Avoiding The Eye of the Storm

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Abstract

- With an approaching hurricane, emergency managers face a set of logistical action timing decisions: supply, pre-positioning, mobilization, evacuation, and humanitarian aid. The location, time and intensity of the hurricane at landfall are random variables governed by nature. We developed a stochastic dynamic program incorporating economic, social, and logistical impacts of alternative sequential decisions. Results are given for a set of global case studies.

Overview

- Hurricane Costs
- Tracking and Predicting Hurricanes
- Decisions
- Outline of Stochastic Dynamic Programming Decision Model
- Computational Example
- Future Goals

Hurricane Costs

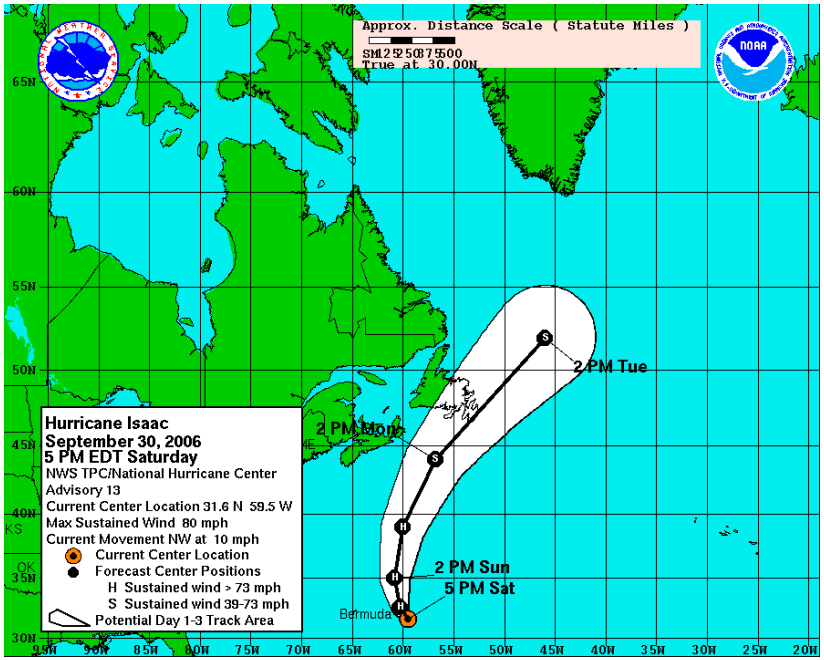
- Average cost of $6.3 billion per year in the US.
- 2004 had $40 billion in damages
- 2005 Hurricane Katrina caused more then $75 billion in damages
- Damages can be mitigated through proper planning and decision making
- Our goal is to develop a model to accomplish this

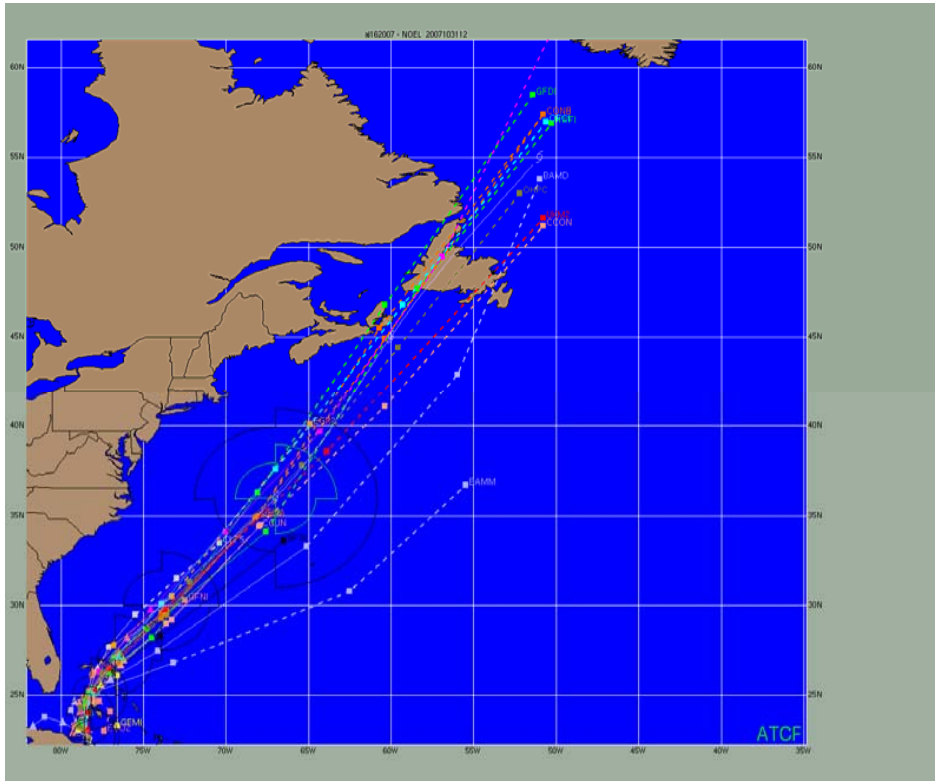
Hurricane Categories

- Based on Sapphire-Simpson Scale
- **Category 1 Hurricane** — winds 74-95 mph. No real damage to buildings.
- **Category 2 Hurricane** — winds 96-110 mph. Some damage to building roofs, doors and windows.
- **Category 3 Hurricane** — winds 111-130 mph. Some structural damage to small residences and utility buildings.
- **Category 4 Hurricane** — winds 131-155 mph. More extensive curtain wall failures with some complete roof structure failure on small residences.
- **Category 5 Hurricane** — winds 156 mph and up. Complete roof failure on many residences and industrial buildings.

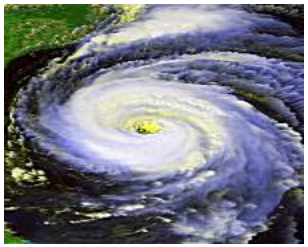
Hurricane Tracking

- Convex Combination of Atmospheric Models
  - Discretion on part of NHC

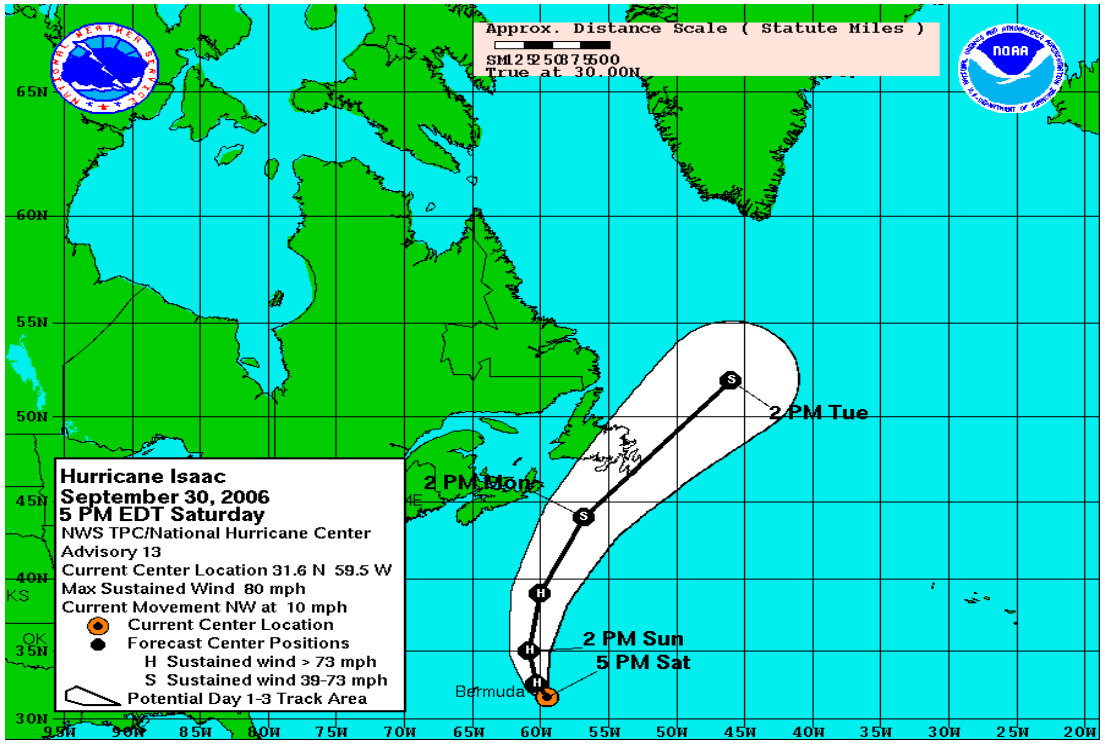




Hurricane Tracking



- Error Cone
  - Based on 10 years of historical errors
  - Concentric circles are connected to form cone



Our Problem

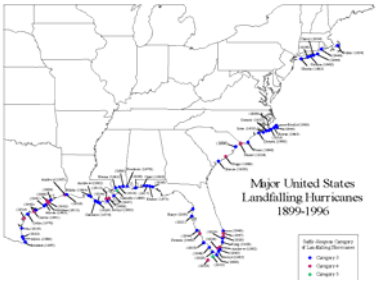
- With an approaching hurricane, government decision makers face a set of action timing decisions:
  - Supply pre-positioning
  - Mobilization
  - Evacuation.
- The location, time and intensity of the hurricane at landfall are random variables governed by nature.
- We develop a stochastic dynamic program incorporating economic, social, and logistical impacts of alternative sequential decisions.

Defining the Dynamic Program

- Our DP Will have a set of
  - States:
    - These represent the current position or set of decisions and hurricane parameters
  - Stages:
    - We will have 11 stages where we make decisions
  - Variables:
    - We have two types of variables: deterministic (decision parameters) and probabilistic (storm parameters)

Time Index	Time(Hours)
11	72
10	48
9	36
8	24
7	18
6	12
5	9
4	6
3	4
2	2
1	1

Defining the State



- We consider the state at index i to be

$$s_i(E,P,M,D,W)$$

- D is the current track or direction with respect to the coast
- W is the wind speed discretized to the current category
- E is Evacuation Vector(0-1)
- P is Propositioning Vector(0-1)
- M is Mobilization Vector(0-1)

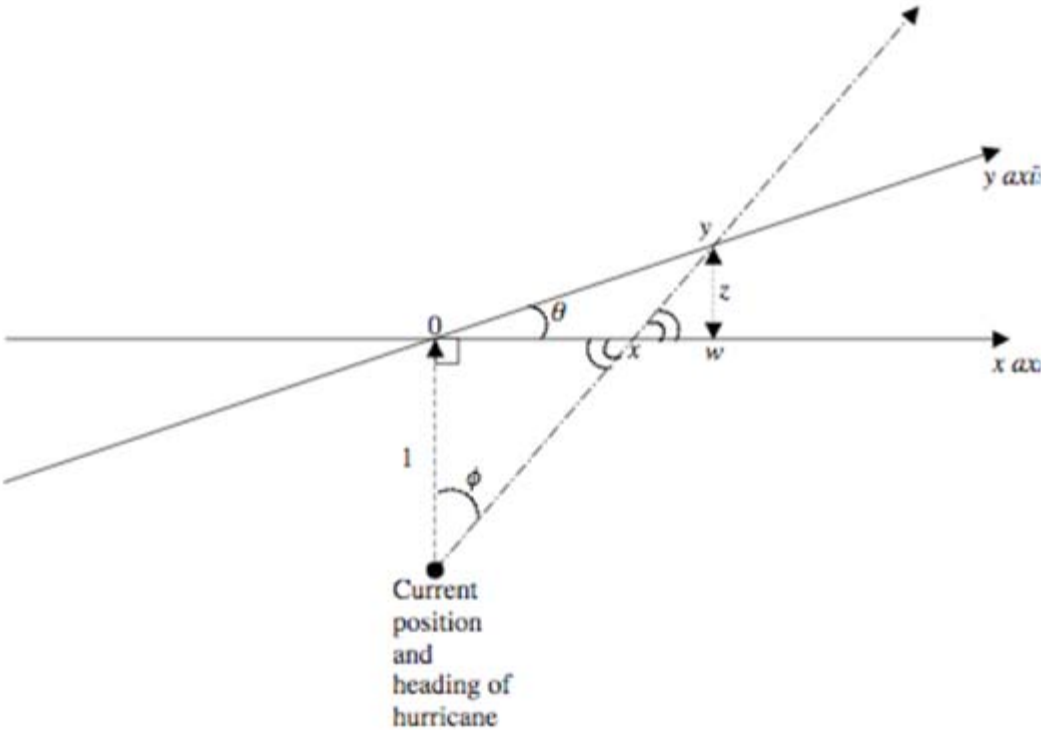
$$\overline{E_i} = [E_{1_i}, E_{2_i}, \ldots, E_{n_i}]$$

$$\overline{P_i} = [P_{1_i}, P_{2_i}, \ldots, P_{n_i}]$$

$$\overline{M_i} = [M_{1i}, M_{2_i}, \ldots, M_{n_i}]$$

Describing the Hurricane

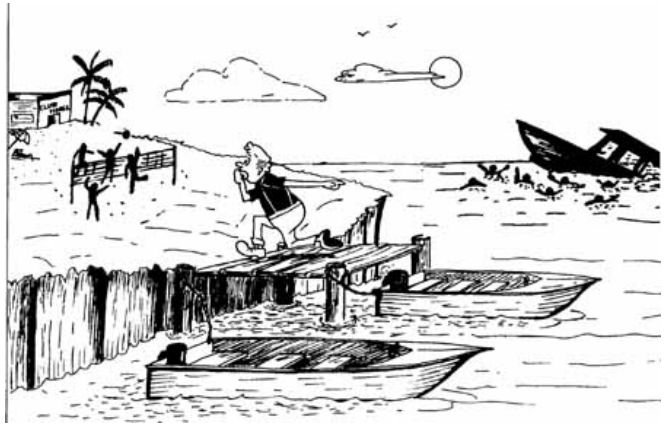
- Determining the risk of given location "x"
  - Expected landfall location with respect t "x"
    - View coast as a straight line
  - Current strength
    - Hurricane Category



$$F_Y(y)=P\left\{\frac{X\tan(\theta)}{\sin(\theta)[1-X\tan(\theta)]}\le y\right\}=P\left(X\le\frac{y\sin(\theta)}{\tan(\theta)[1+y\sin(\theta)]}\right\}=F_x\left(\frac{y\sin(\theta)}{\tan(\theta)[1+y\sin(\theta)]}\right),\quad 1-\frac{1}{\sin(\theta)}<y\le\infty$$

Decisions

- Three Main Types:
  - Evacuation
  - Pre-positioning
  - Mobilization



Evacuation

Figure 19 – South Carolina DOT Contraflow Operations

- Example of List
  - Elderly in nursing homes
  - Hospital patients
  - Elderly
  - Tourists
  - Families with children
  - Families in mobile homes
  - General population

Evacuation: Initial Constraints

- Divide population into priority subgroups
  - Input from emergency manager
- Evacuation order can not be reversed
- Constraint is if i>j group i can not evacuate before group j
- Flow constraint on number that can be evacuated at any given stage
  - Traffic Congestion
- Each group has a required lead time
  - Input from emergency manager

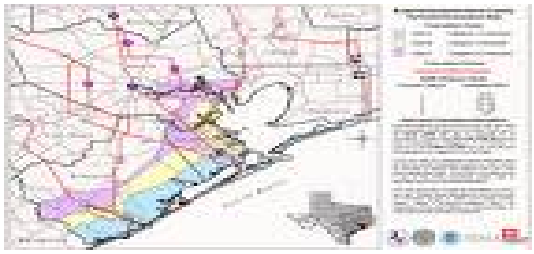
Prepositioning

- Decisions to Think About
  - Making sure buses have fuel
  - Setting up reverse traffic lanes
  - Setting up potential shelter locations
  - Planning evacuation routes
  - Ensuring food and water are available to those stuck in traffic

Mobilization

- Decisions to Think About
  - Call in National Guard
  - Send police to given points to help with evacuation
  - Reverse traffic
  - Call in aid from nearby communities

Defining Costs



- Each Time we take an action (i.e. change a vector state from 0 to 1) we incur a cost.
- We assume the cost for each action does not vary over time
- Let: $f_i(d_i, s_i, \tilde{r}_i)$ be the cost of the decision's we make in stage I
- Our objective is to minimize the total cost:

$$v(s_j) = \min[E(\sum_{i=j}^{n} f_i(d_i, s_i, \tilde{r}_i))]$$

- Or by the principle of optimality we get:

$$v(s_i) = \min[E(f_i(d_i, s_i, \tilde{r}_i) + v_{i+1}(\tilde{s}_{i+1})]$$

Defining Costs

- Some costs are easier to calculate then others
  - Propositioning Costs: Easier
    - Ordering extra tape for windows
    - Fueling up buses to assist in evacuation
  - Evacuation Costs: Harder
    - What is the cost to evacuate the elderly population in Miami?
      - Economists have a general notion of 1 million per mile
    - Costs Based On: Whitehead, John C. "One Million Dollars Per Mile? The Opportunity Costs of Hurricane Evacuation." *Ocean and Coastal Management* 46 (2003), p. 1069-1083.

Terminal Cost

- Depending on if the hurricane hits or not there is a large balloon cost/benefit (B) at the last state
- B is a function of all the current state parameters
- If the hurricane misses then the community incurs all costs without the benefits
- If the hurricane hits there is some benefit cost to the evacuation
  - This depends partly on the state of the hurricane when it hits

The Dynamic Program

- Using these we can define the Bellman equations:

$$v(s_i) = \min[E(f_i(d_i, s_i, \tilde{r}_i) + v_{i+1}(\tilde{s}_{i+1})]$$

$$ST:$$

$$\tilde{s}_{i+1} = t_i(d_i, s_i, \tilde{r}_i)$$

$$d_i \in D_i$$

- With the following initial conditions

$$v(s_n) = \min[E(f_n(d_n, s_n, \tilde{r}_n)]$$

$$ST:$$

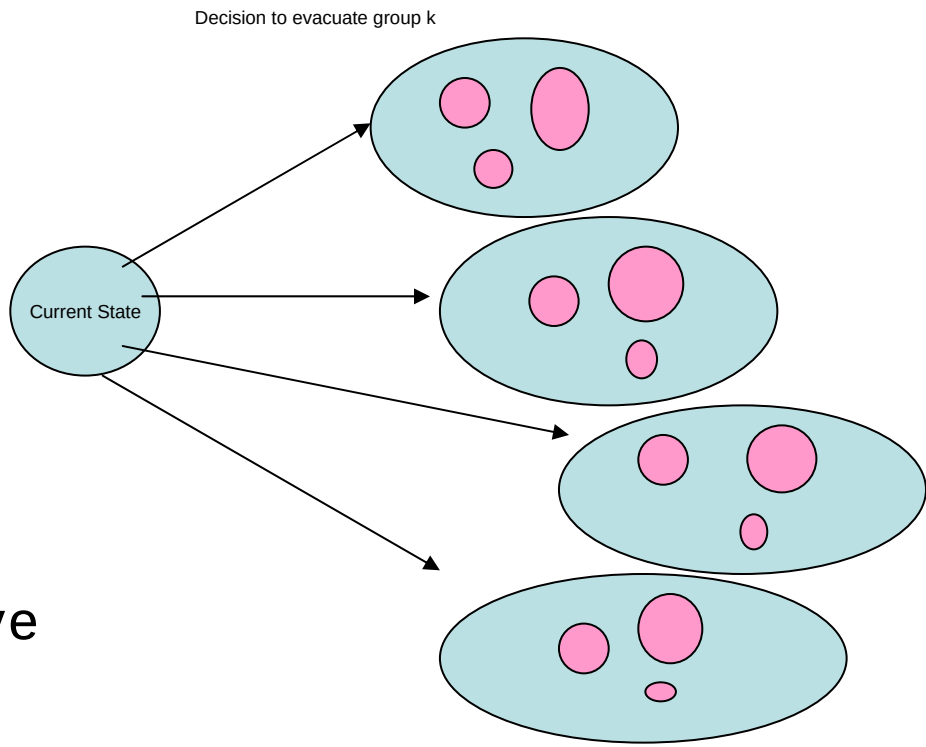
$$d_n \in D_n$$

The Rolling Horizon Nature

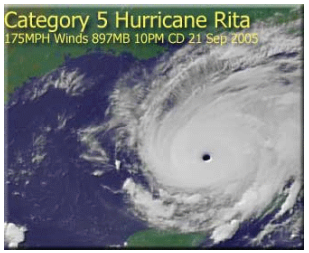
1. Make a decision
2. Random event occurs
3. Arrive at new state
4. Repeat decision process

We solve n dynamic programs where each is one stage shorter

- This makes the problem live in nature
- Exponentially increases the complexity of the problem
- Using linear decision vectors helps cut down the curse of dimensionality



Computational Example



Computational Example

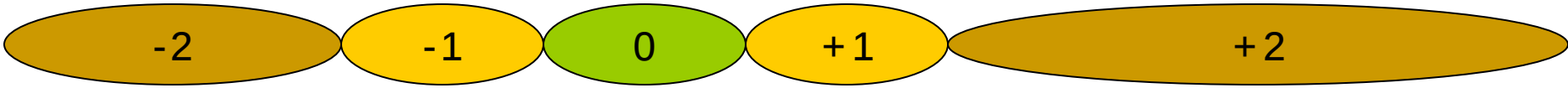
- Hurricane is expected to hit Marathon in 48 Hours

Group	Population	Evacuation Cost	Lead Time Needed
Elderly	13%	16 Million	36 Hours
Poor	26%	12 Million	28 Hours
Torist	12%	10 Million	24 Hours
Middle Class	49%	10 Million	24 Hours
Total	50 Million	48 Million	

  - Congestion constraint that at most two groups can be evacuated during a stage.
  - We have four decision stages:48, 36, 28, and 24 hours out.
  - Costs Based On: Whitehead, John C. "One Million Dollars Per Mile? The Opportunity Costs of Hurricane Evacuation." *Ocean and Coastal Management* 46:11-12 (2003), p. 1069-1083.
  - Evacuation times taken from FEMA's Hurricane Evac Program.

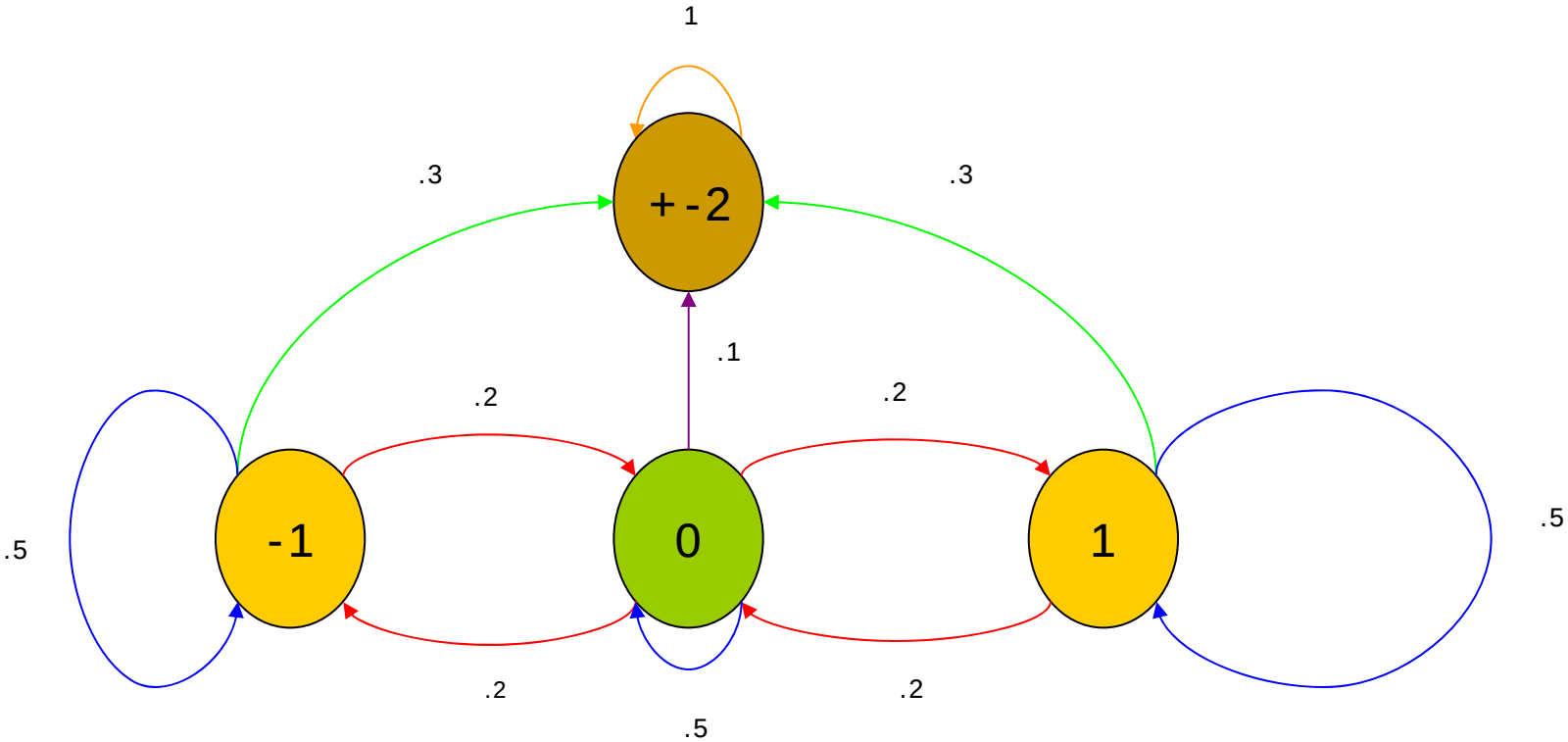
Example: Directional Movement

- Scenario (continued):
  - We break up the coast into four segments
    - 0 Represents within 30 miles of Marathon
    - +-1 Represents between 30 and 60 miles of Marathon
    - +-2 Represents more the 60 miles away from Marathon
    - View the hurricanes movement as linear with respect to the coast



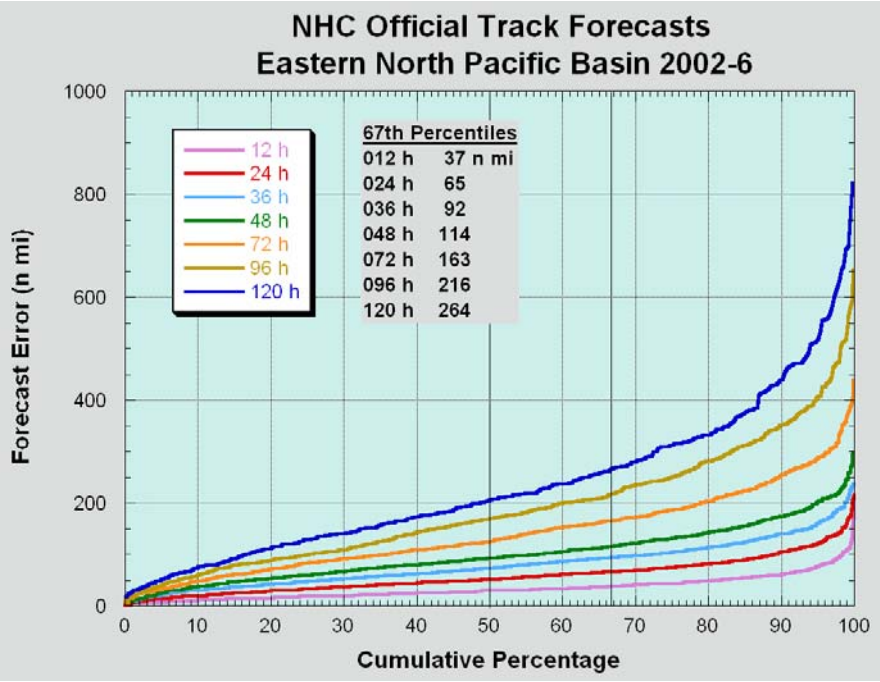
Computational Example

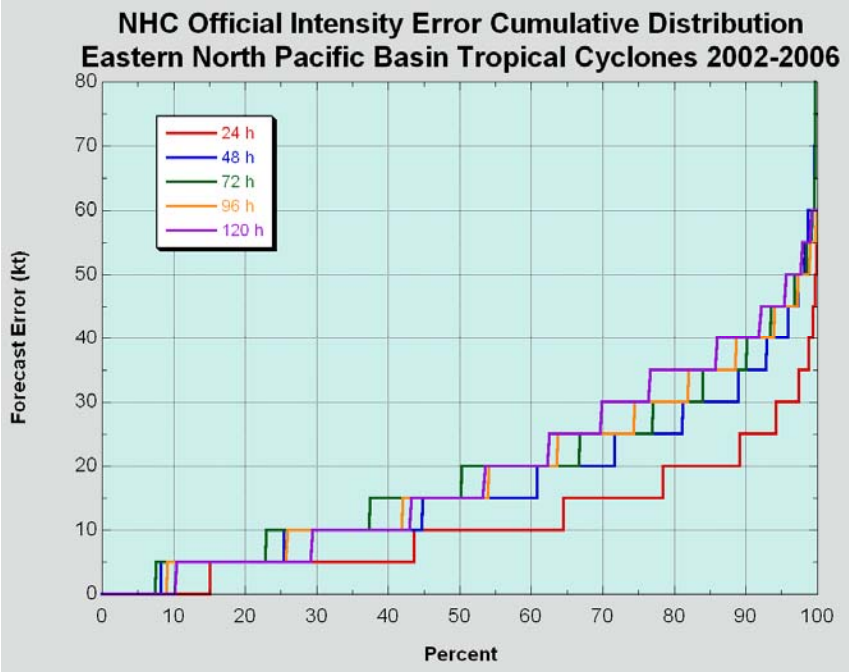
- We Model the Hurricane Position as a Markov Chain



Example: Category Movement

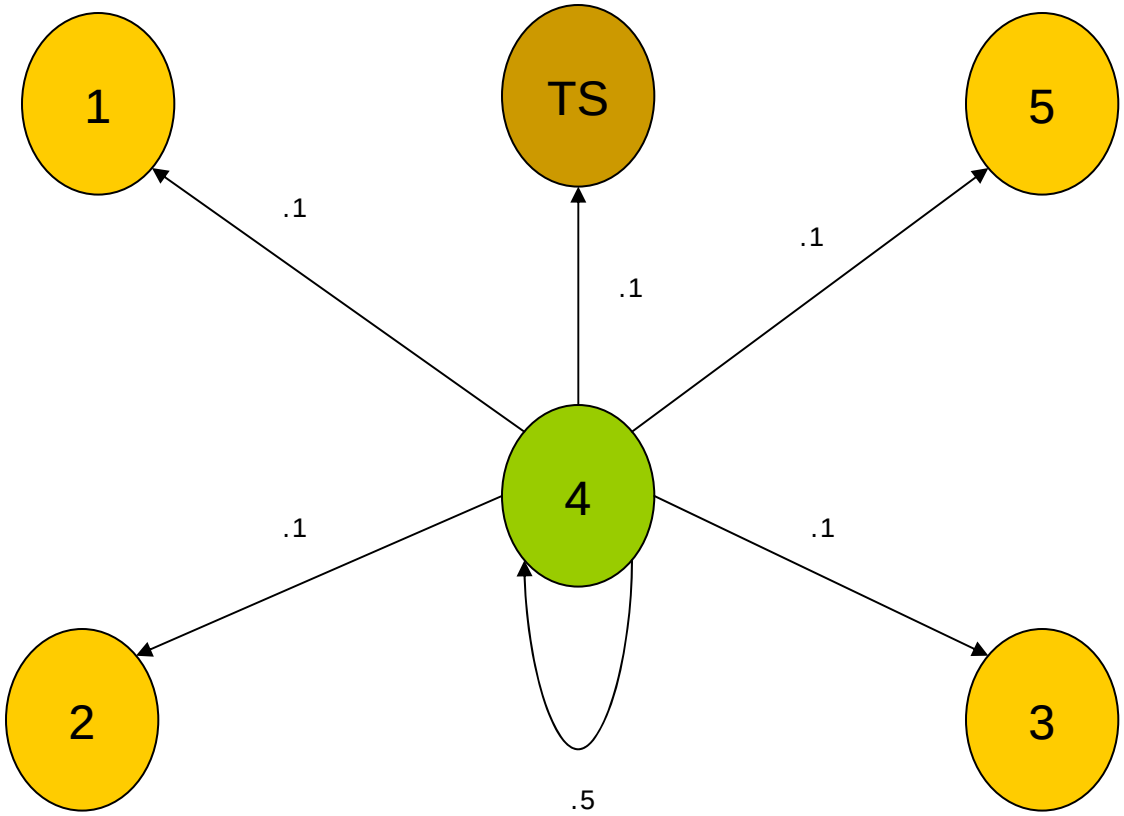
- Scenario (continued):





Computational Example

- We Model the Hurricane Category as a Markov Chain:

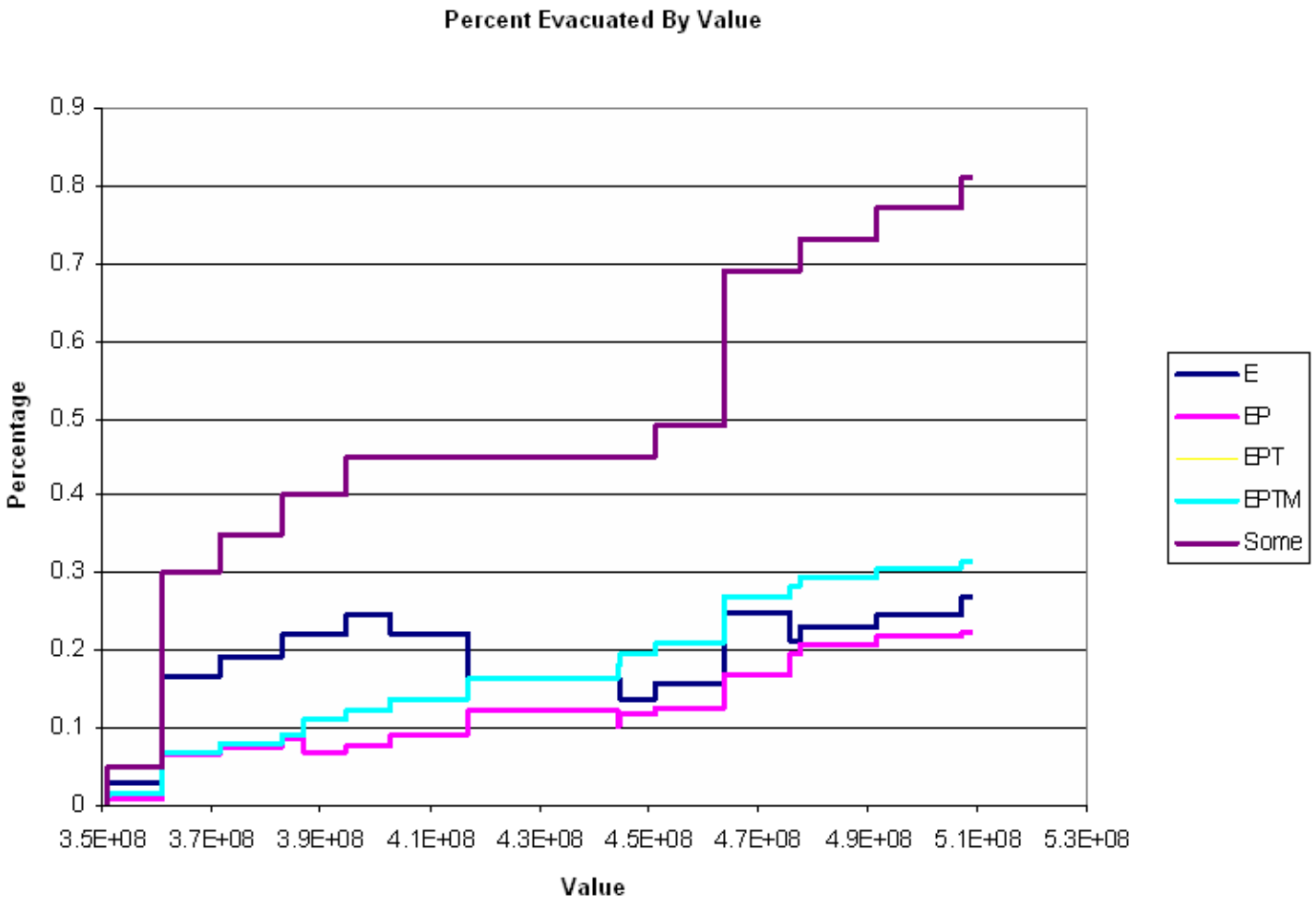


Computational Example: Costs

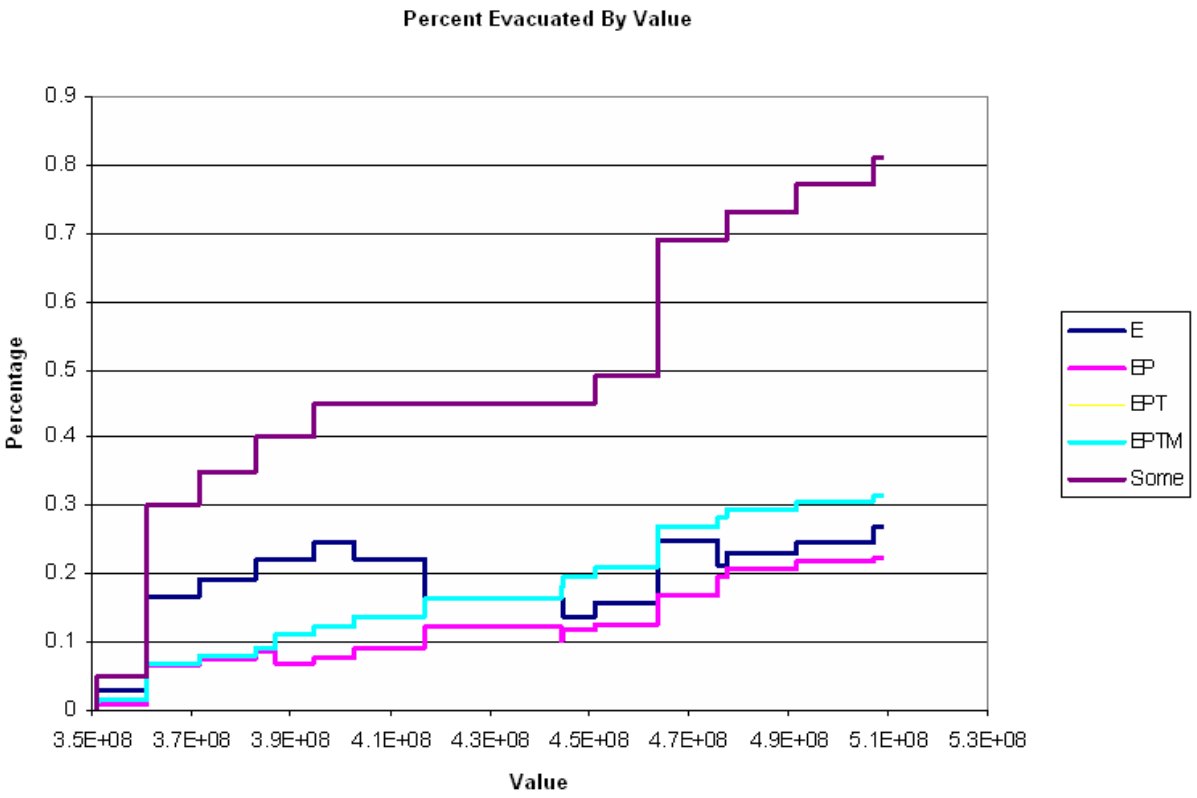
- Scenario (continued):
  - One of the hardest values to calculate is the amount saved from evacuating a group
  - We set x to be the total benefit from evacuating the entire population when a category 5 storm hits.
  - By performing sensitivity analysis we can see how decisions are made based on x

Terminal Costs		Group	Population	%
		E	16	0.333333
		P	12	0.25
X Value		T	10	0.208333
-451039579		MI	10	0.208333
Category 5			% Of Pop	
-451039579		None	0	
		E	0.333333333	
Category 4		E,P	0.583333333	
-360831663.2		E,P,T	0.791666667	
		E,P,T,MI	1	
Category 3				
-270623747.4				
Category 2				
-180415831.6				
Category 1				
-90207915.8				
30+ Miles				
0				

Results

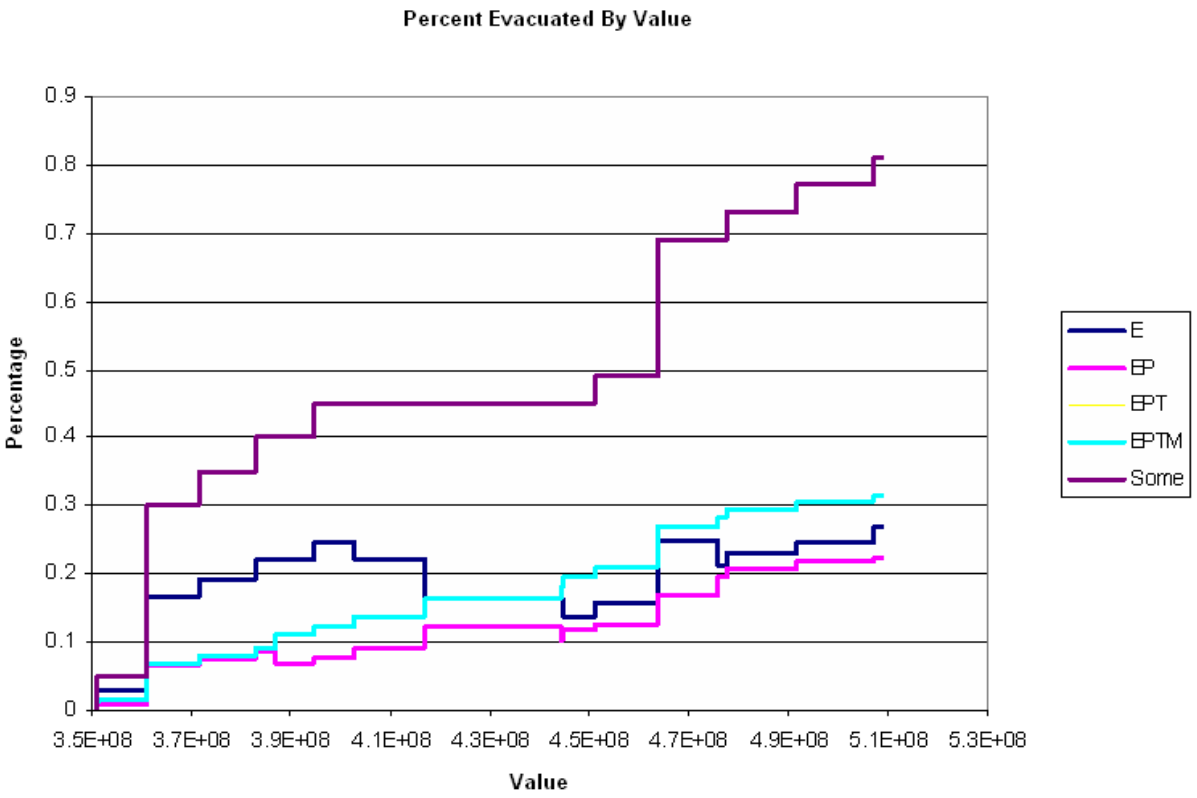

Percent Evacuated By Value
Percentage
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3.5E+08
3.7E+08
3.9E+08
4.1E+08
4.3E+08
4.5E+08
4.7E+08
4.9E+08
5.1E+08
5.3E+08
Value
E
EP
EPT
EPTM
Some

Results



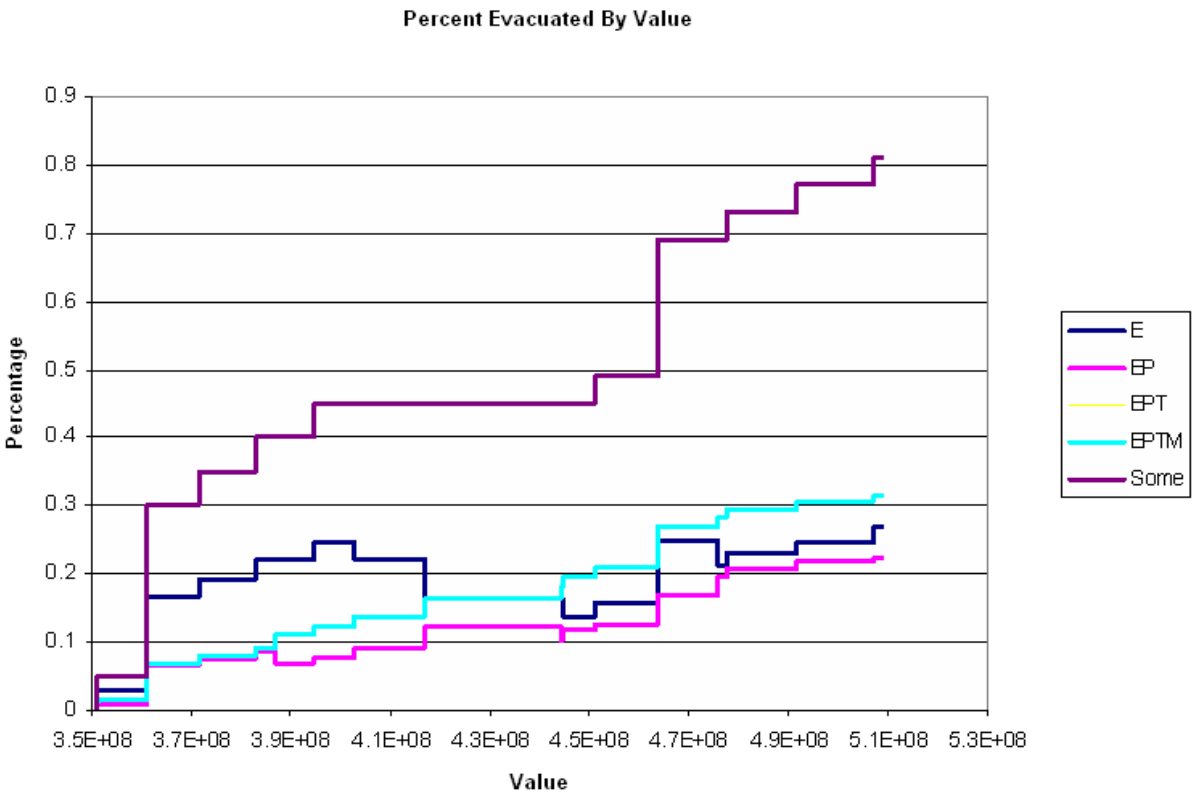
Wait as long as you can to evacuate group i so long as not evacuating group i does not affect the evacuation of subsequent groups.

Results



EPT is never evacuated

Results

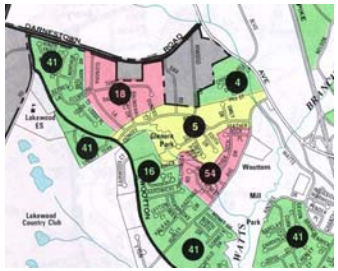


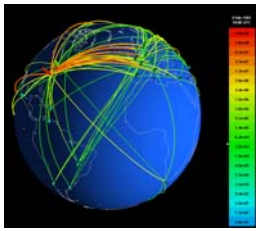
The graph of EPTM is a piecewise linear non-decreasing function

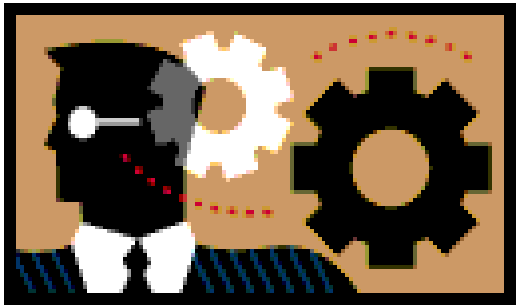
Case Study Results

- Case Studies were run on five past hurricanes
  - Karina, Charlie, and Floyd
- Results show on average a 23% estimated decrease in lives lost compared to when no mathematical model was used
- The percentage improvement is large for the stronger storms

Building A Robust Model







Main Idea

- By using a mathematical based stochastic decision model to assist the emergency manager a significant percentage of lives can be saved when a community is faced with the threat of a severe hurricane.