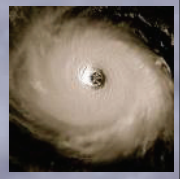
A Stochastic Decision Model For Hurricane Preparedness, Logistics, and Response



Michael D. Metzger PHD. Student, Professor Richard Larson

CREATE Center of Excellence (affiliated with Structured Decisions Corporation), Massachusetts Institute of Technology

Introduction

Hurricanes: Deadliest Natural Disaster in the US

Hurricanes can result in thousands of deaths and tremendous costs. In fact, as of 2008, hurricanes caused 7 of the 10 deadliest disasters in the US. Since 2004, hurricanes have cost the US over $200 billion.

Hurricane	Year	Deaths	Damages
Katrina	2005	1836	$1.2 Billion
Ivan	2004	92	13 Billion
Rita	2005	107	10 Billion
Gilbert	1988	341	5.5 Billion
Mitch	1998	18000	6.2 Billion

Examples of some of the costliest hurricanes since 1980

Unfortunately, hurricanes are stochastic in nature and are tough to predict. Emergency managers, responsible for a given geographic area, must make these decisions in the face of uncertainty. Currently, these decisions are made qualitatively. To date, no one has developed a quantitative model for hurricane decision making under uncertainty.

The Stages of a Storm

Our model will be divided into a set of discrete stages

- Stages are indexed by the expected time until landfall.
- As the hurricane approaches, the time between stages decreases exponentially.
- We will have at most 11 stages.
- The specific number of stages is defined by the emergency manager.

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

Modeling the Hurricane

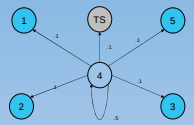
Hurricanes can be classified according to two main variables:

- Expected landfall location
- Intensity

The NHC predicts hurricane position and intensity using wind probability tables.

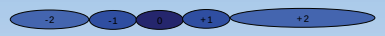
Category	Windspeed(mph)	Surge(feet)
1	74-95	4-5
2	96-110	6-8
3	111-130	9-12
4	131-155	13-18
5	155+	18+

Categories are based on a scale. Between each stage, a transition in both location and intensity can occur. In order to capture these in our model, we represent them as discrete time Markov process. The transition probabilities are region specific based on historical data mining.

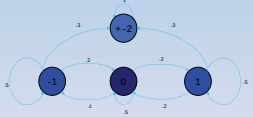


Transition diagram conditional on the current category being 4

Similarly, in order to capture the transition effect of the expected location of landfall, we divide the coast into discrete segments.



The transition of expected distance between states is conditional with respect to the angle the hurricane makes with the coast. This is abstracted to form a Markov process.



How the Angle with the Coast Influences the Transition Matrix

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

Modeling the Dynamic Program

Emergency managers have three types of decisions to make:

•Evacuation

Decisions include:

- Elderly
- Poor
- Middle Class

•Prepositioning

Decisions include:

- Fueling Busses
- Positioning Police
- Distributing Supplies

•Mobilization

Decisions include:

- Acquiring Aid
- Reversing Lanes
- Calling in Guard

We model each type of decision as an independent preordered priority based vector. The input order comes from the emergency manager. We impose the following constraints:

- Once a decision is made, it can not be reversed.
- If $i>j$ decision i cannot be executed before decision j
- In order to avoid congestion, a maximum cap is put on the percentage of the population that can be evacuated during a given stage.
- Since some activities take longer than others, a lead time constraint is imposed on each activity.

Our Forward Bellman Recursion Equations for the Stochastic Dynamic Program:

$$f_i(s(l,w,e)) = \min_a [E[d_a + \sum_j p(j \mid l,w,e,a,i)\, f_{i+1}(j)])]$$

Here:

- $s(l,w,e)$ is the current state of the model
- l is the current expected landfall location of the hurricane with respect to the city
- w is the current category of the storm
- e is the state of the evacuation vector
- d_a is the cost of making decision a
- $f_i(s(l,w,e))$ represents the minimum expected cost from the current state
- The min in the equation is taken over all feasible decisions
- $p(j \mid l,w,e,a,i)$ is the probability that the next stage will be j given that the current stage is i and action a is chosen.
- The summation represents the minimum expected cost from stage $i+1$

Where our terminal cost function is given by:

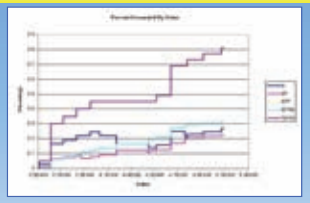
$$B(s(l,w,e_n) = xvalue * e_n * \frac{w}{5} = \%ofPopulationEvacuated * \% \frac{Category}{5}$$

- Is the negative cost associated with property and lives saved due to evacuation if the storm makes landfall at the city. If the hurricane's position is not zero, the value of the function is zero.

Results and Conclusions

We tested our model on examples, as well as five historical case studies.

- Examples show a reduction in deaths by up to 23%
- Large percentage gains come from stronger storm examples
- Case studies for five past hurricanes include: Katrina, Charlie, and Floyd
- By adding to the robustness of the model, even more promising results are achieved



Program Results for Sensitivity Analysis on Balloon Cost

- Using a robust stochastic dynamic program can aid in the decision process and has the potential to save a significant number of lives and property.

Acknowledgements

This project was funded through the CREATE Center of Excellence by a grant from the Department of Homeland Security, Science and Technology Directorate, Office of University Programs.

Further Information

- Please contact: Michael D. Metzger mmetzger@mit.edu
- Alternate Contact: Professor Richard Larson rclarson@mit.edu

- Larson, Metzger, Cahn; Emergency Response for Homeland Security: Lessons Learned and the Need for Analysis; INTERFACES (Special issue on Applications of Homeland Security), January 2007.

- The following is a link to the above paper: http://www.sdcorp.net/public/Pub_Emergency_Response_Homeland_Security.pdf
- For other papers on this subject see: http://www.sdcorp.net/metadot/index.pl?id=2064&isa=Category&op=show