated are the same. Therefore, none of the SpNSs is in the set of the most critical shelters (up to the most critical five shelters). This is due to (a) the lack of SpNSs compared to the regular shelters (there are 13 available SpNSs that are considered available for Case 1 whereas there are 137 regular shelters in total), (b) the geographic distribution of those shelters, and (c) having no abnormal demand among different population age segments.

There are differences in the selected shelters for different demand segments and the greatest difference is observed for the 85 + population (which is known as the oldest old segment). The selections are also slightly different for the 65 + population; however, not as apparent compared to the 85 + population. Since the same population block groups are used in each setting spatially, the differences are due to the distribution of different population segments (other than the shelters' dedication). The differences in selected shelters are observed in a weaker sense in the SpNS selections. Most of the selections are the same for each setting; however, there is some variance for the 18- and 5- population segments.

For the Case 2 (when disaster severity is high), with the scenarios including all shelters and those focus on regular shelters, results are the same for the first three *r* levels ($r = 1$, $r = 2$ and $r = 3$). When $r = 4$ and $r = 5$, there are differences in the selected shelters between all and regular shelters. For example, in the scenario of 85 + population and $r = 4$, the critical shelters for all-shelter scenario are S_{16}, S_{128}, S_{116} and S_{57} whereas the regular-shelter scenario results include S_{16}, S_{128}, S_{116} and S_{48}. Thus, there is a shift from S_{57} to S_{48}. Although there are differences between scenarios, there are no SpNS identified as critical in the total population scenarios (all are regular shelters). Therefore, in the most severe disaster conditions (where the number of shelters decrease and the number of population block groups under surge zones increase), the selected regular shelters are geographically more critical than the SpNS.

Moreover, all the critical shelters changed from Case 1 to Case 2 since (a) some shelters identified as critical in Case 1 are not available in Case 2, and (b) additional population blocks require sheltering when disaster severity increases. However, the differences in the selected shelters observed in Case 1 for different population segments are not observed in Case 2. All the identified critical shelters are the same for all population segments for all *r* values. This pattern is valid for all the scenarios (All, Regular, and SpNS).

In Fig. 5, those changes in the set of the most critical shelters according to varying demand distributions and shelter categories for some problems are depicted. For Case 1, 85 + population has significantly different results than Total, 5- and 18- population results for both All and Regular shelter categories. For Total, 5- and 18- populations, the most critical shelters are in the south sections of the studied region (S_{98}, S_{109}, and S_{39}) whereas the most critical shelters are S_{56}, S_2 and, S_{51} for the 85 + population which are in the north sections. Accordingly, the distribution of the population segments, which could have conflicting requirements, are critical in shelter planning. In Case 2, as the hurricane severity increases, resulting critical shelters are similar as compared to the low severity case. Moreover, it could be seen that the critical shelters in Case 1 for Total, 5- and 18- populations has shifted slightly to the north since southern shelters are not available for Case 2. In addition, the critical shelters for 85 + population has shifted to the south again because of the unavailable shelters in the south and newly added population block groups. Additionally, the changes in the selection of the most critical special needs shelters for the 65 + population from Case 1 to Case 2 are depicted in Fig. 5. When some SpNSs are not available due to the hurricane severity, shelters' importance changes. Although the most critical shelter in Case 1 (S_{141}) is still available in Case 2, it is not among the most critical three shelters. As seen in Fig. 5, there are additional population block groups in the south and three SpNS shelters that could serve those population groups are not available. Therefore, the closest SpNS to that region (S_{138}) becomes the most critical shelter.

According to the computational results presented in Table 3, there are some generalizable patterns. Firstly, for each setting, as *r* (the number of shelters to be interdicted) increases, objective function value (demand weighted cost of assigning all demand to remaining shelters) strictly increases. For example, for a Case 1 setting in which the 85 + population is assigned to regular shelters, the objective function value increases sequentially as *r* increases in a sequence of 1, 2, 3, 4, and 5 as follows: 225.7, 236.0, 255.5, 263.8, and 273.7 (*10^3 person-miles). This pattern is the same for each setting. This is since it is more costly to assign demand to the remaining shelters as the number of shelters to be interdicted increases (so, not only the number of available shelters decreases but also the most critical ones are eliminated). Secondly, it is more costly to assign the demand to only regular shelters than to all (special needs and regular) shelters. For instance, in a Case 2 setting in

Table 2
Computational results of *r*-interdiction median models.

		r	Shelter ID																								
			Total					85+					65+					5-					18-				
Case 1	All	1	98					56					2					98					98				
		2	98	109				56	2				98	109				98	109				98	109			
		3	98	109	39			56	2	51			98	109	39			98	109	39			98	109	39		
		4	98	109	39	45		56	2	51	54		98	109	39	2		98	109	39	45		98	109	39	45	
		5	98	109	39	45	110	56	2	51	54	25	98	109	2	51	56	98	109	39	45	110	98	109	39	45	110
	Regular	1	98					56					2					98					98				
		2	98	109				56	2				98	109				98	109				98	109			
		3	98	109	39			56	2	51			98	109	39			98	109	39			98	109	39		
		4	98	109	39	45		56	2	51	54		98	109	39	2		98	109	39	45		98	109	39	45	
		5	98	109	39	45	110	56	2	51	54	25	98	109	2	51	56	98	109	39	45	110	98	109	39	45	110
	SpNS	1	141					141					141					141					141				
		2	141	147				141	147				141	147				141	147				141	147			
		3	141	139	142			141	139	142			141	139	142			147	140	143			145	149	150		
		4	141	139	142	148		141	139	142	148		141	139	142	148		147	140	143	141		140	141	143	147	
		5	141	139	142	148	146	141	139	142	148	146	141	139	142	148	144	147	140	143	141	146	140	141	143	147	146
Case 2	All	1	16					16					16					16					16				
		2	16	128				16	128				16	128				16	128				16	128			
		3	16	128	116			16	128	116			16	128	116			16	128	116			16	128	116		
		4	16	128	116	57		16	128	116	57		16	128	116	57		16	128	116	57		16	128	116	57	
		5	16	128	116	33	91	16	128	116	33	91	16	128	116	33	91	16	128	116	33	91	16	128	116	33	91
	Regular	1	16					16					16					16					16				
		2	16	128				16	128				16	128				16	128				16	128			
		3	16	128	116			16	128	116			16	128	116			16	128	116			16	128	116		
		4	16	128	116	48		16	128	116	48		16	128	116	48		16	128	116	48		16	128	116	48	
		5	16	128	116	48	57	16	128	116	48	57	16	128	116	48	57	16	128	116	48	57	16	128	116	48	57
	SpNS	1	138					138					138					138					138				
		2	138	146				138	141				138	141				138	146				138	146			
		3	138	146	142			138	141	146			138	141	146			138	146	140			138	146	140		
		4	138	140	143	147		138	140	143	147		138	140	143	147		138	140	143	147		138	140	143	147	
		5	138	140	143	147	146	138	140	143	147	146	138	140	143	147	146	138	140	143	147	147	138	140	143	147	146

Note: Shelter IDs from 1 to 137 are the regular shelters and 138–150 are SpNSs. In the “all” formulations, there is no shelter dedication.

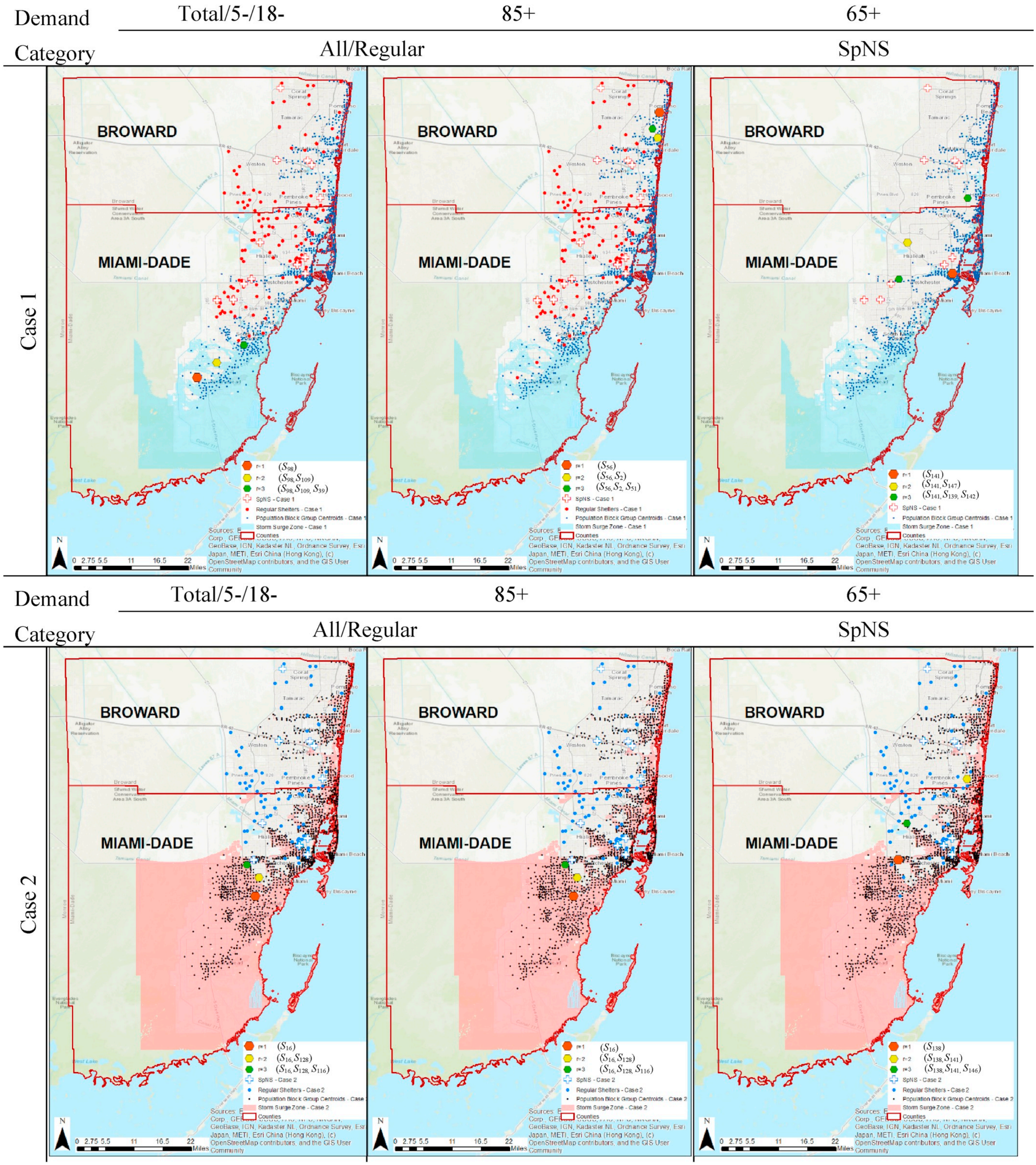


Fig. 5. Some of the most critical shelters for selected demand distributions and shelter categories.

which 65 + population is assigned to regular shelters, the most critical two shelters ($r = 2$) are identified as S_{16} and S_{128}, and the objective function value is 4679.1*10^3 person-miles. On the other hand, in the same setting, the objective function value is 4576.9*10^3 person-miles when demand is assigned to all shelters although the selected shelters are the same (S_{16} and S_{128}). That is, when the number of alternative shelters decreases, the total cost of assigning demand increases. In a similar fashion, it is always more costly to assign all the demand to only special needs shelters than to all shelters. In this case, assigning to only SpNS is also more costly than assigning to only regular shelters. For instance, in the aforementioned example, the objective function value is 8098.5*10^3 person-miles, which is strictly greater than the other two objective function values. Thirdly, in each setting, CPU time increases generally (140 of 150 instances) as the number of shelters to be interdicted (r) increases. For example, for a Case 1 setting in which 18- population is assigned to regular shelters, the CPU time increases

Table 3
Objective function values and computational times of *r*-interdiction median models.

		r	Total		85+		65+		5-		18-	
			Objective value (*10ˆ3 person-miles)	CPU time (seconds)	Objective value (*10ˆ3 person-miles)	CPU time (seconds)	Objective value (*10ˆ3 person-miles)	CPU time (seconds)	Objective value (*10ˆ3 person-miles)	CPU time (seconds)	Objective value (*10ˆ3 person-miles)	CPU time (seconds)
Case 1	All	1	9176.8	0.01	218.5	0.02	1422.4	0.01	550.9	0.02	1959.8	0.02
		2	10349.9	0.39	228.8	0.25	1535.7	0.39	642.0	0.25	2287.2	0.25
		3	11150.0	0.48	248.3	0.77	1607.5	0.56	705.4	0.47	2517.9	0.48
		4	11527.1	0.64	256.5	0.50	1658.1	0.67	729.1	0.66	2604.6	0.72
		5	12016.6	1.06	264.0	0.69	1769.8	0.74	765.5	0.84	2735.6	1.06
	Regular	1	9504.09	0.00	225.7	0.02	1472.9	0.00	570.0	0.01	2017.2	0.02
		2	10677.0	0.22	236.0	0.24	1586.2	0.25	661.0	0.23	2344.7	0.27
		3	11477.2	0.42	255.5	0.45	1658.0	0.53	724.4	0.44	2575.3	0.58
		4	11854.2	0.86	263.8	0.69	1708.6	0.86	748.2	0.72	2662.0	1.08
		5	12343.7	1.27	273.7	0.75	1820.3	0.80	784.6	1.25	2793.1	1.48
	SpNS	1	25042.5	0.13	603.7	0.02	4049.3	0.01	1488.4	0.02	5400.0	0.02
		2	26157.0	0.66	634.4	0.69	4241.7	0.58	1551.6	0.66	5601.0	0.63
		3	28740.8	0.89	694.1	0.80	4625.6	0.88	1719.4	0.94	6069.2	0.83
		4	31079.1	1.83	773.5	1.17	5165.3	1.14	1834.5	1.52	6428.1	2.11
		5	33796.2	3.42	884.0	1.63	5900.2	1.59	1976.8	2.99	6881.7	3.50
Case 2	All	1	29971.0	0.02	606.7	0.02	4278.6	0.02	1829.4	0.02	6612.6	0.02
		2	32184.0	0.94	649.6	0.86	4576.9	0.84	1969.1	0.84	7135.4	0.95
		3	34514.1	1.31	692.1	1.31	4899.0	1.31	2099.1	1.33	7624.6	1.31
		4	35464.1	1.73	708.5	2.13	5014.3	1.75	2163.0	1.72	7857.1	1.70
		5	36542.4	1.94	748.3	1.88	5258.8	1.88	2203.0	2.30	8001.2	2.34
	Regular	1	30608.1	0.03	622.5	0.02	4380.6	0.02	1866.8	0.02	6726.8	0.02
		2	32822.0	0.81	665.4	0.80	4679.1	0.80	2007.0	0.80	7250.0	0.81
		3	35156.0	1.17	708.0	1.17	5001.8	1.20	2136.8	1.17	7740.2	1.17
		4	37174.7	1.58	764.0	1.56	5360.0	1.63	2225.6	1.58	8086.7	1.56
		5	38310.0	2.27	783.8	3.13	5502.2	2.22	2299.4	2.24	8355.9	2.25
	SpNS	1	49734.9	0.03	1111.6	0.05	7621.4	0.02	2874.1	0.02	10419.1	0.02
		2	51891.6	1.34	1188.5	1.11	8098.5	1.11	3009.6	1.13	10921.5	1.09
		3	54063.4	5.59	1229.5	3.67	8377.9	3.94	3137.2	3.78	11376.9	4.14
		4	63156.2	5.38	1400.0	5.03	9626.9	5.08	3652.3	2.59	12970.8	5.06
		5	90393.1	3.61	1988.3	3.03	13610.6	3.05	5226.5	3.02	18629.5	3.06

sequentially in the following manner, 0.02, 0.63, 0.83, 2.11, and 3.5 s as *r* increases in a sequence of 1, 2, 3, 4, and 5 (Note: All of the cases are solved in less than 6 s).

Table 4 shows the results obtained by the revised *p*-median models when the parameter *r* is changed from 1 to 3. In this scenario, the regular shelters that should be repurposed as SpNS are decided based on the critical shelter identifications from the first-step (*r*-interdiction median model solutions presented in Table 2). The number of shelters to repurpose is changed from 1 to 3 similar to the number of shelters to be interdicted. Therefore, in a setting if the number of interdicted shelters is 1 ($r = 1$), a single regular shelter is selected for repurposing as SpNS. If the number of interdicted shelters is 2 ($r = 2$), both the problems in which a single shelter is repurposed and two shelters are repurposed as SpNS are solved. Finally, if the number of interdicted shelters is 3 ($r = 3$), the problems of repurposing a single shelter, two shelters, and three shelters are all solved. Other than the hurricane severity (Case 1 and Case 2), there are two main scenarios studied: special needs-focused (in which only the demand weighted cost of SpNS assignment is minimized), and system-focused (in which cost of both regular and SpNS assignments are minimized). For this focus, demand data is paired with total population by four other population distributions (85+, 65+, 5- and 18-). For example, when 85 + population is used as the demand distribution of SpNS, the regular shelter demand is assumed to be the difference between the total population and 85 + population for each population block (total population – 85 + population).

Based on the Case 1 results, there are differences in repurposed shelters according to different demand segments. This is due to the variations in identifying the *r*-interdiction median model solutions and differences among demand distributions. For example, under the special needs-focused scenario, when the interdicted SpNS is S_{141}, the regular shelter to be repurposed is S_{135} and S_{39}, under 85 + population and total– 85 + population pair and 65 + population and total– 65 + population pair, respectively. The most critical three shelters for 65 + population (when it is assumed as the SpNS demand distribution) are S_{139}, S_{141}, and S_{142}, and the regular shelter to be repurposed is S_2. While this is different when all 5- population is assumed to have special needs, the three critical shelters are S_{140}, S_{143} and S_{147}, and the shelter to be repurposed is S_{109}. Moreover, although the critical shelters of each population distribution for both special needs-focused and system-focused scenarios are the same, the selected shelters for repurposing are different, except for 18- population, in which the identified shelter S_{39} is the same for repurposing in both scenarios.

When Case 2 results are considered, all the special needs-focused scenarios yielded the same solution as $S_{16.}$ This is because the number of shelters decreases due to unavailability of many shelters under Case 2, and S_{16} becomes the next best alternative for the special needs demand under all demand patterns. This consistency cannot be observed when the overall system is the focus. For each demand scenario, the selected shelter is the same (except for the 65 + demand scenario); however, it varies by one demand scenario to the other. For example, the shelter to be repurposed is S_{40} for 85 + population and it is S_{57} for 5- population for all three interdiction cases.

In Fig. 6, the interdicted SpNS and repurposed regular shelter pair examples are given when both special needs-focused and system-focused models are solved. The comparison of those pairs of 85 + population in Case 1 is exemplified when three SpNS shelters are interdicted. On the graphs, the selection of one, two, and three regular shelters to repurpose under different foci could be observed. Those two different foci of models yielded totally different results. However, the results under both foci yielded a similar pattern. For instance, the first shelter selected is at the northern section of the region, the second shelter is in the mid-section, and the third one is at the southern section under both foci. Additionally, S_2 is selected as one of the regular shelters to repurpose under the special-needs focus; however, this shelter is one of the most

Table 4
Computational results of revised *p*-median models.

Shelter ID – Total – 85+

Case	Focus	n	Interdicted			Repurposed r=1	Repurposed r=2		Repurposed r=3		
Case 1	Special needs-focused	1	141			135					
Case 1	Special needs-focused	2	141	147		135	135	56			
Case 1	Special needs-focused	3	141	139	142	2	2	135	2	39	135
Case 1	System-focused	1	141			74					
Case 1	System-focused	2	141	147		27	27	54			
Case 1	System-focused	3	141	139	142	78	78	74	78	74	16
Case 2	Special needs-focused	1	138			16					
Case 2	Special needs-focused	2	138	141		16	16	51			
Case 2	Special needs-focused	3	138	141	146	16	16	51	16	51	74
Case 2	System-focused	1	138			40					
Case 2	System-focused	2	138	141		40	40	21			
Case 2	System-focused	3	138	141	146	40	40	21	40	21	78

Shelter ID – Total – 65+

Case	Focus	n	Interdicted			Repurposed r=1	Repurposed r=2		Repurposed r=3		
Case 1	Special needs-focused	1	141			39					
Case 1	Special needs-focused	2	141	147		135	135	39			
Case 1	Special needs-focused	3	141	139	142	2	2	39	2	39	135
Case 1	System-focused	1	141			110					
Case 1	System-focused	2	141	147		135	135	110			
Case 1	System-focused	3	141	139	142	51	51	110	51	110	135
Case 2	Special needs-focused	1	138			16					
Case 2	Special needs-focused	2	138	141		16	16	56			
Case 2	Special needs-focused	3	138	141	146	16	8	56	16	56	78
Case 2	System-focused	1	138			116					
Case 2	System-focused	2	138	141		116	74	116			
Case 2	System-focused	3	138	141	146	128	128	74	128	74	56

Shelter ID – Total –5-

Case	Focus	n	Interdicted			Repurposed r=1	Repurposed r=2		Repurposed r=3		
Case 1	Special needs-focused	1	141			109					
Case 1	Special needs-focused	2	141	147		109	109	135			
Case 1	Special needs-focused	3	147	140	143	109	109	134	134	39	98
Case 1	System-focused	1	141			110					
Case 1	System-focused	2	141	147		110	110	67			
Case 1	System-focused	3	147	140	143	110	110	134	110	67	132
Case 2	Special needs-focused	1	138			16					
Case 2	Special needs-focused	2	138	146		16	16	116			
Case 2	Special needs-focused	3	138	146	140	16	16	116	16	116	51
Case 2	System-focused	1	138			57					
Case 2	System-focused	2	138	146		57	57	40			
Case 2	System-focused	3	138	146	140	57	57	40	57	40	78

Shelter ID – Total –18-

Case	Focus	n	Interdicted			Repurposed r=1	Repurposed r=2		Repurposed r=3		
Case 1	Special needs-focused	1	141			39					
Case 1	Special needs-focused	2	141	147		39	39	135			
Case 1	Special needs-focused	3	145	149	150	39	39	98	39	98	2
Case 1	System-focused	1	141			39					
Case 1	System-focused	2	141	147		39	39	67			
Case 1	System-focused	3	145	149	150	39	45	109	45	109	67
Case 2	Special needs-focused	1	138			16					
Case 2	Special needs-focused	2	138	146		16	16	116			
Case 2	Special needs-focused	3	138	146	140	16	16	116	16	116	51
Case 2	System-focused	1	138			128					
Case 2	System-focused	2	138	146		128	128	78			
Case 2	System-focused	3	138	146	140	128	128	75	128	78	40

critical shelters for 85 + population. Thus, under a system-based focus, it is not selected as one of the regular shelters to repurpose.

According to the computational results presented in Table 5, there is a consistent pattern when the number of shelters to repurpose is considered. For all the settings studied (for both Case 1 and Case 2, both special-needs focus and system-focus, all population distributions, and all r values), it is more costly to repurpose a lower number of shelters than the number of shelters to be interdicted. That is, it is less costly (measured in terms of weighted demand assignment cost) to repurpose three regular shelters than to repurpose two regular shelters as SpNS when three SpNS shelters are interdicted. For example, in Case 2, when special needs and regular shelter demands are 5- population and total – 5- population, respectively, and the overall system is considered, total cost of repurposing a single regular shelter is 9788.5*10ˆ3 person-miles, repurposing two regular shelters is 9571.4*10ˆ3 person-miles and repurposing three regular shelters is 9510.5*10ˆ3 person-miles. This pattern is straightforward when the problems with special-needs focus are solved since only the SpNS demand is considered and the critical issue is to decide on those shelters to repurpose, where each additional shelter to repurpose is an additional alternative to decrease the cost of assignment. However, for the system focused solutions, with each additional shelter to repurpose, there will be fewer alternatives for the regular shelter demand. According to the results, the identification of shelters to repurpose are totally different with respect to the focus of the model. When the results in Tables 2 and 4 are compared, it could be seen that the resulting identifications could be in the list of most critical shelters when special-needs focused problems are solved. For example, in Case 2, for the solutions of 5- population and total – 5- population pair, S_{16} is in the list when one, two and three regular shelters are to be repurposed. This shelter is also the most critical shelter for 5- population when it is solved for regular shelters in the first-step of the model. But, rather than S_{16}, S_{57} seem to be the best alternative to repurpose in the same setting with a system-focus. Note that regular demand in both cases are not the same in both problem settings. In the first-step, the stated population (i.e., total population) is assigned to regular shelters whereas, in the second-step, regular shelter demand is obtained by deducting SpNS demand from total population. When overall system is the focus, the number of regular shelters identified as the most critical shelters in the first-step is limited. Therefore, the model shifts the decision from the most critical regular shelters to other regular shelters

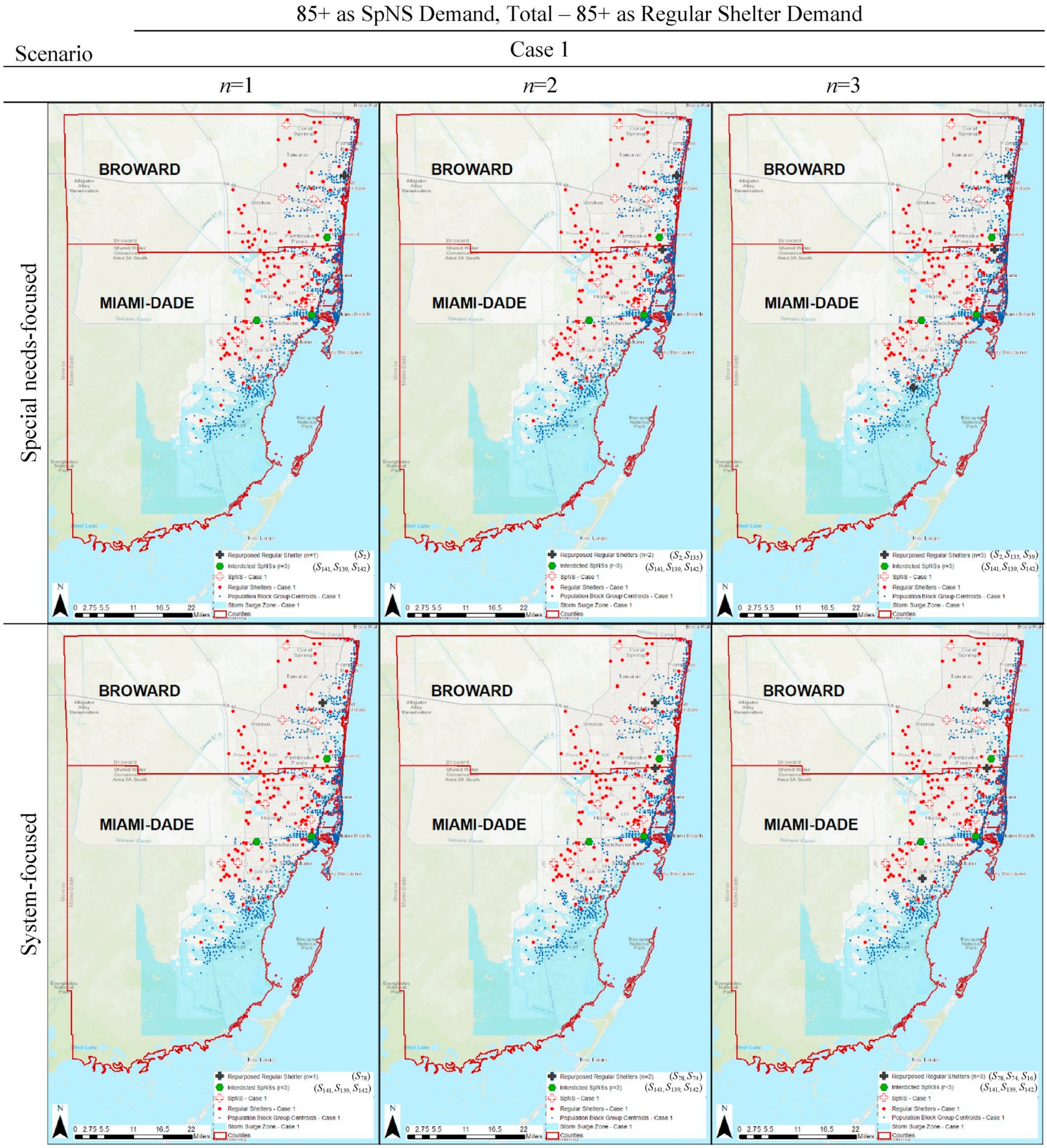


Fig. 6. Depiction of interdicted SpNS and repurposed regular shelter pairs with different foci.

when the focus of the problem is changed from special-needs to system. This leads to better objective function values as the number of regular shelters to repurpose increases.

According to the CPU times, all the problems are solved in less than 23 s, and as expected, system-focused problems take more time to solve (the maximum is 22.98 s) than special-needs focused problems (the maximum is 7.52 s).

5. Discussion

The two-step model developed in this study helps to identify the most critical shelters. As a result, those shelters could be improved or detailed plans could be designed to better protect them. The mathematical models presented in this study try to optimize network problems under changing supply and demand conditions due to the possible variation in hurricane severity. From Case 1 to Case 2, the severity increases. Therefore, it is assumed that the number of available shelters decreases

Table 5
Objective function values and computational times of revised *p*-median models.

			Shelter ID																	
			Total – 85+									Total – 65+								
			Interdicted			Repurposed						Interdicted			Repurposed					
		n				1		2		3					1		2		3	
		r				Obj.	CPU t.	Obj.	CPU t.	Obj.	CPU t.				Obj.	CPU t.	Obj.	CPU t.	Obj.	CPU t.
Case 1	Special needs-focused	1	141			500.0	6.16					141			3378.9	7.02				
		2	141	147		508.0	6.89	417.5	6.36			141	147		3492.4	7.34	2821.9	6.55		
		3	141	139	142	530.2	7.20	419.9	6.39	336.7	6.38	141	139	142	3616.9	7.52	2946.5	6.50	2281.7	6.56
	System-focused	1	141			9249.1	17.97					141			11005.3	19.52				
		2	141	147		9260.7	19.64	9209.1	20.78			141	147		11110.2	21.70	10555.1	21.41		
		3	141	139	142	9282.4	19.59	9209.3	20.58	9162.5	20.58	141	139	142	11244.6	22.41	10689.5	22.92	10135.5	20.47
Case 2	Special needs-focused	1	138			866.8	5.59					138			5771.0	5.27				
		2	138	141		943.7	5.81	839.8	5.44			138	141		6248.1	6.28	5676.2	5.78		
		3	138	141	146	956.2	5.94	852.3	5.75	772.8	5.70	138	141	146	6328.5	6.27	5756.5	6.08	5242.5	5.86
	System-focused	1	138			26418.6	14.80					138			28730.1	16.25				
		2	138	141		26495.5	16.69	26429.2	16.36			138	141		29207.2	18.11	28758.9	18.69		
		3	138	141	146	26530.7	17.44	26464.4	17.00	26404.3	17.66	138	141	146	29286.0	18.53	28835.4	18.25	28451.3	20.58

			Total –5-									Total –18-								
			Interdicted			Repurposed						Interdicted			Repurposed					
		n				1		2		3					1		2		3	
		r				Obj.	CPU t.	Obj.	CPU t.	Obj.	CPU t.				Obj.	CPU t.	Obj.	CPU t.	Obj.	CPU t.
Case 1	Special needs-focused	1	141			1025.2	6.67					141			3704.2	5.86				
		2	141	147		1088.4	6.66	935.3	6.34			141	147		3914.1	6.78	3375.4	6.59		
		3	147	140	143	1256.2	7.02	996.6	6.50	877.9	6.94	145	149	150	3498.6	6.49	3068.8	6.19	2861.2	6.34
	System-focused	1	141			9560.0	18.30					141			10897.3	19.97				
		2	141	147		9623.2	21.33	9494.9	20.84			141	147		11107.3	20.58	10630.6	20.89		
		3	147	140	143	9788.5	22.98	9571.4	22.22	9510.5	22.19	145	149	150	10691.8	21.53	10488.7	20.30	10323.1	20.80
Case 2	Special needs-focused	1	138			2043.4	5.19					138			7285.7	5.19				
		2	138	146		2063.5	6.06	1931.5	5.48			138	146		7361.5	6.42	6858.3	5.50		
		3	138	146	140	2097.9	6.23	1965.6	5.55	1878.3	5.49	138	146	140	7457.3	6.05	6952.7	5.67	6657.5	5.61
	System-focused	1	138			27099.0	15.81					138			29205.6	15.63				
		2	138	146		27148.0	18.72	27055.5	18.31			138	146		29270.7	17.56	29035.6	16.58		
		3	138	146	140	27167.9	18.13	27075.3	17.95	27000.8	17.02	138	146	140	29362.1	17.67	29127.1	16.63	28972.8	18.98

Note: Objective function values are in 10^3 person-miles, and CPU time in seconds.

while the number of population block groups in need of sheltering increases. Thus, this pattern explains some of differences in results. For example, under the scenario where both regular and special needs shelters are considered with the demand of 65 + population, the most critical shelter is found to be S_2 in Case 1 whereas the selection shifts to S_{16} in Case 2. This is because the number of demand points increases and shelter S_2 is closed. However, there are some shifts even though the most critical shelter identified is not closed in Case 2, such as the regular shelter scenario with the demand of 85 + population, where the most critical shelter changes from S_{56} to S_{16} (Table 2). The result is again due the impact of increased demand and reduced number of shelters.

It is clear that different population distributions could yield different demands and shelter identifications since at the end of the day, the cost minimized is the demand-weighted distance between population block group centroids and shelters. For Case 1, there is a common pattern for population distributions except for the 85 + population. This shows that the distribution of the older adults is different from the 65+, 5-, 18- and total population. Although the demand figures are only approximations of the actual relief need, it is apparent that some population segments would have differing needs. When Case 1 and Case 2 are compared in this respect, almost all shelters in the southern sections of the region are not available, and therefore they are eliminated in Case 2. This creates a huge unavailability of shelters for the population block groups in the south. This is the reason why S_{16} is identified as the most critical shelter under all demand distributions. As such, the impact of distributional difference disappears. In addition, if some demand distributions were so distinct than the others were, different results could have been obtained even under Case 2.

For the second-step shelter repurposing scenarios, the identified shelters vary by the critical shelters selected in the first-step, hurricane severity, demand distribution, the number of shelters available and the focus of the problem (Table 3). Therefore, the results vary significantly. There is a higher level of robustness in the Case 2 solutions (though special needs-focused and system-focused solutions are distinct), which is similar to the *r*-interdiction identifications obtained in the first-step. The only exception for the diverse solutions of the special needs-focused versus system-focused solutions (either in Case 1 or in Case 2) is the set of scenarios with 18- population in Case 1. Shelter S_{39} is selected to be repurposed as an SpNS for both the system-focused and special needs-focused problems and when the number of interdicted shelters is 1, 2, or 3. Although the critical shelters are the same for each population distribution under both special needs-focused and system-focused scenarios, the selected shelters for repurposing are different. For example, in Case 1, for the 65 + population segment, when only S_{141} is interdicted, special needs-focused and system-focused solutions identify S_{39} and S_{110} to be repurposed, respectively.

6. Conclusions and future work

This paper has detailed a two-step modeling framework that utilizes (a) *r*-interdiction median models to identify the most significant shelter (s) with respect to demand-weighted travel cost and the spatial distribution of population groups, and (b) revised *p*-median models to identify shelters to repurpose during such an interdiction where shelters are rendered off-line. A region in the Southeast Florida with two highly populated counties, Broward and Miami-Dade was selected as the study area. Different hurricane strengths, special needs shelters (SpNSs) and regular shelters were used to generate the scenarios. In the models utilized, the origins were the centroids of the U.S. census population block groups and the destinations (accessible facilities) were regular and special needs shelters. Free flow travel times were estimated between the origins (U.S. census population block groups) and destinations (shelters locations). Five different segments of the population were selected for the analyses: total population, 85 + population, 65 + population, 5- population and 18- population. In addition, revised *p*-median models were used to decide on which regular shelters to repurpose as SpNS when one or more SpNS shelters were interdicted.

Findings indicate that the model is more sensitive to population demand differences when the hurricane severity is lower. In the case of more severe hurricanes, the number of population block groups in need of sheltering would increase and the number of available shelters would decrease since they cannot withstand higher strength hurricanes. Thus, some shelters gain importance for serving both the population block groups that are newly added and the ones that are previously served by unavailable shelters in severe conditions.

The study has several limitations to discuss. Firstly, the demand is assumed proportional to some segments of the population. Rather than this assumption, a demand-forecasting model could be used to get more realistic results. From this perspective, stochastic modeling could be adopted. Other than the lack of uncertainty in the model parameters, those types of extensions would require heuristic algorithms to determine the solutions. Thus, in terms of looking at a larger study area, it may not be possible to solve the model with the addition of shelter capacities although a state-wide implementation of the model is possible. Moreover, scenarios under which shelters have capacity constraints could be formulated at a localized study area. In addition, roadway disruptions (i.e., as studied in Refs. [12,13]), could be employed in further studies. Since the aim of this paper is to generate guidance to agencies, these modeling extensions are not considered; however, those could be the topics of upcoming studies. Secondly, the assumption of having no limitations on cross-county assignments is a simplifying one and may not be applicable in practice. In addition, the assumption of having no limitations on shelter repurposing could be re-evaluated for real-life planning purposes. For a conversion availability from one type to another, a detailed site analysis maybe required for each shelter. Lastly, the ***r***-interdiction median model is used to define the most critical shelters in the context of a specific cost structure. The modeling could be used with different cost definitions to identify the most critical shelters. Since it is hard to know which shelter(s) be interdicted, specific action plans for the interdiction of each shelter could be prepared following our findings. Since the hurricane conditions are usually uncertain, there are several scenarios used in this study (i.e., using different hurricane severity levels and demand estimations); however, stochasticity of demand or capacity can be added into the proposed framework, which would be a very interesting direction for future research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2019.101380.

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