DESAUTELS Faculty of Management
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STORMSHEILD

A Strategic Model For Safe Relocation & Disaster Readiness

Project Report - MGSC 662

Group

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1 Introduction

In 2017, Hurricane Irma devastated Florida, forcing over 6.5 million residents to evacuate. Surrounded by the chaos, hospitals faced two challenges: maintaining operations while ensuring patient safety. ICU patients, reliant on life-sustaining machines, often experienced critical delays in care as Emergency Medical Services (EMS) struggled to manage relocations. These delays, exacerbated by strained resources, frequently led to life-threatening risks, with 12 patients on average dying in the ICU because of hurricane power outages [7]. Unfortunately, this scenario is far from unique. Florida endures 1–2 hurricanes annually, including catastrophic Category 4 or 5 storms, placing immense strain on its healthcare infrastructure and vulnerable populations. On average, these events result in hundreds of injuries, 64 fatalities annually, and economic losses totaling $17 billion per year [9].

Hospitals in high-risk areas currently depend on reactive measures, such as barricading facilities during hurricanes, to sustain operations. However, this approach exposes patients and staff to significant risks, including power outages, equipment failures, and limited access to essential supplies. ICU patients are particularly at risk due to their dependence on uninterrupted advanced medical care. When evacuations occur, they are often initiated post-storm, compounding challenges during transit and further burdening EMS resources already overwhelmed by the hurricane's aftermath.

To address these challenges, the Florida government uses tools like the **National Risk Index (NRI)**, developed by the Federal Emergency Management Agency (**FEMA**). The NRI evaluates community risks for 18 natural hazards, including hurricanes, by analyzing factors such as expected annual losses, social vulnerability, and community resilience [3]. This analytical approach identifies high-risk areas and informs emergency response efforts, serving as a cornerstone for proactive evacuation strategies.

The **StormShield** project builds on these efforts by offering a proactive, data-driven framework for patient relocation. EMS personnel often encounter operational barriers during hurricanes, including resource shortages, high ICU utilization rates, and the risks associated with last-minute evacuations. The **StormShield** model mitigates these issues by employing integer programming techniques. This multi-objective framework addresses several priorities:

1. **Maximizing the number of evacuated patients,** with a focus on ensuring all ICU patients are relocated safely.
2. **Minimizing the environmental impact** by reducing fuel consumption and CO_2 emissions.
3. **Optimizing cost-efficiency** to deliver a scalable and practical strategy within the resource constraints of local governments.

Targeted at Florida counties and local governments, **StormShield** empowers decision-makers to shift from reactive to proactive planning. This ensures patient safety, minimizes healthcare disruptions, and optimizes EMS resource utilization. By enhancing disaster preparedness, the model not only saves lives but also positions Florida as a leader in hurricane resilience and response.

2 Problem Description and Formulation

Mathematical Formulation

Our optimization model key components are as follows:

Sets

- E: Set of EMS stations.
- R: Set of risky hospitals.
- S: Set of safe hospitals.
- V: Set of vehicle types (ambulance, air ambulance, fire ambulance, bus).

Decision Variables

- $u_{e,r,v}$: Number of vehicles of type v allocated from EMS station e to risky hospital r.
- $x_{r,s,v}$: Number of vehicles of type v allocated from risky hospital r to safe hospital s.
- $z_{r,s,v}$: Number of round trips made by vehicle type v from risky hospital r to safe hospital s.

Parameters

- f_v: Fuel efficiency of ground vehicle v (miles per gallon).
- p_d: Diesel pollution factor (pounds of CO_2 per gallon).
- p_j: Jet fuel pollution factor (pounds of CO_2 per gallon).
- c_d: Diesel fuel price (dollars per gallon).
- c_j: Jet fuel price (dollars per gallon).
- f_{air}: Fuel consumption rate for air vehicles (gallons per hour).
- t^{air}_{rs}: Travel time from risky hospital r to safe hospital s by air vehicle (hours).
- t^{air}_{er}: Travel time from EMS location e to risky hospital r by air vehicle (hours).
- $VC_{e,v}$: Vehicle capacity of EMS station e for vehicle type v.
- AS_s: Available space at safe hospital s.
- t^v_{er}: Travel time from EMS location e to risky hospital r by vehicle v (hours).
- d^{ER}_{er}: Distance from EMS to risky hospital (miles).
- d^{RS}_{rs}: Distance from risky hospital to safe hospital (miles).
- PC_v: Capacity of a vehicle v.
- $PC_{v=bus}$: Capacity of a bus (vehicle type 3).
- w_{emt}: Emergency Medical Technician (EMT) wage (dollars per hour).
- $w_{paramedic}$: Paramedic wage (dollars per hour).
- w_{pilot}: Pilot wage (dollars per hour).
- NP_v: Number of paramedics required per vehicle.
- ICU_r: Number of ICU patients at risky hospital r.

Objective Functions

1. **Maximize Non-ICU Patients Evacuated**

   The goal of this objective was to maximize the number of non-ICU patients evacuated using buses. It calculated the total number of patients transported from risky hospitals to safe hospitals based on the capacity of buses and the number of trips they made.

   Maximize:
   $$B = \sum_{r\in R}\sum_{s\in S} PC_{v=bus} \cdot z_{r,s,v=bus}$$

2. **Minimize CO_2 Emissions**

This objective aimed to minimize the total CO_2 emissions generated during the evacuation process. Emissions were calculated based on the distances traveled by different vehicle types (ground and air), their respective fuel efficiencies, and pollution factors for both diesel and jet fuel. By reducing CO_2 emissions, this objective ensured that the evacuation process aligned with sustainability goals while maintaining efficiency.

Minimize:

$$P = 2 \cdot \sum_{e \in E} \sum_{r \in R} \sum_{v \in V_g} \left(\frac{d_{er}^{ER}}{f_v} \cdot p_d \cdot u_{e,r,v} \right) + 2 \cdot \sum_{e \in E} \sum_{r \in R} \left(t_{er}^{air} \cdot f_{air} \cdot p_j \cdot u_{e,r,1} \right)$$

$$+2 \cdot \sum_{r \in R} \sum_{s \in S} \sum_{v \in V_g} \left(\frac{d_{rs}^{RS}}{f_v} \cdot p_d \cdot z_{r,s,v} \right) + 2 \cdot \sum_{r \in R} \sum_{s \in S} \left(t_{rs}^{air} \cdot f_{air} \cdot p_j \cdot z_{r,s,1} \right)$$

Since we have different units for fuel efficiency — miles per gallon for road vehicles (ambulance, fire ambulance, and bus) and gallons per hour for air vehicle (air ambulance) — we adjusted the calculations accordingly. Here's a breakdown:

Calculation for One Vehicle, One Way

- **Road Vehicles:** Emissions are calculated by dividing the distance traveled (d) by the fuel efficiency (f_v in miles per gallon) and multiplying by the pollution factor for diesel fuel (p_d). For one-way trips:

$$Emissions_{road} = \frac{d}{f_v} \cdot p_d$$

- **Air Vehicle:** Emissions are calculated by multiplying the travel time (t) by the fuel consumption rate (f_{air} in gallons per hour) and the pollution factor for jet fuel (p_j). For one-way trips:

$$Emissions_{air} = t \cdot f_{air} \cdot p_j$$

Accounting for Round Trips

Since each vehicle typically makes multiple round trips, the total emissions are scaled by the number of round trips, $z_{r,s,v}$ and number of vehicles for each type, $u_{e,r,v}$:

- For road vehicles:

$$TotalEmissions_{road} = 2 \cdot \sum \left(\frac{d}{f_v} \cdot p_d \cdot z \right) + 2 \cdot \sum \left(\frac{d}{f_v} \cdot p_d \cdot u \right)$$

- For air vehicles:

$$TotalEmissions_{air} = 2 \cdot \sum (t \cdot f_{air} \cdot p_j \cdot z) + 2 \cdot \sum (t \cdot f_{air} \cdot p_j \cdot u)$$

The final equation will be obtained by aggregating both of these equations above and will provide the total carbon emissions generated during the evacuation process.

3. **Minimize Costs**

This objective aimed to minimize the total cost of the evacuation process, which included fuel costs, wages for EMS staff (EMTs, paramedics, and pilots), and additional costs related to the number of paramedics required. Costs were calculated for all vehicle types (ground and air) and incorporated travel distances and times.

Minimize:

$$C = 2 \cdot \sum_{e\in E}\sum_{r\in R}\sum_{v\in V_g}\left(\left(\frac{d_{er}^{ER}}{f_v}\cdot c_d + t_{er}^{v}\cdot w_{emt}\right)\cdot u_{e,r,v}\right)$$
$$+2\cdot\sum_{e\in E}\sum_{r\in R}\left(t_{er}^{air}\cdot(f_{air}\cdot c_j + w_{pilot})\cdot u_{e,r,1}\right)$$
$$+2\cdot\sum_{r\in R}\sum_{s\in S}\sum_{v\in V_g}\left(\left(\frac{d_{rs}^{RS}}{f_v}\cdot c_d + t_{rs}^{v}\cdot(w_{emt} + w_{paramedic}\cdot NP_v)\right)\cdot z_{r,s,v}\right)$$
$$+2\cdot\sum_{r\in R}\sum_{s\in S}\left(t_{rs}^{air}\cdot(f_{air}\cdot c_j + w_{pilot} + w_{paramedic}\cdot NP_1)\cdot z_{r,s,1}\right)$$

The above equation minimizes the total cost (C) incurred during the evacuation process. Here's a detailed breakdown:

Calculation for One Vehicle, One Way

Road Vehicles: The cost includes the fuel cost and wages of EMS Technicians. Fuel cost is calculated by dividing the distance traveled (d) by the fuel efficiency (f_v in miles per gallon) and multiplying by the diesel fuel price (c_d) (similar to Objective 2). Total wages are calculated by multiplying the travel time (t) by the EMT wage (w_{emt}). For one-way trips:

$$Cost_{road} = \frac{d}{f_v}\cdot c_d + t\cdot w_{emt}$$

This term was scaled by u, which is the number of vehicles assigned, to calculate the cost for all vehicles.

Additionally, a new term was added to the second term in the equation to account for paramedic costs. The cost is calculated by multiplying the number of paramedics required per vehicle type (NP_v) by the paramedic wage ($w_{paramedic}$). The paramedic cost for all trips is:

$$Cost_{paramedics} = NP_v\cdot w_{paramedic}$$

This is then scaled by z, the number of trips made by the vehicle.

Similarly, the terms were produced for Air Ambulance.

Constraints

To achieve our goal, we needed satisfy several constraints, as the resources available for evacuation were limited. These constraints ensured that vehicles, staff, and time were allocated efficiently while respecting the operational and logistical limitations. By adhering to these constraints, the model balanced evacuation priorities with the practical availability of resources. Below, we outlined the constraints that formed the foundation of our decision-making process.

1. **EMS Vehicle Capacity Limits**

   For each EMS station, the sum of vehicle allocations to high-risk hospitals must not exceed its capacity for each vehicle type since we can only use 50% of the EMS vehicles.

$$\sum_{r\in R} u_{e,r,v} \le p_v\cdot VC_{e,v}, \quad \forall e\in E and v\in V$$

2. **Continuity Between Stages**

   The number of vehicles provided from all EMS stations to each risky hospital must be equal to the number of vehicles dispatched from that hospital to safe hospitals for evacuations.

$$\sum_{e\in E} u_{e,r,v} = \sum_{s\in S} x_{r,s,v}, \quad \forall r\in R, and v\in V$$

3. **Evacuation Time Limit**

   With 5 days between the general path forecast and landfall, and 1 day for preparations, evacuation efforts must not exceed 4 days (96 hours), accounting for turnaround time.

$$z_{r,s,v} \cdot \left(2 \cdot t_{r,s}^{v} \cdot 1.1 + 0.5\right) \leq 96 \cdot x_{r,s,v}, \quad \forall r \in R, \forall s \in S, \forall v \in V$$

   Where:

   - 1.1 is a fatigue factor, accounting for driver fatigue and potential delays
   - 0.5 represents a 30-minute turnaround time for each trip (0.5 hours)
   - 96 is the maximum evacuation time

4. **All ICU Patients Must Be Evacuated**

   The sum of the product of round trips and vehicle patient capacity must be at least equal to the number of ICU patients at each risky hospital.

$$\sum_{s \in S} \sum_{v \in V} PC_v \cdot z_{r,s,v} \geq ICU_r, \quad \forall r \in R$$

5. **Safe Hospital Capacity Limits**

   The sum of the product of round trips and vehicle patient capacity must be at most equal to the number of available beds at the receiving hospital.

$$\sum_{r \in R} \sum_{v \in V} PC_v \cdot z_{r,s,v} \leq AS_s, \quad \forall s \in S$$

3 Numerical Implementation and Results

Data Sources and Preprocessing

Our model integrated data from three primary sources:

1. EMS Dataset: Information on emergency medical services stations across Florida (Table2)
2. Hospital Dataset: Details on hospital capacities, locations, and patient numbers (Table3)
3. Hurricane Risk Dataset: County-level data on hurricane frequency and risk levels

Data integrity checks were performed and handled missing values to ensure data reliability. Geographical filtering was applied to ensure all locations are within Florida's boundaries:

$$\text{Florida} = \left\{ (x, y) \in R^2 \;\middle|\; \begin{array}{c} 24.396308 \leq y \leq 31.000888 \\ -87.634938 \leq x \leq -80.031362 \end{array} \right\} \text{ where } x\text{: Longitude, and } y\text{:}$$

Latitude

Risk Assessment and Hospital Classification

As mentioned earlier, the NRI score was used to classify the hospitals into **high-risk** and **safe** regions. Hospitals were classified based on a predefined risk threshold, which reflected the statistic of the Florida Climate Center[6]:

$$\text{Risk Classification} = \begin{cases} High-risk, & if HRCN\_RISKS \geq 98.0, \\ Safe, & if HRCN\_RISKS < 98.0. \end{cases}$$

where HRCN_RISKS is the standardized risk score for hurricanes.

This classification formed the foundation of our evacuation planning process, identifying which hospitals need to be evacuated (high-risk) and which can serve as safe destinations for patients. The result of safe vs risky zone can be found in the Figure 1.

Assumptions of the Parameters

Assumptions were made for vehicle capacities, fuel efficiency, paramedic requirements, turnaround times, and percentage allocation based on standard operational practices and realistic constraints.

Vehicle Capacities:

- `ambulance`: Typically able to accommodate up to 2 patients for transportation [11]. Reserved for patients in critical condition (ICU).
- `air_ambulance`: Capacity of 1 patient per vehicle. Air ambulances are used for transporting highly critical patients requiring urgent medical attention.
- `fire_ambulance`: Capacity of 2 patients per vehicle, as they usually have a similar internal layout compared to regular ambulances.
- `bus`: Capacity of 20 patients per vehicle. Buses are used exclusively for evacuating non-critical patients who do not require advanced medical care during transport.

EMS Vehicle Capacity: The model assumptions regarding EMS Station capacities of emergency vehicles are discussed in Section B.3 of the appendix.

Fuel Efficiency:

- `ambulance`: 4.9 miles per gallon. This value represents the average fuel efficiency of a regular ground ambulance under standard operating conditions, with the Ford F150 taken as an example. [12].
- `fire_ambulance`: 4.9 miles per gallon. The fire station ambulances have similar fuel efficiency to standard ground ambulances.
- `air_ambulance`: 39.63 gallons per hour. This value reflects the average fuel consumption rate for air ambulances during flight operations, taking the H135 as an example [13].
- `bus`: 7.0 miles per gallon [14].

These values represents the average consumption rates under normal operating conditions and are used to calculate the cost and pollution estimates for the model

Number of Paramedics:

- `ambulance`: Requires 2 paramedics per vehicle. A paramedic is assigned to each critical care patient during transportation.
- `air_ambulance`: Requires 1 paramedic per vehicle. Air ambulances are staffed with minimal personnel to maximize space for critical care equipment.
- `fire_ambulance`: Requires 2 paramedics per vehicle. These vehicles are equipped for emergency response and disaster scenarios.

- `bus`: Requires 2 paramedics per vehicle. Buses, used for non-critical patients, ensure basic medical oversight during transport, assuming 1 paramedic is allocated to every 10 patients.

Paramedic presence is essential and will ensure that the patients get adequate medical care and oversight during transport, aligning with emergency response protocols

Turnaround:

The turnaround time accounts for the time required per round trip to load and unload the patient, as well as to refuel, clean, and replenish supplies if needed, mirroring the realistic scheduling for vehicle reuse in continuous operations. Emergency Medical Services typically aim for a turnaround of 30 minutes or less [15]. Although information on air ambulance turnaround is limited, we assume 60 minutes to account for the added complexities of patient handover, aircraft refueling and maintenance, pre-flight safety checks, and regulatory compliance, ensuring both operational readiness and safety.

- `ambulance`: Turnaround time of 0.5 hours per trip.
- `air_ambulance`: Turnaround time of 1 hour per trip.
- `fire_ambulance`: Turnaround time of 0.5 hours per trip. Similar to ambulances, these vehicles are quickly readied for subsequent missions.
- `bus`: Turnaround time of 0.5 hours per trip.

Percentage Allocation(p):

Despite the need for emergency vehicles during evacuation efforts, it is important to ensure that some are reserved for other emergencies that may arise.

- `ambulance`: 50% of available ambulances can be allocated for hurricane evacuation efforts.
- `air_ambulance`: 50% of available air ambulances can be deployed for critical patient evacuations.
- `fire_ambulance`: 50% of available fire ambulances are dedicated to evacuation operations.
- `bus`: 50% of buses are allocated for non-critical patient evacuations during hurricane response.

The percentage allocation represents resource constraints during emergencies, ensuring a balanced distribution of vehicles for both patients and inhabitants in the risker regions

Additional Parameters

To develop a realistic model, we had to define additional parameters including time constraints, vehicle speeds, fuel costs, wages, and environmental impact factors:

- **Maximum Evacuation Time:** Set to 96 hours (4 days), allowing for a swift response.
- **Vehicle Speeds:** Differentiated based on type:
  - `Air Ambulances:` 160 mph, assumed similar to the Airbus H145 air ambulance. [16]
  - `Ground Ambulances:` 55 mph. [17]
  - `Buses:` 40 mph. [18]
- **Fuel Prices:** Current fuel prices are incorporated:
  - `Diesel:` \$3.471 per gallon of fuel burnt. [19]
  - `Jet Fuel:` \$2.12 per gallon of fuel burnt. [20]
- **Staff Wages:** Account for staff earnings:
  - `Pilots:` \$36.02 per hour. [21]
  - `Paramedics:` \$19.70 per hour. [22]
  - `EMTs:` \$15.25 per hour. [23]
- **Pollution Factors:** Include environmental considerations:
  - `Diesel Engines:` Produce 22.45 pounds of CO_2 per gallon. [24]
  - `Jet Engines:` Produce 21.5 pounds of CO_2 per gallon. [24]

Distance and Travel Time Calculations

To obtain the distances between hospitals and between hospitals and EMS stations, we initially considered using the Google Maps Distance Matrix API, which provides actual road distances. However, this approach required purchasing additional credits, making it infeasible due to budget constraints. To maintain simplicity and ensure cost-effectiveness, we used the Haversine formula, which calculates the straight-line distance between two geographical points based on their latitude and longitude. While this method does not account for road networks or terrain, it provides a reasonable approximation suitable for our model's requirements.

$$\mathrm{d} = 2\mathrm{R} \arcsin\left(\sqrt{\sin^2\left(\frac{\phi_2-\phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right)$$

Where:

- $R = 6371km$ (Earth's radius)
- $\phi_1, \phi_2 = latitudesinradians$
- $\lambda_1, \lambda_2 = longitudesinradians$
- Travel times are calculated using: T = dv

Where:

- T is the travel time
- d is the distance
- v is the average speed of the vehicle

Optimization Model Implementation

Gurobi was leveraged to implement the model, using hierarchical optimization, prioritizing the evacuation of patients, followed by minimizing pollution and cost.

4 Model Results

The results of the evacuation model demonstrated the effective allocation of resources and achievement of the objectives under the defined constraints. Below is a detailed summary of the results:

Vehicles Used

The total number of vehicles utilized and the corresponding number of patients evacuated are as follows:

- **Ambulances:** 177 vehicles, evacuating 1596 patients.
- **Fire Station Ambulances:** 126 vehicles, evacuating 1208 patients.
- **Air Ambulances:** 32 vehicles, evacuating 34 patients.
- **School Buses:** 18 vehicles, evacuating 1706 patients.

Objective Values

- **Non-ICU Patients Evacuated:** 1760 patients.
- **Total Pounds of CO_2 Emitted:** 1,524,680 pounds.
- **Total Costs:** $759,017.

Evacuation Success

- **Total Evacuated Patients:** 4598.
- **All ICU Patients Evacuated:** Achieved.

Example Allocation and Routes

The following example illustrates how resources were allocated between EMS stations, risky hospitals, and safe hospitals (the full route maps can be found in Figure 2:

EMS Station	Risk Zone Hospital	Vehicle Allocation
EMS Holly Hill Fire Rescue	FL Hosp Oceanside	1 Fire Ambulance
Risk Zone Hospital	**Safe Zone Hospital**	**Round Trips**
FL Hosp Oceanside	Flagler Hosp	4 Fire Ambulance Round-Trips

Table 1: Example Allocation and Routes

In this example, the EMS station at **Holly Hill Fire Rescue** was assigned to the risk zone hospital **FL Hosp Oceanside**. The station deployed **1 fire ambulance** to transport patients. This fire ambulance completed **4 round-trips** to the safe hospital **Flagler Hosp**, ensuring the evacuation of all assigned patients from the risk zone hospital to safety. This allocation demonstrates the efficient coordination between EMS stations, risk zone hospitals, and safe hospitals to maximize the utilization of limited resources.

Vehicle Utilization and Resource Distribution

The analysis of vehicle utilization highlights the evacuation process's alignment with the project's objectives. School buses, with their larger capacity, evacuated the highest number of patients (1,706, 37.5%), followed by ambulances and fire ambulances, while air ambulances, though limited at 0.7%, served specialized roles. The cumulative evacuation over time underscores the steady deployment of resources, with buses and ambulances handling most of the workload and air ambulances contributing in targeted cases. Resource distribution among EMS stations and hospitals further demonstrates the model's prioritization. Coral Gables Fire and Rescue led in vehicle dispatches, supported by Florida Medi-Van and Trauma One. Cape Coral Hospital LMHS received the most vehicles, primarily ambulances, reflecting higher demand, while other hospitals showed a balanced allocation of resources. These insights confirm the model's effectiveness in optimizing resource use for efficient evacuations. The visualization can be found in Figures 3, 4 and 5.

Limitation of the Model

Although the model achieved a high level of efficiency given the defined parameters, it is important to note certain limitations. Not every patient was successfully relocated due to capacity constraints in some safe zone hospitals. These capacity limitations restricted the full utilization of available resources and hindered the complete evacuation of all patients from risk zone hospitals. Addressing this issue requires further refinement of the model, including incorporating additional safe zone hospital capacity or alternative facilities. Solutions to these challenges will be explored in the recommendations section to ensure a more robust and comprehensive evacuation strategy in future scenarios.

5 Problem Extensions

Having reached a sub-optimal solution under the given constraints, further direct improvements within the model were not feasible. To explore alternative scenarios, we adjusted the rescue time threshold, which resulted in higher costs the same capicty of patients being evacuated. This is reflected in Table 4, highlighting the trade-offs associated with modifying a key parameter. These findings reinforce that the current solution is the most effective within the defined parameters, balancing resource utilization and patient safety.While the current model demonstrates efficiency and reliability, disaster response requires adaptability to address unpredictable challenges. Enhancing the model by addressing its limitations—such as expanding hospital capacities or incorporating real-time data—could enable more robust and dynamic evacuation strategies. These advancements have the potential to transform the model into a comprehensive tool that not only optimizes current operations but also prepares for evolving disaster scenarios.

Real-time Risk Assessment

Hurricanes don't always follow the path we expect. In such a high-stakes scenario, relying on static risk classifications could lead to misallocated resources. By integrating real-time data from tools like the Google Maps API for traffic patterns or NOAA for hurricane tracking, hospitals can constantly adjust their evacuation priorities, by knowing exactly when and where conditions will worsen, allowing ambulances to reroute in real-time or focus efforts on the most at-risk areas. This approach ensures resources aren't wasted on low-risk zones and enhances operational precision.

This capability can be formalized as a stochastic programming problem:

$$\min_{x \in X} E_{\xi}[f(x, \xi)]$$

where ξ represents the uncertain hurricane path, and $f(x, \xi)$ is the cost function dependent on decisions x and the realized path ξ.

Anticipating Challenges

Evacuations are full of unknowns—road congestion, damaged infrastructure, or sudden spikes in patient numbers. What if these uncertainties could be accounted for in advance? By combining historical data on hospital capacities and real-time traffic feeds from apps like Waze, our model can create strategies that are ready for anything. For instance, if congestion is reported on a key route, resources could be dynamically redistributed to avoid delays. The ability to simulate and prepare for multiple scenarios adds resilience, ensuring the plan doesn't falter under unexpected pressure. Hospitals gain confidence that every decision is backed by data, even when conditions are unpredictable.

This approach can be formulated using chance constraints:

$$P(g_i(x, \xi) \leq 0) \geq 1 - \alpha_i, \quad i = 1, \ldots, m$$

where $g_i(x, \xi)$ represents constraints affected by uncertainty, and α_i is the allowed probability of constraint violation.

Multi-Stage Evacuation

Not all patients require immediate evacuation, and time is a precious resource. A phased approach to evacuations can prioritize critical care patients in the first wave, while non-urgent cases are handled later. By tapping into electronic health records (EHR), hospitals can identify high-priority patients, such as those in ICUs, and ensure they're the first to receive attention. This phased strategy breaks down the chaos of evacuation into manageable steps. Decision-makers can focus resources where they're needed most, without overwhelming the system. It's a practical way to stretch limited resources further while ensuring no one is left behind.

This can be formalized as a multi-stage stochastic program:

$$\min_{x_1} c_1^T x_1 + E_{\xi_2}[\min_{x_2} c_2^T x_2 + \cdots + E_{\xi_T}[\min_{x_T} c_T^T x_T]]$$

where x_t represents decisions at stage t, and ξ_t represents the information revealed at stage t.

Resource Sharing and Mutual Aid

When a hurricane hits, the boundaries between counties disappear. Sharing resources like ambulances and air transport across regions can bridge gaps in capacity and ensure every patient gets the care they need. By integrating regional EMS and hospital network data, we can identify areas with surplus resources and channel them where they're needed most. This collaborative approach not only maximizes the use of available resources but also reduces redundancies, making the entire operation more efficient.

This can be represented as a network flow problem:

$$\sum_{i \in N} \sum_{j \in N} x_{ij} = \sum_{i \in N} \sum_{j \in N} x_{ji}, \quad \forall k \in K$$

where x_{ij} represents the flow of resources from node i to node j, and K is the set of counties or states.

Post-Evacuation Planning

Evacuating patients is just one side of the equation. Once the storm passes, the focus shifts to getting patients and resources back to normal operations. Using geographic information systems (GIS) and FEMA recovery data, we can map the safest, fastest routes for returning patients. Paired with hospital readiness data, this ensures that facilities are prepared to handle the returning surge. By planning for the return journey, hospitals minimize downtime, restore operations quickly, and position themselves to handle the next emergency with greater resilience. It's not just about responding to disasters—it's about recovering stronger.

This can be captured as a bi-objective optimization problem:

$$\min_{x} (f_1(x), f_2(x))$$

where $f_1(x)$ represents the evacuation cost, and $f_2(x)$ represents the return cost.

6 Recommendations and Business Insights

Effective disaster response requires solutions that not only address immediate needs during hurricanes but also create lasting value for the community and stakeholders. Below are four recommendations, ensuring both short-term impact and long-term resilience to this type of natural disaster.

Safe Haven 365: Multi-Use Hurricane Shelters

Temporary shelters are a lifeline during hurricanes, providing a secure space for non-critical patients and evacuees. However, these shelters should serve the community year-round to maximize their utility. *Safe Haven 365* proposes using modular, hurricane-proof facilities as community centers, training hubs, or recreational spaces during non-hurricane periods. When a hurricane is imminent, these facilities can be swiftly converted into shelters through a pre-scheduled cleaning and sanitization protocol that meets hospital standards. Teams trained in disaster preparedness could transition the spaces efficiently, ensuring they are ready to accommodate evacuees. Partnerships with local organizations and businesses could provide funding, supplies, and volunteers, fostering a shared sense of ownership and community.

Stormshield: Database for Coordination

A centralized, real-time database is essential to coordinate evacuations effectively. *Stormshield* envisions an integrated system that tracks ambulance locations, hospital bed availability, and patient conditions across Florida. By leveraging cloud-based technologies and collaborating with existing EMS and hospital management systems, this platform can scale to handle real-time data during emergencies.The system would also incorporate weather forecasts and predictive analytics to anticipate resource needs before the storm hits. During non-hurricane periods, this database could be maintained as part of routine hospital and EMS operations, ensuring data remains accurate and ready for future emergencies.

EcoRescue: Sustainable Emergency Operations

Hurricanes put a significant strain on the environment, and evacuation processes shouldn't add to the burden. *EcoRescue* focuses on transitioning EMS and public transport vehicles to electric or hybrid models, significantly reducing CO_2 emissions during evacuations. Pilot programs could begin by converting a portion of the fleet in urban areas with established charging infrastructure. Additionally, pre-emptive traffic management strategies, powered by AI simulations, could identify and alleviate congestion hotspots hours before the storm arrives. These measures would not only cut emissions but also make evacuations faster and more efficient. Over time, *EcoRescue* would position Florida as a leader in sustainable disaster response, setting an example for other states.

Florida Emergency Resilience Task Force (FERT): Florida's Resilience Team

Disaster response requires rapid and seamless coordination across multiple entities, and *FERT* aims to provide the leadership needed. This state-level emergency resilience task force would bring together representatives from state agencies, local governments, private sector partners, and community leaders from vulnerable populations. Its role would be to establish clear protocols, allocate resources efficiently, and address gaps in disaster response planning. During non-hurricane periods, the task force could run training workshops, simulate disaster scenarios, and evaluate evacuation strategies to improve readiness.

More information can be found in Tables 5, 6 and 7.

7 Conclusion: A Call to Action for Florida Government

Hurricane evacuation in Florida had long been a reactive endeavor, plagued by inefficiencies, resource misallocation, and missed opportunities to save lives. As of now, the Florida government had disregarded the urgency of proactive measures, likely unaware of the lives they could have saved and the financial losses they could have prevented. It was time to act decisively and acknowledge the significant impact that could be achieved through thoughtful, data-driven strategies.Today, this data-driven evacuation model proved its ability to optimize emergency relocations during hurricanes, demonstrating enhanced resource allocation, prioritization of vulnerable populations, and reduced environmental impact. Its success underscores the importance of inter-county collaboration and informed decision-making during crises. By adopting the strategies outlined in this report, Florida can transition from crisis response to proactive disaster resilience. This model's flexibility extends beyond hurricanes; it could be adapted for other emergencies, such as war zone evacuations or large-scale industrial accidents, showcasing its versatility in saving lives under varying circumstances.With the increasing frequency of climate-driven disasters, Florida cannot afford to delay. This model provides a blueprint for a sustainable, data-driven approach to emergency management that evolves with changing needs and demographics. By acting now, Florida can protect its residents, its economy, and its future, setting a benchmark for disaster preparedness across the nation.

A Appendix

B Data Descriptions

B.1 Emergency Medical Services Dataset

The Emergency Medical Services (EMS) dataset provides key information about EMS providers, including their location, available vehicles, and population coverage.

Variables	**Description**
Name	Name of the EMS provider
Address	Physical address of the EMS facility
City	City where the EMS facility is located
Zip	ZIP code of the EMS facility's location
COUNTY	County in which the EMS facility operates
LONGLAT	Longitude and latitude combined
Facility_Type	EMS facility type (Air Ambulance, Ambulance)
Number_Ambulance	Total ambulances available
Number_Air_Ambulance	Total air ambulances available
Population	Population served by the EMS

Table 2: Description of the Emergency Medical Services Dataset

B.2 Hospital Dataset

The Hospital dataset includes details about hospital capacity, such as total beds, ICU patients, and vacancies. This data is essential for prioritizing evacuation efforts.

Column Name	**Description**
Name	Name of the hospital
Address	Physical address of the hospital
City	City where the hospital is located
Zip	ZIP code of the hospital's location
COUNTY	County where the hospital operates
Total_Beds	Total number of hospital beds
ICU_Patients	Total ICU patients currently admitted
Vacancy	Available vacant hospital beds

Table 3: Description of the Hospital Dataset

B.3 Modeling the Missing Information

To address gaps in the dataset, assumptions and estimations were made to model vehicle availabilities and hospital capacities based on publicly available data and U.S. national averages.

B.3.1 Estimating Vehicle Availabilities

- **Ambulance**:
  - Per Population: Assumed 1 ambulance per 21,057 residents.
  - Workload: Each ambulance handles approximately 2,408 calls annually, averaging 6.5 calls per day.

- **Fire Station Ambulance**:
  - Populations under 2,500: 1.13 ambulances per 1,000 population.
  - Populations over 1,000,000: 0.03 ambulances per 1,000 population.
- **Air Ambulance**: Florida's 19 cities providing air ambulance services each have 5 air ambulances, totaling 95 statewide.
- **School Buses for Non-Critical Evacuations**:
  - Cities with more than 200,000 residents: 3 buses per EMS.
  - Cities with 50,000–200,000 residents: 2 buses per EMS.
  - Cities with 10,000–50,000 residents: 1 bus per EMS.
  - Cities with less than 10,000 residents: 0 buses per EMS.

B.3.2 Hospital Capacity Estimation

- **Total Beds**: Data for total beds was obtained from hospital records.
- **Critical Care Patients (ICU)**: Hospitals are classified by total bed counts:
  - Hospitals with 100 or more beds: Assumed 13 ICU patients on average.
  - Hospitals with 50–100 beds: Assumed 8 ICU patients on average.
  - Hospitals with less than 50 beds: Assumed 6 ICU patients on average.
- **Vacancy Rate**: The average hospital bed vacancy rate is estimated between 30

Note: All estimations were calculated based on U.S. national averages and publicly available census data (referenced in the Bibliography).

B.4 Florida Hospital Risk Map

This map highlight the safe zone hospital(in green) and the risky-zone hospitals (in red).

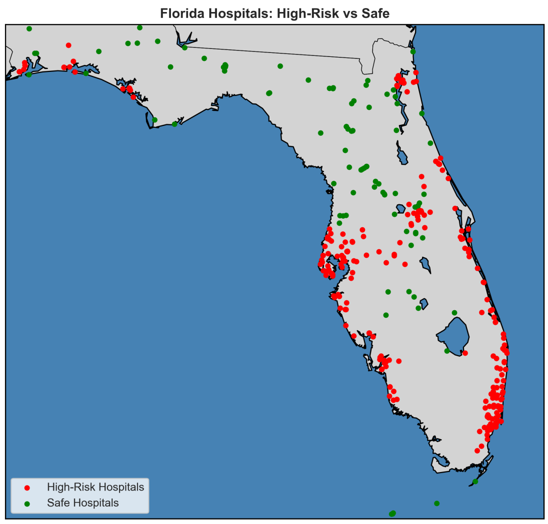
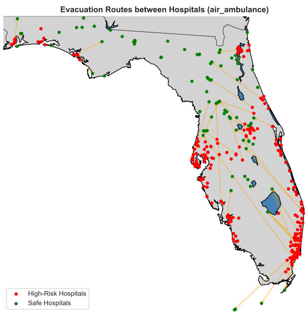


Figure 1: Florida Hospitals: High-Risk vs Safe

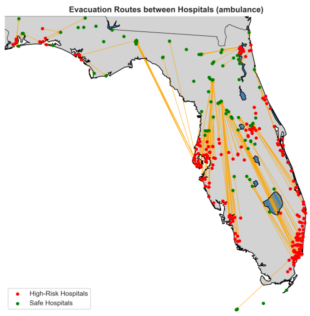
C Results

C.1 Optimized Route Maps

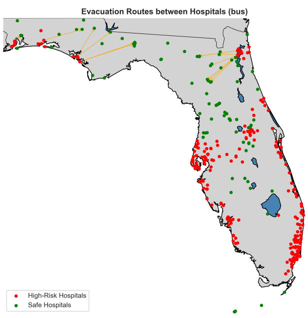
The figures below illustrate the riskier regions, hospital classifications, and evacuation routes as determined by the model.



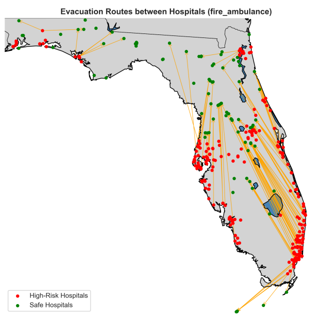
(a) Air Ambulance



(b) Ambulance



(c) Bus

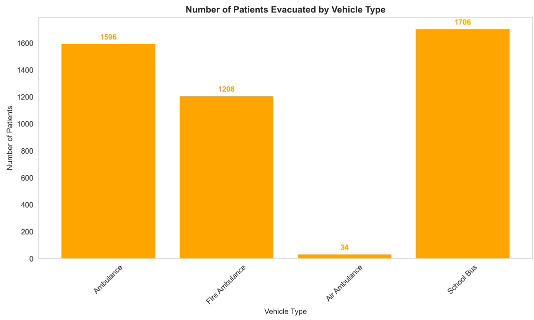


(d) Fire Ambulance

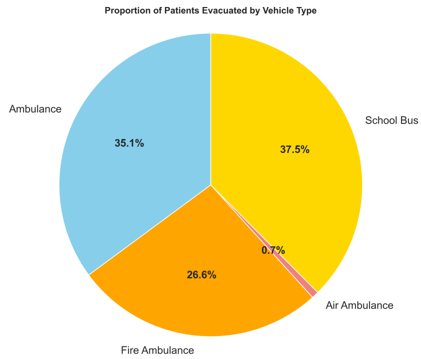
Figure 2: Evacuation Routes Between Hospitals by Vehicle Type

C.2 Vehicle Distribution and Proportion of Patients Evacuated

The visualizations collectively provide a detailed analysis of patient evacuations by vehicle type. The bar chart highlights the absolute number of patients evacuated, with school buses transporting the highest at 1,706 patients, followed by ambulances and fire ambulances, while air ambulances have a minimal role. The pie chart complements this by showcasing the proportional contribution of each vehicle type, where school buses dominate (37.5%), and air ambulances contribute only 0.7%, reflecting their specialized but limited capacity. The cumulative evacuation over time graph illustrates the steady progress of evacuations, with school buses and ambulances demonstrating consistent performance, while air ambulances maintain a marginal but critical presence.



(a) Vehicle Distribution for Top 10 Risky Hospitals



(b) Proportion of Patients Evacuated by Vehicle Type

Figure 3: Comparison of Vehicle Distribution and Patient Proportion by Evacuation Type

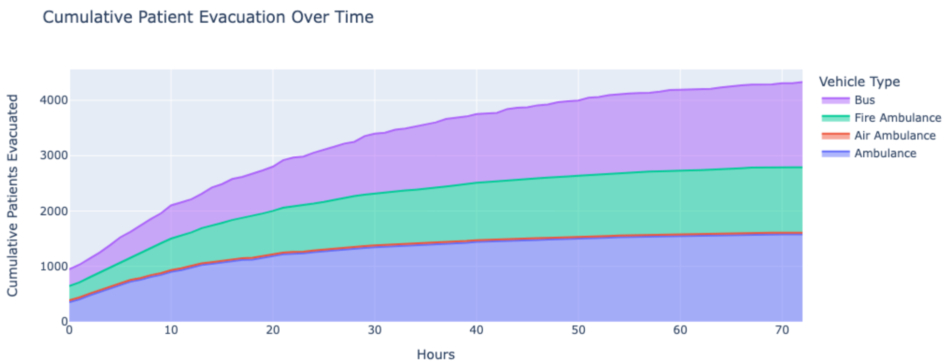
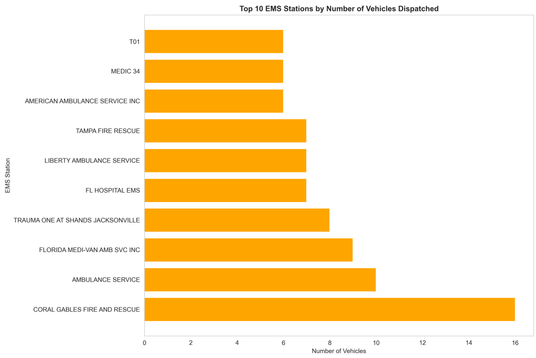


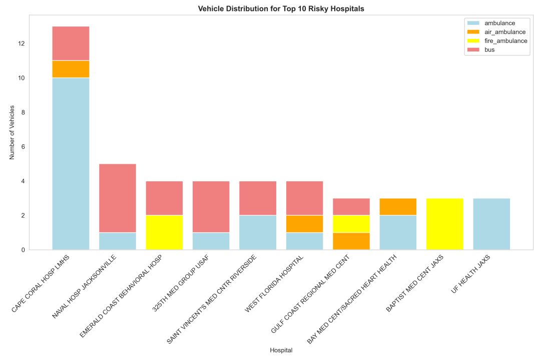
Figure 4: Cumulative Patient Evacuation Over Time

C.3 EMS and Hospital Vehicle Analysis

The first graph, Top 10 EMS Stations by Number of Vehicles Dispatched, highlights the distribution of resources across emergency medical services. Coral Gables Fire and Rescue leads with the highest number of vehicles dispatched, showcasing its pivotal role in evacuation efforts. Other EMS stations, such as Florida Medi-Van and Trauma One, also play significant roles, indicating the importance of a concentrated yet diverse allocation of vehicles. The second graph, Vehicle Distribution for Top 10 Risky Hospitals, illustrates the variety of vehicle types allocated to hospitals. Cape Coral Hospital LMHS receives the highest number of vehicles, primarily ambulances, reflecting its critical needs. Other hospitals also show a mix of vehicle types, emphasizing a strategic balance between buses, fire ambulances, and ambulances to address varying patient requirements effectively.



(a) Top 10 EMS Stations by Number of Vehicles Dispatched



(b) Vehicle Distribution for Top 10 Risky Hospitals

Figure 5: Comparison of EMS Stations and Vehicle Distribution for Risky Hospitals

D Problem Extensions

Sensitivity analysis was not conducted due to the limitations of solving problems with multiple objective functions using Gurobi. This restriction prevented us from directly examining the impact of varying parameters on the results. Instead, our approach involved adjusting key constraints to observe how the system responds.

As an example, the table below summarizes how the solution would change if we decrease the time to prepare for the evacuation:

Metric	**96 Hours**	**80 Hours**	**64 Hours**	**48 Hours**	**32 Hours**	**16 Hours**
Total Patients Evacuated	4598	4598	4598	4598	4958	4598
Total Cost	\$759,017	\$756,896.57	\$756,718.11	\$756,915.36	\$759,911.32	\$769,163.68
Total Pollution (pounds)	1,524,680	1,524,688.44	1,523,323.09	1,525,463.71	1,528,049.56	1,554,927.50
Patients Evacuated by Ambulance	1596	1592	1594	1568	1500	1294
Patients Evacuated by Air Ambulance	34	34	38	34	32	32
Patients Evacuated by Fire Ambulance	1208	1212	1206	1236	1306	1512
Patients Evacuated by Bus	1706	1760	1760	1760	1760	1760

Table 4: Comparison of Evacuation Metrics different response time scenarios

The table shows how the evacuation process shifts as the time available decreases, and it highlights some interesting trade-offs. With 96 hours, everything runs smoothly—4,598 patients are evacuated, costs stay manageable at \$759,017, and CO_2 emissions are kept at 1,524,680 pounds. This scenario gives the model enough time to plan resource allocation efficiently without overloading any part of the system. As the time shortens to 80 hours, costs drop slightly, but CO_2 emissions creep up a bit. This suggests the model compensates by using faster, less fuel-efficient options to maintain the pace of evacuations. By the time we hit 64 and 48 hours, these changes become more noticeable. Ambulance usage starts to dip, and fire ambulances take on more of the workload. While this shows the model's flexibility, it also hints at growing inefficiencies as the system works harder to keep up. At 16 hours, the system hits its breaking point. Ambulance use drops drastically, evacuating just 1,294 patients, while costs climb to over \$769,000 and emissions jump to 1,554,927 pounds.

Despite the changes in Objective Values 2 and 3 (Costs and Emissions), it is clear that tightening the time limit constraint to as low as 16 hours has no impact on Objective Value 1 (Total number of patients evacuated). The number of patients which can be evacuated is therefore bounded by the limited vacancies in the safe hospitals.

E Recommendations and Cost Forecast

E.1 Cost Breakdown for Recommendations

This table outlines the estimated costs for implementing and maintaining the proposed recommendations.

Recommendation	**Estimated Initial Cost**	**Estimated Annual Maintenance Cost**
Safe Haven 365: Multi-Use Shelters	\$200,000–\$400,000 per shelter	\$10,000–\$20,000 per shelter
Emergency Grid: Real-Time Database	\$500,000–\$1,000,000	\$50,000–\$100,000
EcoRescue: Sustainable Operations	\$50,000–\$100,000 per vehicle	\$5,000–\$10,000 per vehicle
Task Force One: Resilience Team	\$200,000–\$300,000	\$100,000–\$150,000

Table 5: Estimated Costs for Recommendations Implementation

E.2 Key Stakeholders and Roles

This table identifies the key stakeholders involved in the evacuation process and their responsibilities.

Stakeholder	Role and Importance
Local Government Agencies	Oversee evacuation orders and allocate resources on the ground.
State Government Agencies	Provide large-scale coordination and funding.
Federal Agencies (e.g., FEMA)	Offer disaster relief funding and logistical support.
Healthcare Facilities	Manage evacuations and provide continuous patient care.
EMS Providers	Facilitate patient transport and logistics for evacuations.
Private Sector Partners	Supply fuel, communication tools, and transport infrastructure.
Community Members	Support preparedness efforts and evacuation compliance.

Table 6: Key Stakeholders and Their Roles

E.3 Simulation Scenarios

This table summarizes the scenarios simulated to evaluate the evacuation model under different conditions.

Scenario	Conditions Simulated	Outcome Summary
Baseline	Normal conditions: 50% EMS availability	All ICU patients evacuated; partial relocation of non-ICU patients.
High Congestion	Reduced travel speeds (40%)	Delays for non-ICU patients; ICU patients prioritized.
Limited Resources	30% EMS availability	Evacuations focused only on high-risk hospitals.

Table 7: Summary of Simulation Scenarios

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