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A Novel Model for Emergency Evacuation Planning

Abstract

Emergency evacuation planning is the key to ensuring the safety and efficiency of transportation networks in the event of approaching natural hazards. A sound evacuation plan can save human lives and avoid congestion. In order to develop an effective emergency evacuation plan, this study presents a mixed-integer programming model that assigns individuals to emergency shelters through evacuation routes during the available time periods. The objective of the mathematical model is to minimize the total travel time of individuals leaving an evacuation zone. Unlike many emergency evacuation models presented in the literature, the proposed mathematical model directly accounts for the effects of socio-demographic characteristics of evacuees, evacuation route characteristics, driving conditions, and traffic characteristics on the travel time of evacuees. Four heuristic approaches and an exact optimization approach are applied to yield solutions for the developed model. The numerical experiments are conducted for emergency evacuation in Broward County, Florida, United States. The results show that the exact optimization approach cannot tackle large-size problem instances. On the other hand, the proposed heuristic algorithms are able to provide good-quality solutions within a reasonable computational time.

1. INTRODUCTION

1.1. Background

The coastal areas across the U.S. are subject to natural hazards, including severe storms, straight-line winds, severe thunderstorms, tornadoes, flooding, hurricanes, severe freezes, and others. Natural hazards may not only cause significant damages to the existing infrastructure, but also pose a major threat to human lives. Hurricanes Katrina and Sandy, which struck the U.S. coast in 2005 and 2012 respectively, are considered the costliest disasters in the U.S. history. Category 5 Hurricane Katrina landed on the Southeastern Coast of the U.S. and affected Bahamas, South Florida, Central Florida, Cuba, Louisiana, Mississippi, Alabama, and Florida Panhandle (NOAA, 2005). At least 1,245 people were killed by the hurricane, while the total property damage cost reached almost $108 billion (NOAA, 2005). Hurricane Sandy made landfall in Cuba and was classified as a category 2 hurricane (NOAA, 2012). The hurricane killed at least 233 people and caused approximately $75 billion in property damage (NOAA, 2012). When the potential impact is expected to be devastating, state authorities announce a mandatory evacuation. Throughout the evacuation processes, the major Interstate highways are designated as evacuation routes (CBS News, 2016). Using the dedicated evacuation routes, evacuees are able to travel to one of the emergency shelters, where they can temporarily stay until the natural hazard will pass a given metropolitan area.

Generally, the evacuation process happens in a chaotic manner, as the evacuating populations are not instructed to use any specific evacuation route and travel to any specific emergency shelter. The latter negatively affects the overall evacuation process. Specifically, in many cases evacuees are trying to use the same evacuation route, which may further cause the route congestion (as the evacuation routes have a limited capacity) and significantly delay the evacuation. Furthermore, without a proper assignment of evacuees to emergency shelters, the emergency shelters typically are not being utilized effectively (i.e., some of them may operate under capacity, while the others may not have a sufficient capacity to accommodate the arriving evacuees). Driving under both normal conditions and emergency evacuation involves a number of perceptual and cognitive processes (Boot et al., 2014), which are affected significantly with driver's age due to changes in vision, hearing, attention, speed of processing and responsiveness, presence of chronical diseases, and other factors. Driving a vehicle requires an individual to visualize a surrounding environment, and any vision disorders may not only cause difficulties in driving and discomfort, but also increase potential of roadway crashes (Owsley & McGwin, 1999). Furthermore, speed of processing and responsiveness are significantly lower for older adults as compared to their younger counterparts. It takes approximately 1.7-2.0 times longer for an older adult to process elementary information (Jastrzembski & Charness, 2007).

Natural hazards frequently occur in coastal areas with a high percentage of aging population. For example, the state of Florida has the largest proportion of 65+ years old population in the nation (U.S. Census Bureau, 2017) and experiences a relatively often occurrence of devastating natural hazards (FEMA, 2017). Taking into account the aforementioned factors, this project aims to facilitate the natural hazard preparedness operations and develop an optimization model a solution algorithm for assigning evacuees to evacuation routes and emergency shelters, considering major driver characteristics (e.g., age, gender, driving experience under both normal driving and emergency evacuation conditions, health conditions, and others) and evacuation route characteristics (e.g., number of lanes, route capacity). A number of computational experiments will be conducted to demonstrate applicability of the proposed methodology for real-life emergency evacuation scenarios. The proposed methodology is expected to assist State authorities with improving efficiency of the disaster relief operations and ensuring safety of all population groups (including aging population).

2. PROBLEM DESCRIPTION

This section of the report presents a detailed description of the emergency evacuation planning optimization problem and the main assumptions, which were adopted throughout this study. In case of approaching natural hazards, the population, inhabiting areas that would be affected by the hazards, is advised to evacuate. When the potential impact is expected to be devastating, State authorities announce a mandatory evacuation. Let $I = \{1, \dots, n\}$ denote a set of evacuating individuals. Throughout the evacuation process, some routes are designated as evacuation routes. Denote $R = \{1, \dots, o\}$ as a set of evacuation routes. Using the dedicated evacuation routes, evacuees can travel to one of the available emergency shelters $S = \{1, \dots, u\}$. A set of the available emergency shelters for the considered metropolitan area is illustrated in Figure 1. Each evacuation route has a certain capacity during a given time period, and individuals are instructed to evacuate the emergency area during a certain time period (when the assigned emergency evacuation route has a sufficient capacity). Let $P =$

$\{1, \dots, m\}$ be a set of time periods for the considered evacuation planning horizon. Denote $C_{pr}^{1}, p \in P, r \in R$ as the capacity of route r during time period p (vehicles).

In this study, the evacuation route capacity will be set, taking into consideration the important features of emergency evacuation. Specifically, the nominal capacity of a given route segment may be higher under emergency evacuation as compared to the normal driving conditions due to the fact that the route shoulders can be used as additional lanes to accommodate evacuees. In the meantime, it will be necessary to account for the additional demand due to the fact that some individuals will be willing to evacuate for extra safety precaution, even if they were not advised to do so (the latter phenomenon is generally referred to as "*shadow evacuation*"). The additional demand will be assessed based on communication with the appropriate representatives of States that often experience emergency evacuation. Similar to the evacuation routes, the available emergency shelters also have a limited capacity. Let $C_{s}^{2}, s \in S$ be the capacity of shelter s (evacuees).

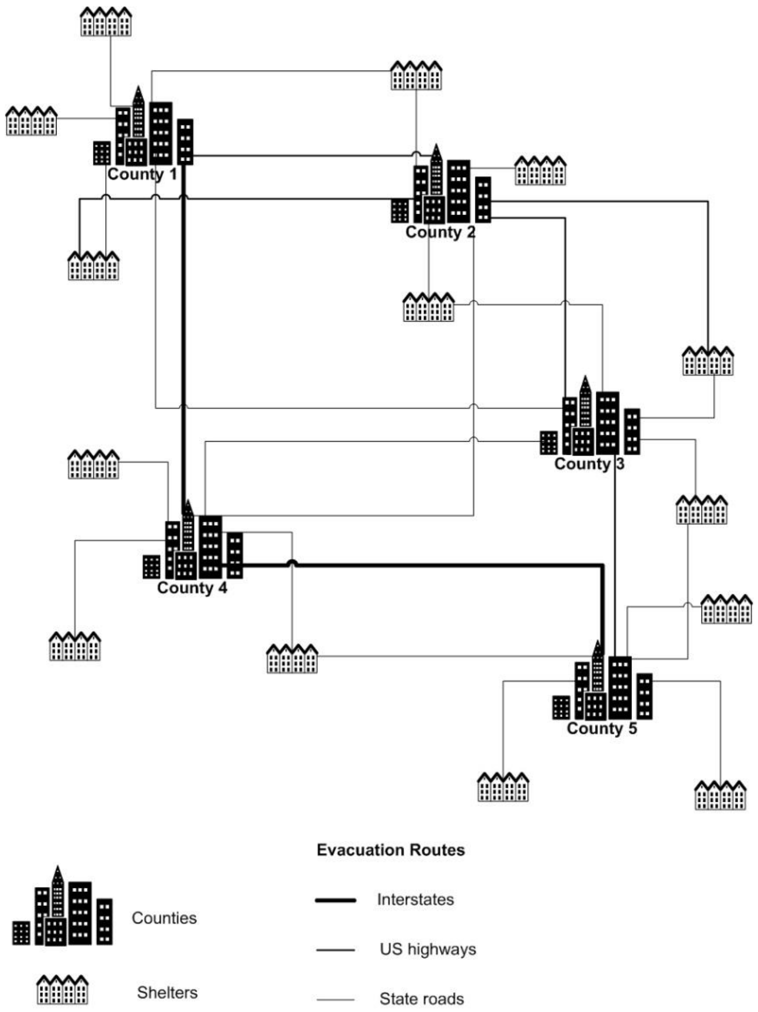

Figure 1 Emergency evacuation planning problem.

Furthermore, this study takes into consideration other passengers, who will be traveling with a given individual to the assigned emergency shelter (e.g., the whole family is trying to evacuate in one vehicle). Denote $q_i, i \in I$ as the total number of individuals, traveling in the vehicle, which is driven by individual i (evacuees). The available emergency shelters can be classified in two categories, including: a) general type shelters; and b) special needs shelters. Certain vulnerable population groups (e.g., individuals with disabilities) should be assigned to the special needs shelters to ensure that these individuals will have the adequate accommodations until the given metropolitan area will be able to recuperate from the natural hazard effects and return to the normal or close to normal operating conditions.

3. MATHEMATICAL MODEL DEVELOPMENT

The emergency evacuation planning optimization problem (**EEPOP**), described in the previous section of the report, is formulated as a mixed integer programming model. Table 1 presents the main components of the **EEPOP** mathematical model and their description.

Table 1 Nomenclature adopted for the **EEPOP** mathematical model.

Model Component		**Description**
Type	**Nomenclature**	
Sets	$I = \{1, \dots, n\}$	set of evacuees (evacuees)
	$P = \{1, \dots, m\}$	set of time periods (time periods)
	$R = \{1, \dots, o\}$	set of available evacuation routes (evacuation routes)
	$S = \{1, \dots, u\}$	set of available shelters (shelters)
	$J_i = \{1, \dots, a_i\}, i \in I$	set of socio-demographic characteristics for individual i (socio-demographic characteristics)
	$K_r = \{1, \dots, b_r\}, r \in R$	set of characteristics for route r (routes characteristics)
	$D_{pr} = \{1, \dots, c_{pr}\}$, $p \in P, r \in R$	set of driving conditions on route r during time period p (driving conditions)
	$F_{pr} = \{1, \dots, h_{pr}\}$, $p \in P, r \in R$	set of traffic characteristics on route r during time period p (traffic characteristics)
Decision Variables	$\boldsymbol{x}_{ipr}, i \in I, p \in P, r \in R$	=1 if individual i is assigned to evacuate via route r during time period p (=0 otherwise)
	$\boldsymbol{z}_{is}, i \in I, s \in S$	=1 if individual i is assigned to emergency shelter s (=0 otherwise)
Auxiliary Variables	$\boldsymbol{t}_{ir}, i \in I, r \in R$	total evacuation time required by individual i assigned to route r (hours)
Parameters	$y_{is}, i \in I, s \in S$	=1 if individual i can be assigned to shelter s (=0 otherwise)
	$w_{rs}, i \in I, s \in S$	=1 if evacuation route r leads to emergency shelter s (=0 otherwise)
	$C^1_{pr}, p \in P, r \in R$	capacity of route r during time period p (vehicles)
	$C^2_s, s \in S$	capacity of shelter s (evacuees)
	$q_i, i \in I$	total number of individuals traveling in the vehicle,

	driven by individual i (evacuees)

Emergency Evacuation Planning Optimization Problem (EEPOP)

$$min \sum_{i \in I} \sum_{r \in R} q_i \boldsymbol{t}_{ir} \tag{1}$$

Subject to:

$$\sum_{p \in P} \sum_{r \in R} \boldsymbol{x}_{ipr} = 1 \; \forall i \in I \tag{2}$$

$$\sum_{s \in S} \boldsymbol{z}_{is} = 1 \; \forall i \in I \tag{3}$$

$$\boldsymbol{z}_{is} \leq y_{is} \; \forall i \in I, s \in S \tag{4}$$

$$\boldsymbol{x}_{ipr} \leq \sum_{s \in S} w_{rs} \boldsymbol{z}_{is} \; \forall i \in I, p \in P, r \in R \tag{5}$$

$$\sum_{i \in I} \boldsymbol{x}_{ipr} \leq C_{pr}^{1} \; \forall p \in P, r \in R \tag{6}$$

$$\sum_{i \in I} q_i \boldsymbol{z}_{is} \leq C_{s}^{2} \; \forall s \in S \tag{7}$$

$$\boldsymbol{t}_{ir} = f\left(J_i, K_r, D_{pr}, F_{pr}, \boldsymbol{x}_{ipr}\right) \; \forall i \in I, p \in P, r \in R \tag{8}$$

$$\boldsymbol{x}_{ipr}, \boldsymbol{z}_{is}, y_{is}, w_{rs} \in \{0,1\} \; \forall i \in I, p \in P, r \in R, s \in S \tag{9}$$

$$C_{pr}^{1}, C_{s}^{2}, q_i \in N \; \forall i \in I, p \in P, r \in R, s \in S \tag{10}$$

$$\boldsymbol{t}_{ir} \in R^{+} \; \forall i \in I, r \in R \tag{11}$$

The objective function (1) of the **EEPOP** mathematical model aims to minimize the total travel time of the individuals, evacuating from a given metropolitan area that expects a devastating natural hazard. Constraint set (2) guarantees that each individual is assigned to one of the available evacuation routes during one of the time periods in the considered planning horizon. Constraint set (3) ensures that each individual will be assigned to only one of the available emergency shelters. Constraint set (4) guarantees that each individual will be assigned to the specific shelter based on the individual needs (e.g., vulnerable population groups may require additional accommodations, and, therefore, should be assigned to special needs shelters; on the other hand, general population groups can be assigned to either general shelters or special needs shelters). Constraint set (5) indicates that the selected evacuation route should lead to the emergency shelter, assigned for a given individual. Constraint set (6) guarantees that the total number of vehicles, traveling along each evacuation route, will not exceed the evacuation route capacity during a given time period. Constraint set (7) ensures that the total number of evacuees, assigned to a given emergency shelter, will not exceed the shelter capacity. Constraint set (7) includes term $q_i, i \in I$ to account for other passengers, who will be traveling with a given individual to the assigned emergency shelter. As discussed earlier, in certain instances, the whole family will be evacuating the emergency area in a one vehicle. Constraint set (8) estimates the total travel time of each individual (and other passengers carpooling with that individual) along the selected evacuation route based on the driver socio-demographic characteristics $(J_i, i \in I)$, evacuation route characteristics $(K_r, r \in R)$, driving conditions $(D_{pr}, p \in P, r \in R)$, and traffic characteristics $(F_{pr}, p \in P, r \in R)$. Constraint sets (9)-(11) define the nature of parameters and variables of the **EEPOP** mathematical model.

4. SOLUTION ALGORITHM DEVELOPMENT

Two groups of algorithms were developed to solve the proposed mathematical formulation for the emergency evacuation planning optimization problem, including: (a) exact solution approach; and (2) heuristic solution approach. CPLEX will be used as the exact solution approach to solve the proposed mathematical model to the global optimality. The heuristic proposed assumes that the individuals, who require the greatest time to travel from the emergency area to the nearest available emergency shelter, should receive a priority and evacuate the emergency area first. This heuristic will be referred to as the Most Urgent Evacuee Group First (MUEGF) heuristic throughout this study. The MUEGF heuristic groups the evacuees based on the total travel time, required to evacuate the emergency area, and assigns the group of evacuees to travel to one of the available emergency shelters along one of the evacuation routes during a certain time period. Denote $G = \{1, \dots, f\}$ as a set of evacuee groups. Let $\tilde{\boldsymbol{x}}_{ig}, i \in I, g \in G$ be the evacuee to group decision variable (=1 if individual i is assigned to group of evacuees g; =0 otherwise). The main steps of the MUEGF heuristic are outlined in **Algorithm 1**.

Algorithm 1. The Most Urgent Evacuee Group First (MUEGF) heuristic

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Step 1:    Assign priorities to evacuees.
Step 2:    Sort evacuees based on their priorities.
Step 3:    Group the evacuees, sorted based on their priorities, and initialize set $G$.
Step 4:    Determine the closest available shelter $s$.
Step 5:    Determine the shortest evacuation route $r$ leading to shelter $s$, which has
           the available capacity during time period $p$.
Step 6:    Assign group of evacuees $g$ with the highest priority to route $r$, leading to
           shelter $s$, during time period $p$.
Step 7:    Update set $G$: $G = G - \{g\}$. Update capacity of route $r$ during time period
           $p$: $C_{pr}^1 = C_{pr}^1 - \sum_{i \in I} \tilde{\boldsymbol{x}}_{ig}$. Update capacity of shelter $s$: $C_s^2 = C_s^2 - \sum_{i \in I} q_i \tilde{\boldsymbol{x}}_{ig}$.
Step 8:    Is set $G$ empty? If yes, STOP; else, go to step 4.
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5. MANAGERIAL INSIGHTS

The developed mathematical model and solution algorithms were applied to evacuate the population inhabiting Broward County (Florida), which is often impacted by tropical storms. The data (including potential evacuation routes and evacuation route capacity, emergency shelters and shelter capacity, demographic characteristics of the population, etc.), required to conduct the computational experiments were collected. A needs-based assignment of evacuees to emergency shelter was also considered in this study to account for individuals, who require special needs (such as vulnerable population groups) during emergency evacuation.

5.1. Shelter Utilization

5.1.1. Total utilization of shelters

The total utilization of available shelters throughout the evacuation process is presented in Figure 2 for each one of the generated large size problem instances. For example, the outmost top left chart shows utilization of available shelters for large size problem instance L-1. GP shelters and SpNS were listed in an increasing order of their distance from the centroid of Broward County; hence, the closest shelters are listed first in both categories. The MUEGF heuristic assigned 100,000 evacuees to 99 shelters for large problem size instance L-20. The charts, presented in Figure 2 for large size problem instances, indicate that an increase in the number of evacuees assigned by the MUEGF heuristic resulted in an increase in the number of shelters utilized. Moreover, the results demonstrated that the MUEGF heuristic generally assigned evacuees to the closest shelters with high capacities. The maps, showing the total utilization of GP shelters and SpNS, are presented in Figure 3 and Figure 4 respectively. From Figures 24 and 25, some shelters, which are closer to Broward County were not fully utilized, while the shelters farther from the centroid of Broward County were utilized. The latter finding may be justified based on the fact that the MUEGF heuristic assigned evacuees in groups to high capacity shelters, while the smaller capacity shelters were used to accommodate the remaining evacuees, who were not assigned to the larger shelters due to the capacity constraints.

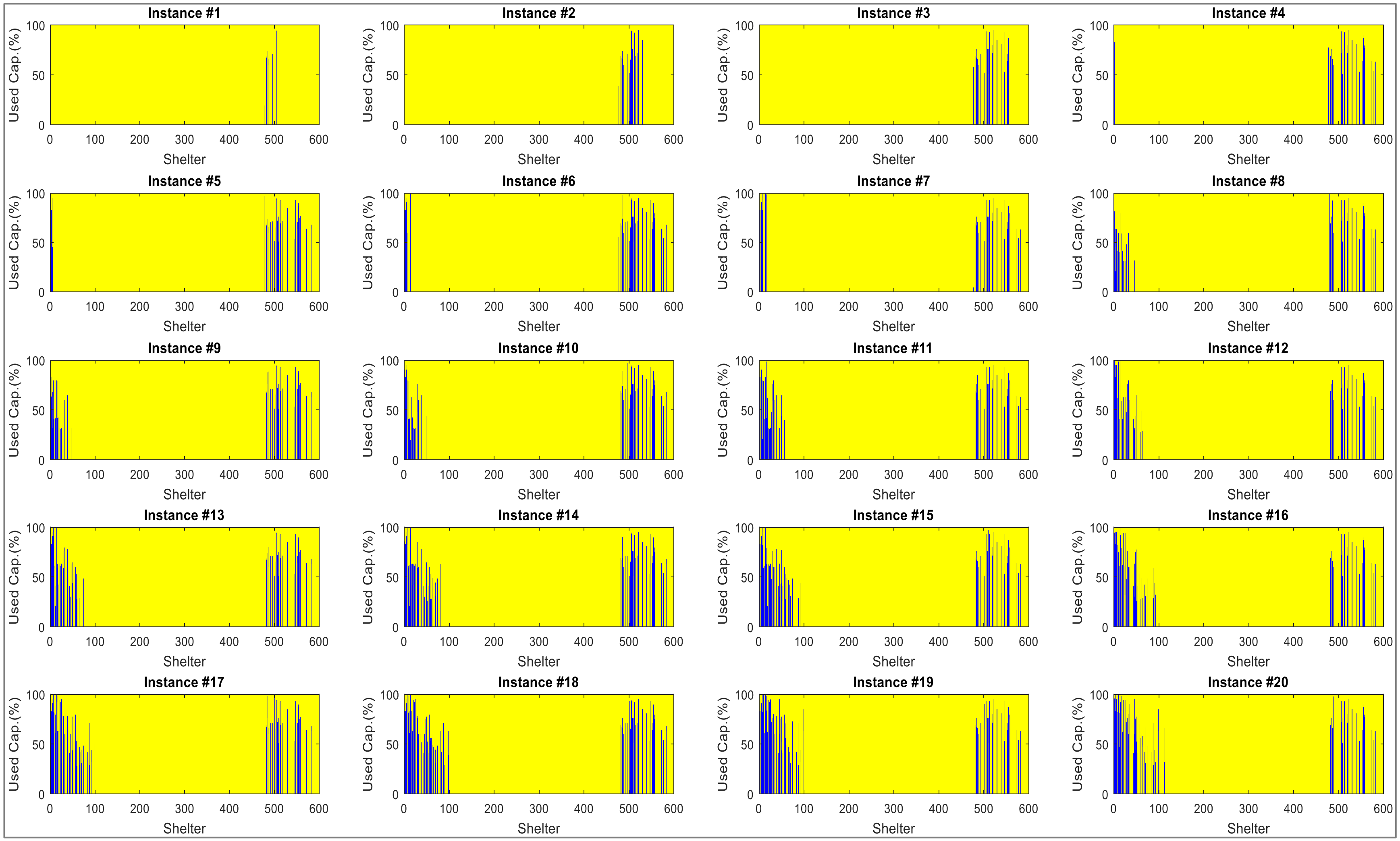

Figure 2 Total utilization of the available shelters throughout the evacuation process for large size problem instances (L-1 through L-20).

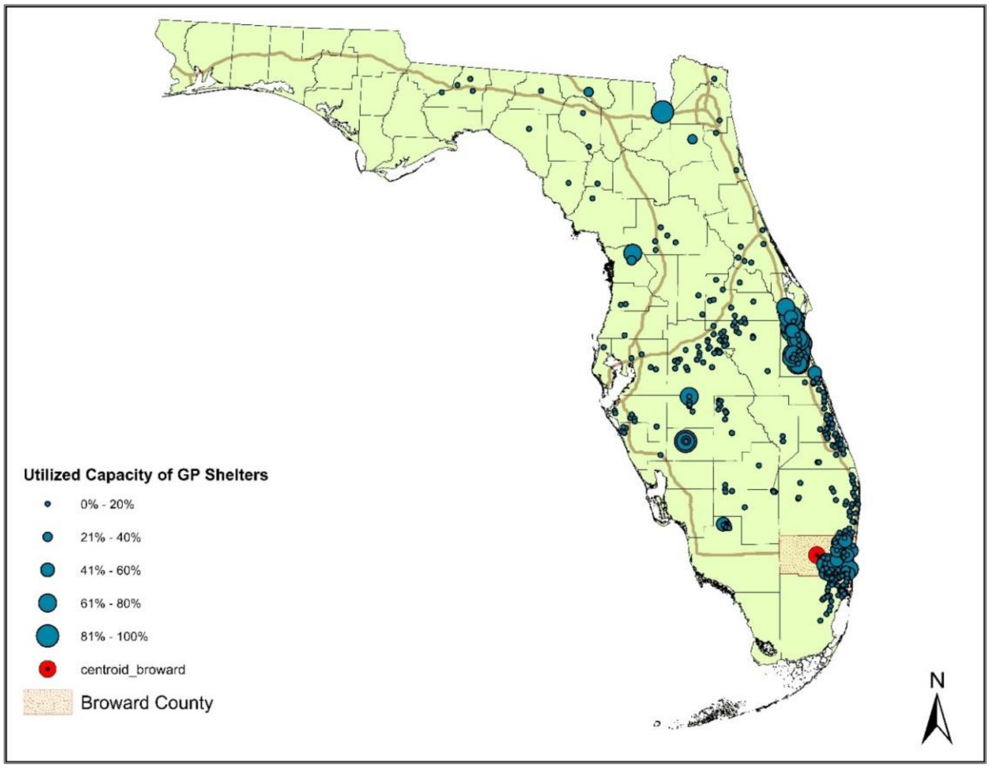

Figure 3 The total utilization of GP shelter capacity for large size problem instance L-20.

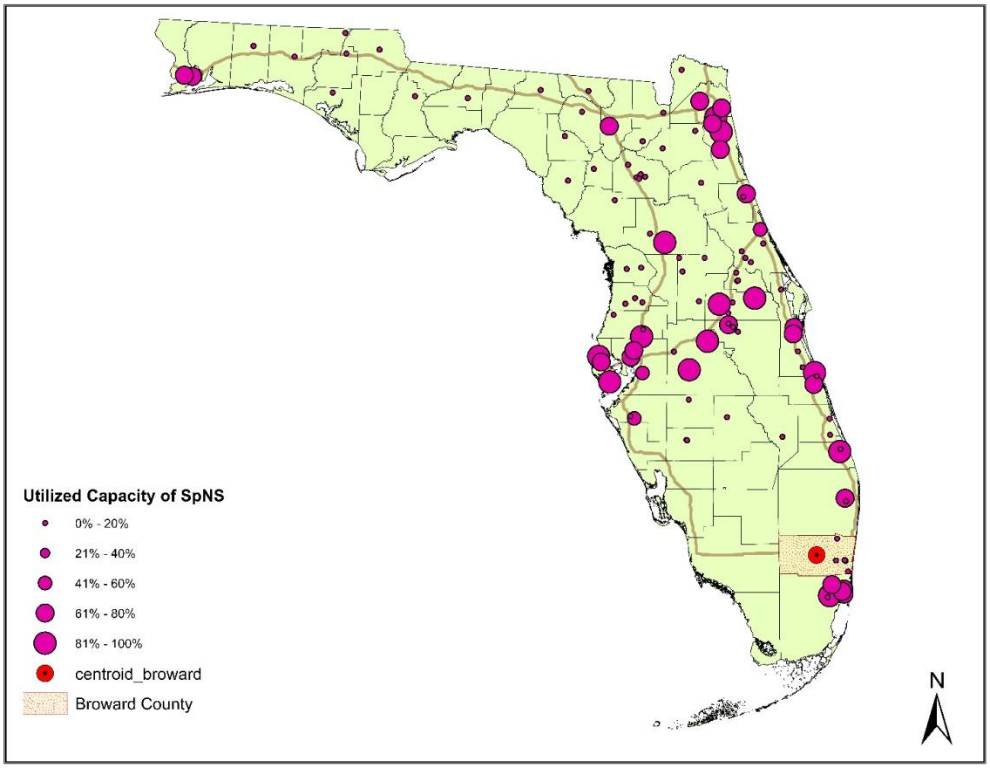

Figure 4 The total utilization of SpNS for large size problem instance L-20.

5.1.2. Cumulative utilization of available shelters by time period

Figure 5 presents the cumulative utilization of available shelters by time period throughout the evacuation process for large size problem instances L1-L20. For example, the outmost top left chart shows the utilization of available shelters for large size problem instance L-1. The chart shows that the MUEGF heuristic assigned 3860 evacuees out of 5000 evacuees within the first time period and the remaining 1140 evacuees were assigned during the second time period. Furthermore, the chart presented in the outmost bottom right of Figure 5 for large problem size instance L-20 (with 100,000 evacuees), shows that the MUEGF heuristic assigned 70,133 evacuees within the first time period and a total of 84,800 were evacuated after the second time period. The remaining evacuees were assigned over 16 time periods for problem size instance L-20. The findings demonstrate the efficiency of the algorithm in assigning the majority of the evacuees to emergency shelters within the first few hours of evacuation.

The utilized capacity of GP shelters after 6-hour time periods was estimated for large problem size instance L-20. The maps, showing the total utilization of GP shelters after 2 time periods, 4 time periods, and 6 time periods, are presented in Figure 6, Figure 7, and Figure 8 respectively for large size problem instance L-20 to illustrate the increase in utilized capacity of the available shelters after 2 hours, 4 hours, and 6 hours of emergency evacuation. A comparative analysis of the three maps suggests that the majority of the evacuees were assigned to shelters within the first 2 hours of emergency evacuation. The percent utilization of GP shelters for some of the available shelters increased within 2 to 4 hours of emergency evacuation. Moreover, utilization of certain GP shelters slightly increased after 4 hours of emergency evacuation as well.

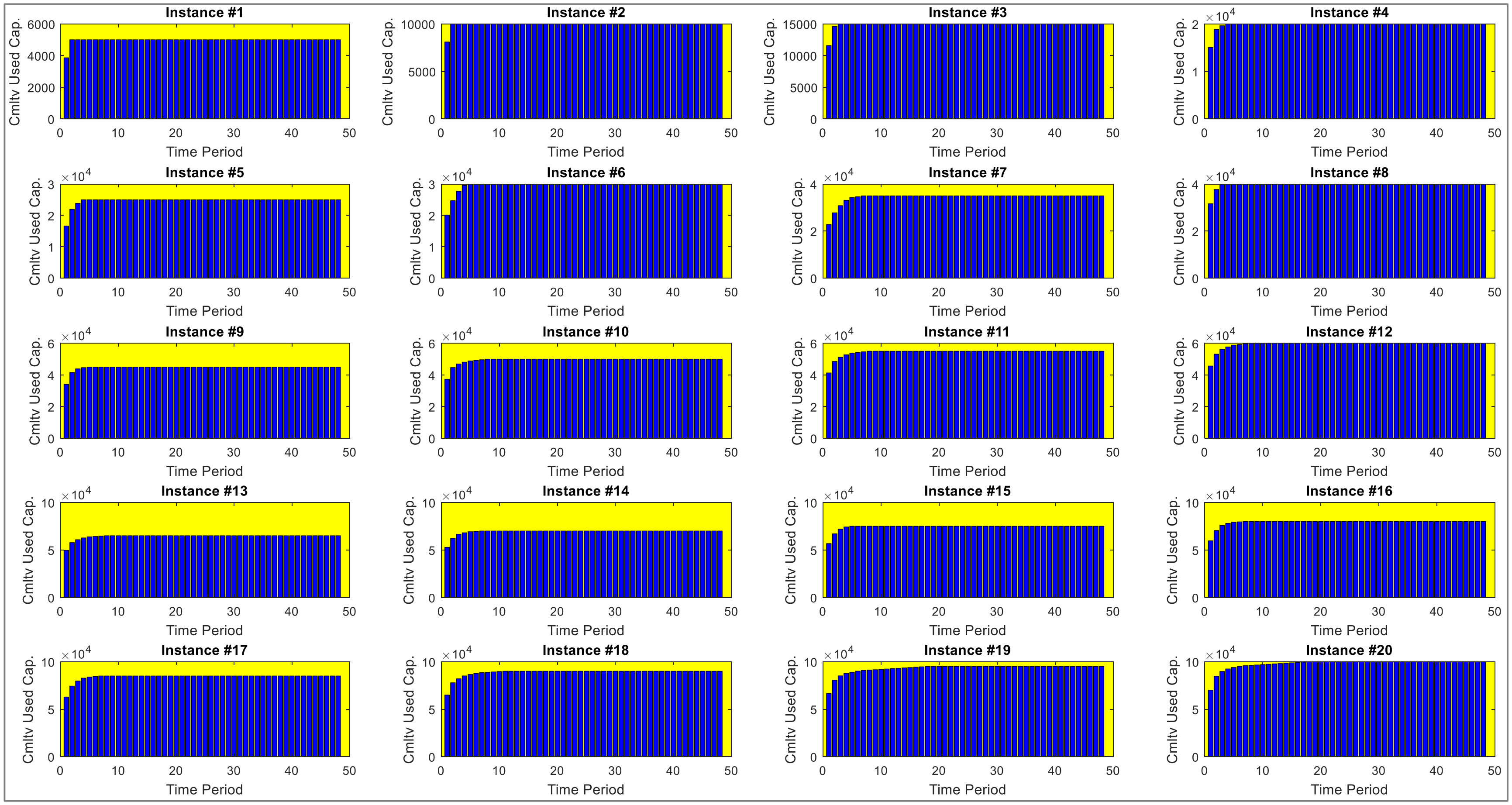

Figure 5 Cumulative utilization of the available shelters by time period throughout the evacuation process for large size problem instances (L-1 through L-20).

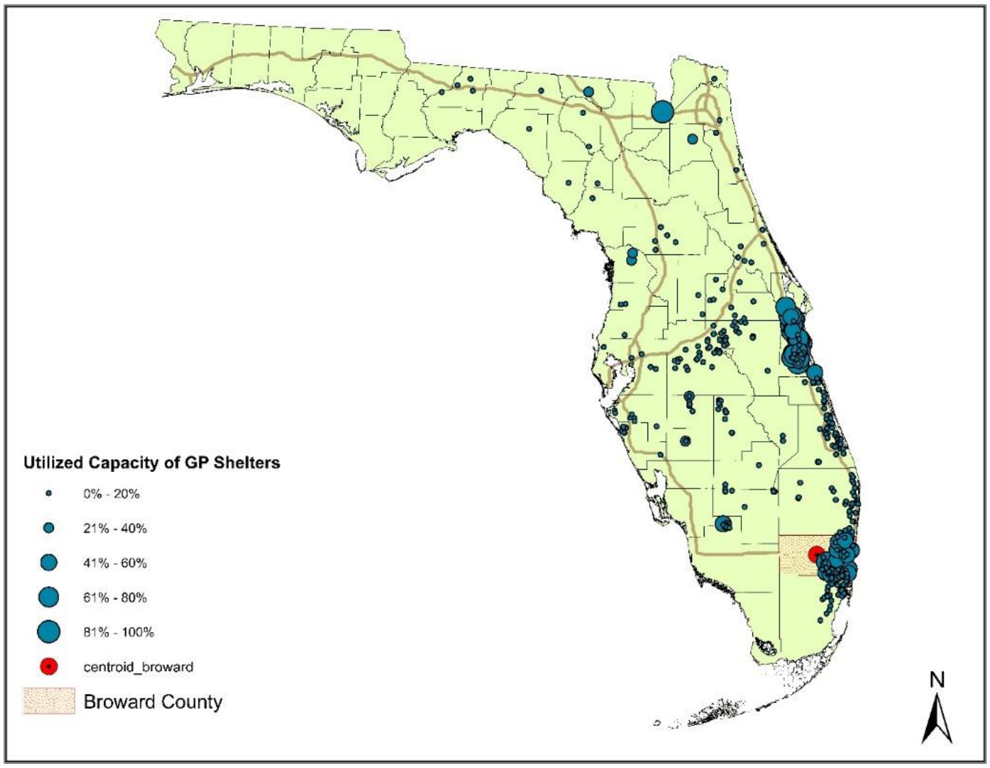

Figure 6 The total utilization of GP shelters after 2 time periods for large size problem instance L-20.

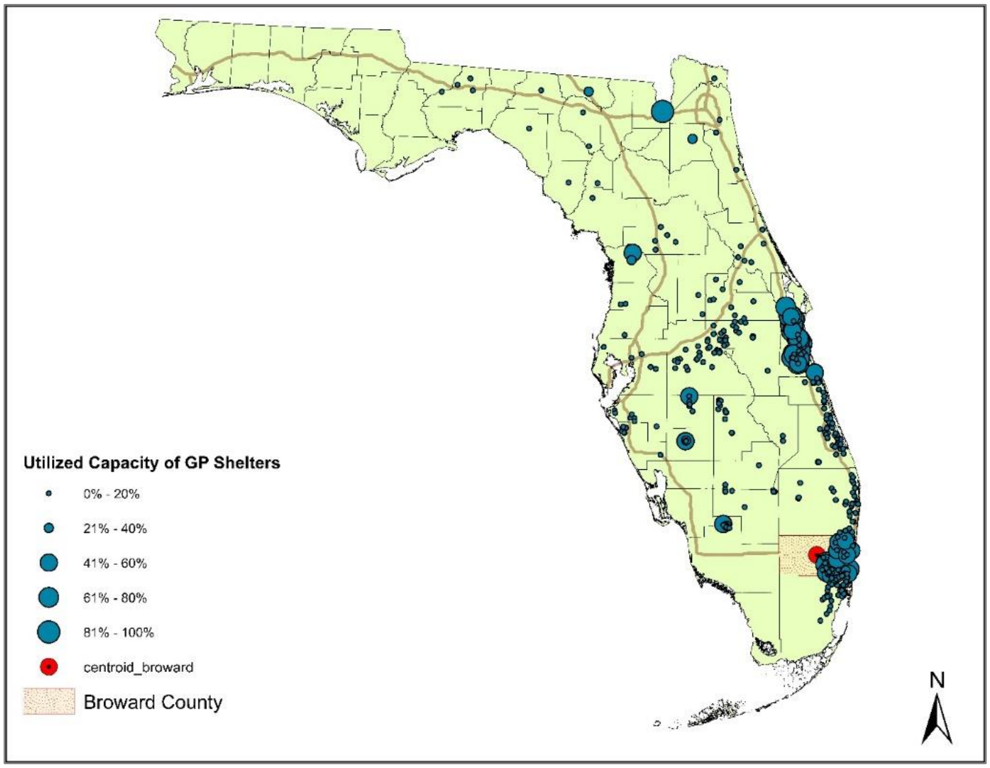

Figure 7 The total utilization of GP shelters after 4 time periods for large size problem instance L-20.

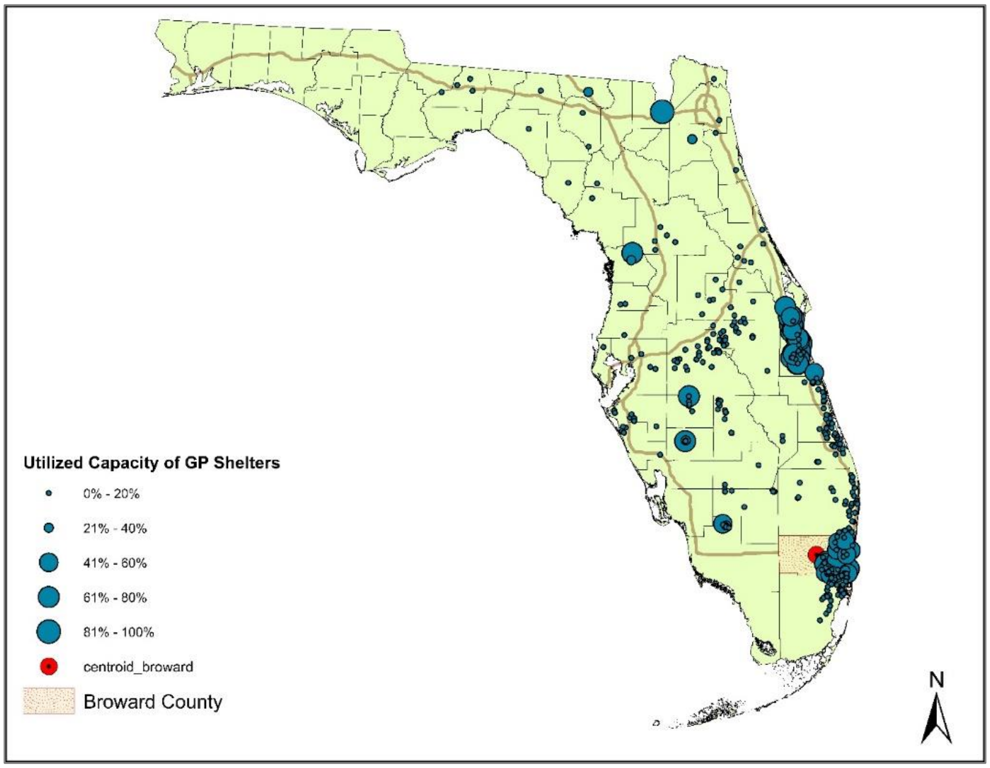

Figure 8 The total utilization of GP shelters after 6 time periods for large size problem instance L-20.

5.2. Utilization of evacuation routes

5.2.1. Average utilization of evacuation routes

The average utilization of evacuation routes over time periods throughout the evacuation process for large size problem instances is shown in Figure 9. For example, the outmost top left chart shows the utilization of available evacuation routes for large size problem instance L-1. Based on the conducted numerical experiments, it was found that the MUEGF heuristic assigned 5,000 evacuees to the shortest evacuation routes leading to SpNS for large size problem instance L-1. The latter finding may be supported by the fact that, there is at least one evacuee in each group created for the large problem instance L-1, who needed to be assigned to a SpNS. Note that based on the input data prepared for the numerical experiments, the first 904 evacuation routes lead to GP shelters, while evacuation routes 905 through 1314 lead to SpNS. Also, the evacuation routes leading to GP shelters and SpNS were listed in an increasing order of route lengths from the centroid of Broward County; thus, the shortest evacuation routes were listed first in both categories. As the problem size instance increased, the MUEGF heuristic assigned evacuees to the shortest evacuation routes, which lead to both GP shelters and SpNS. Furthermore, the average utilization of all evacuation routes did not exceed 80% throughout the evacuation process.

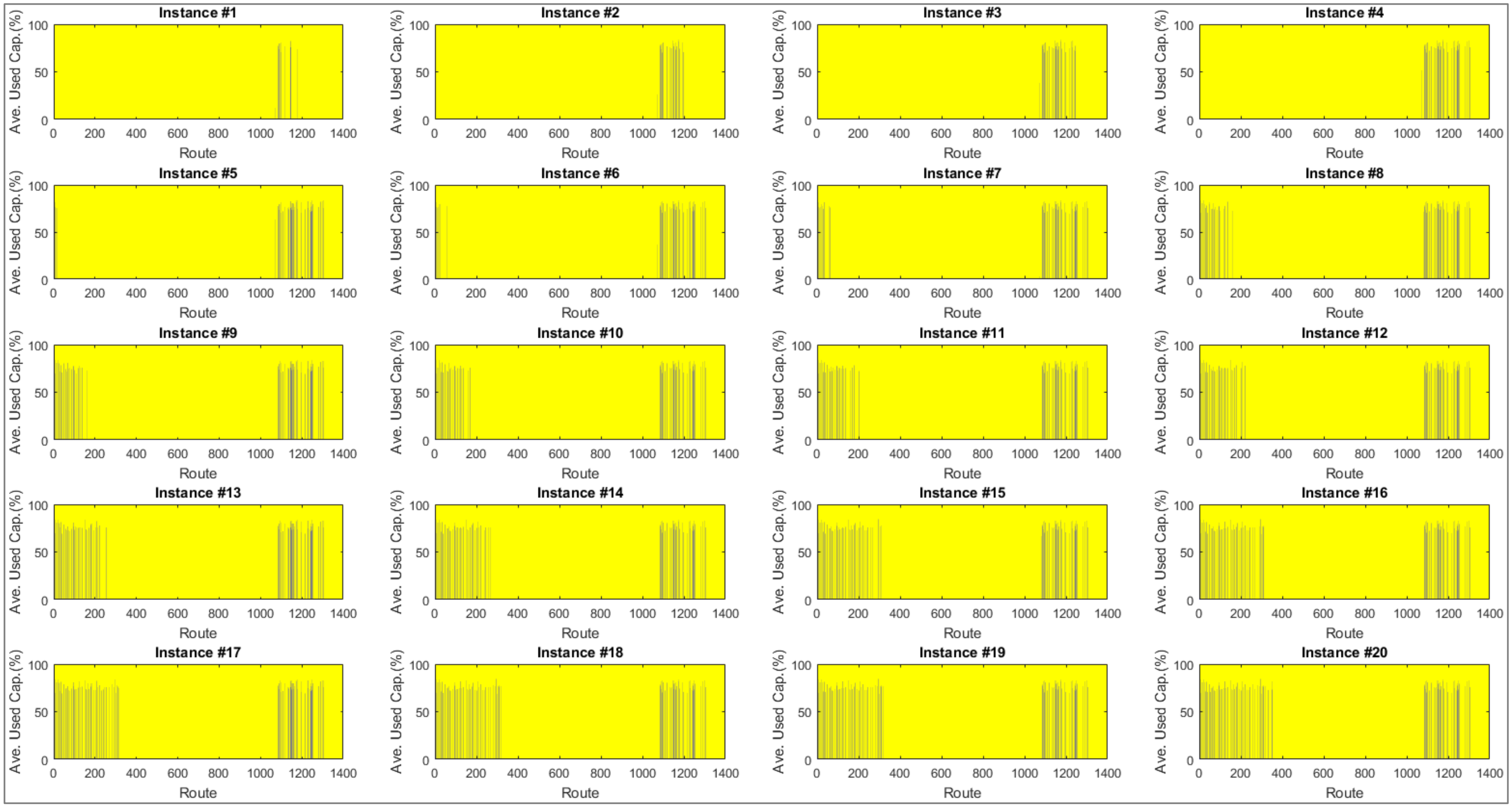

Figure 9 Average utilization of the evacuation routes over time periods throughout the evacuation process for large size problem instances (L-1 through L-20).

5.2.2. Average utilization of the assigned evacuation routes by time period

The average utilization of the assigned routes in each time period throughout the evacuation process for large size problem instances is presented in Figure 10. For example, the outmost top left chart shows the average utilization of assigned routes in each time period for large size problem instance L-1. Based on the conducted numerical experiments, the MUEGF heuristic did not utilize more than 75% of capacity of the assigned evacuation routes during the first and second time periods for large size problem instance L-1. Generally, throughout the evacuation process, it was found the MUEGF heuristic did not utilize more than 80% of capacity of the assigned evacuation routes at each time period. The latter finding suggests that the MUEGF heuristic is conservative and avoids making use of the maximum route capacity to avoid congestion of emergency evacuation routes.

5.3. Average travel time of evacuees

Figure 11 presents the average travel time of evacuees in each time period throughout the evacuation process for large size problem instances. For example, the outmost bottom right chart shows the average travel time of evacuees in each time period for large size problem instance L-20, where 100,000 evacuees were assigned using the MUEGF heuristic. The results presented in Figure 11 indicate that the average travel time of evacuees may vary from one evacuation time period to another for all large problem size instances (L-1 through L-20) considered. The latter finding can be explained by the fact that the travel time function encoded in the MUEGF heuristic is dependent on various human characteristics (which varies among individuals), as well as length of the evacuation routes.

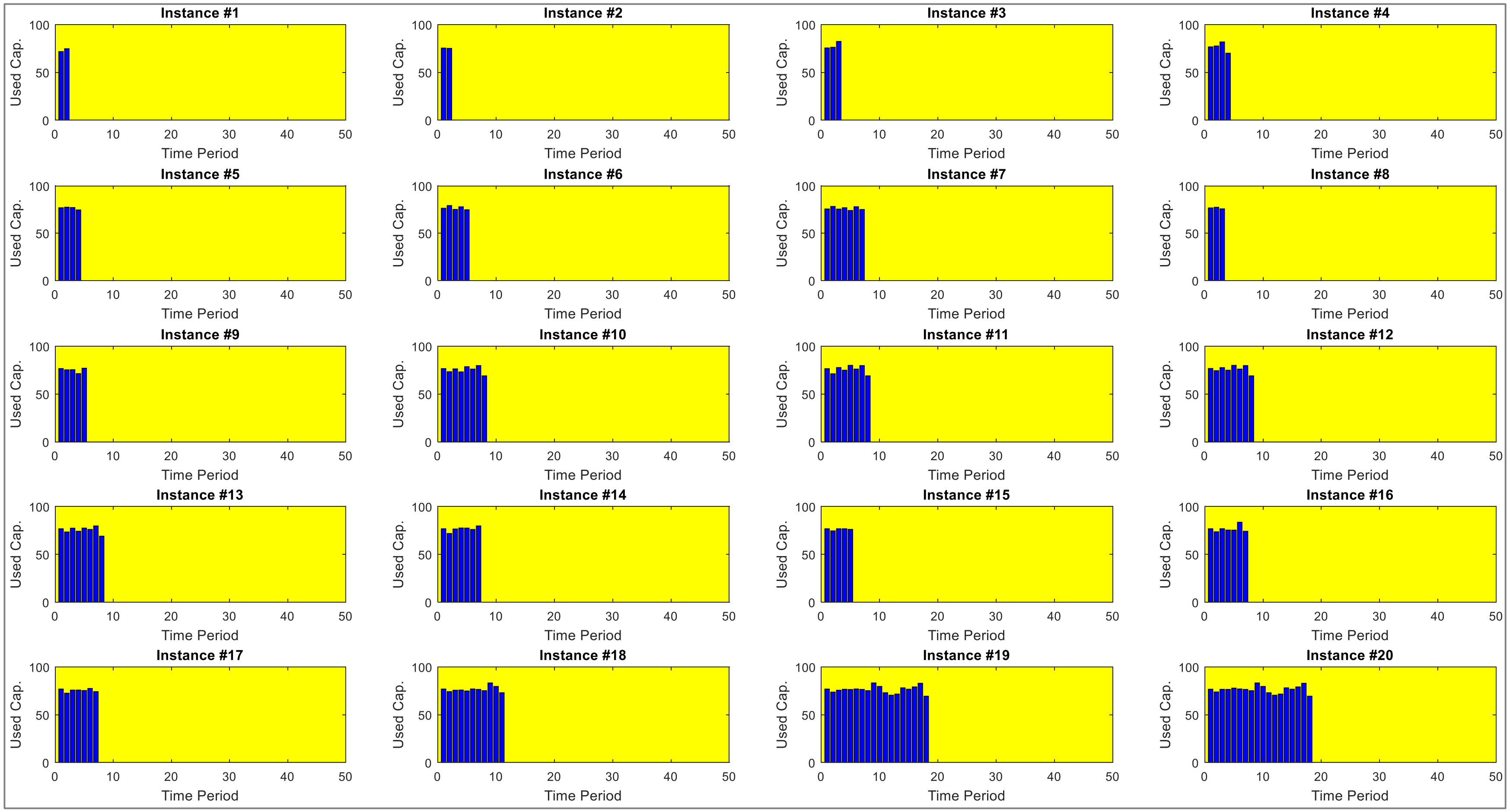

Figure 10 Average utilization of the assigned routes in each time period throughout the evacuation process for large size problem instances (L-1 through L-20).

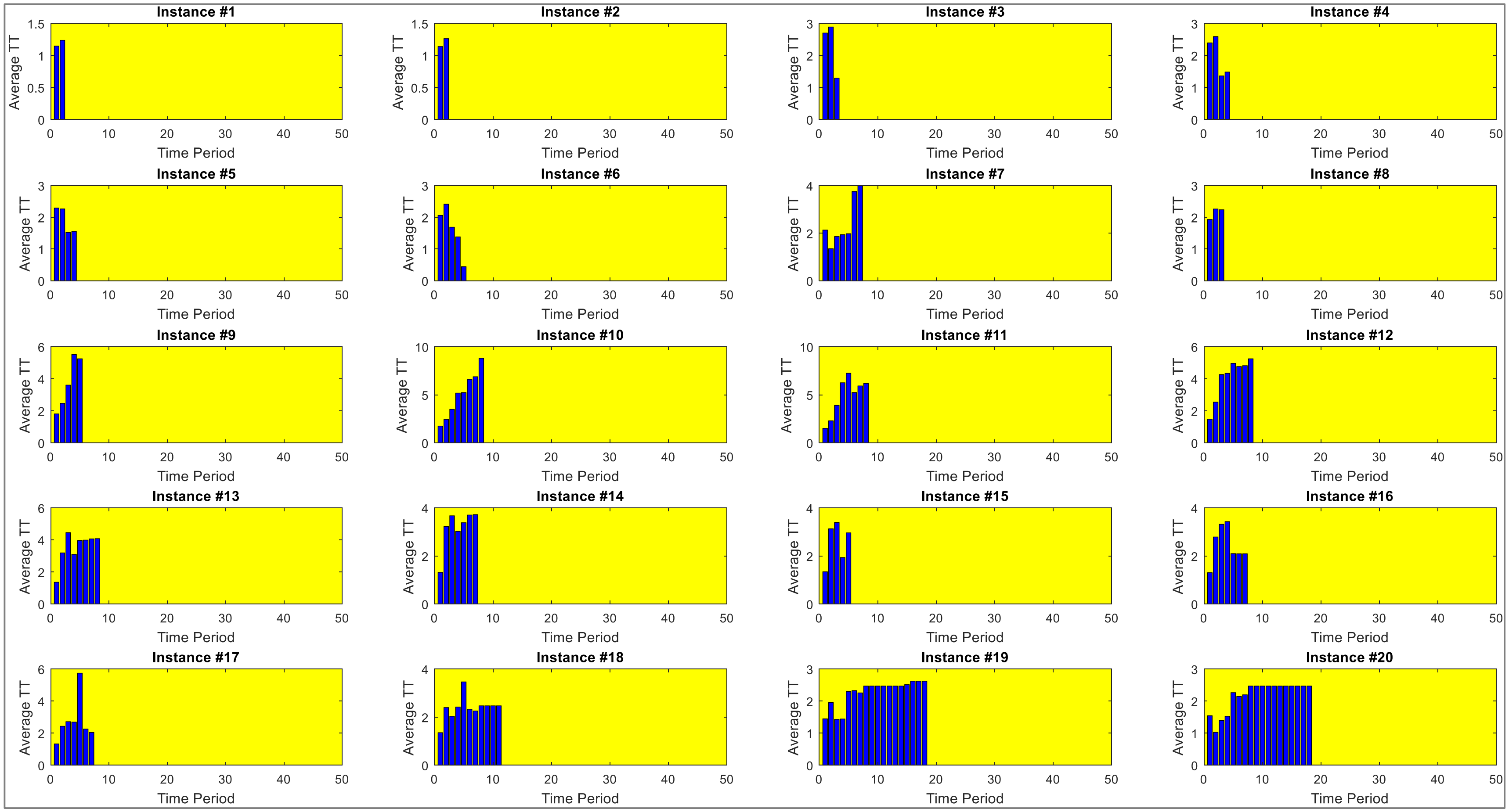

Figure 11 Average travel time (TT) of evacuees (in hours) for each time period throughout the evacuation process for large size problem instances (L-1 through L-20).

6. CONCLUSIONS AND FUTURE RESEARCH

To address the challenges associated with emergency evacuation and facilitate the evacuation process, this study focused on the development of a mathematical model and solution algorithms for the emergency evacuation planning optimization problem. The objective of the proposed mixed integer mathematical model aimed to assign individuals to evacuate the emergency area using one of the available emergency evacuation routes to one of the emergency shelters during a specific time period, by minimizing the total travel time of evacuees and considering the following factors: (1) limited capacity of the available emergency evacuation routes and shelters; (2) potential carpooling of individuals (e.g., the whole family is evacuating); (3) shelter requirements for vulnerable population groups (e.g., assignment of individuals with special needs shelters to ensure that these individuals will have the adequate accommodations); (4) major socio-demographic characteristics of drivers, evacuation route characteristics, driving conditions, and traffic characteristics, which may affect the driving ability of individuals under emergency evacuation and others. Two groups of algorithms were developed to solve the proposed mathematical formulation for the emergency evacuation planning optimization problem, including: (a) exact optimization algorithm (CPLEX) and (2) heuristic algorithm approaches.

In order to assess performance of the proposed solution approaches, the formulated mathematical model and the developed solution algorithms were applied for evacuation of Broward County, Florida, a coastal area in the U.S., which is often impacted by tropical storms. The data (including potential evacuation routes and evacuation route capacity, emergency shelters and shelter capacity, demographic characteristics of the population, etc.), required to conduct the computational experiments, were collected and a set of numerical experiments were conducted to assess the performance of the proposed algorithms in terms of in terms of both solution quality and the computational time for small and realistic size problem instances. Findings from this research provide a lot of insights regarding emergency evacuation route and shelter utilization as well as the average travel time of evacuees throughout the evacuation process. The proposed mathematical model and solution algorithm may be used as an efficient practical tool by state and local authorities (e.g., FEMA, Department of Homeland Security, and others) in improving the utilization of emergency evacuation routes and emergency shelters, reducing or eliminating traffic congestion on roadways during emergency evacuation, and reducing the travel time of evacuees during emergency evacuation. Moreover, the developed decision support tools are expected to improve the overall effectiveness of emergency evacuation process, and ensure safety of evacuees, including vulnerable population groups.

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