An Agent-based Framework for Modeling the Effectiveness of Hurricane Mitigation Incentives

Bin Pei
Graduate Research Assistant, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA
Weichiang Pang
Associate Professor, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA
Firat Y. Testik
Associate Professor, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA
Nadarajah Ravichandran
Associate Professor, Glenn Dept. of Civil Engineering, Clemson University, Clemson, USA

ABSTRACT: To evaluate the effectiveness of different incentives for mitigating regional hurricane hazards, an agent-based hurricane mitigation framework was developed. This framework, which consists of six essential components, is able to consider stakeholders' points of view on the selections of hurricane retrofit measures and the dynamic evolutions of building inventories (i.e. constructions and demolitions). Based on the findings of this study, among different levels of property tax reduction, a reduction between 50% and 75% was found to be the most effective one that leads to the highest hurricane cost reduction the study region can get in a 25-year timeframe.

Agent-based modeling (ABM), which has a rapid growth in the past few decades, is a relatively new computational method (Gilbert 2007). The ABM is known as a "bottom-up" model. In ABM, the behavior of a complex system is studied without having to define the global behavior of the system. Rather, the behavior of individuals or subcomponents (hereafter referred as "agents") is defined and the interactions between the agents are modeled to unveil the global behavior (Borshchev and Filippov 2004). Agents' behaviors are defined using certain rules. Their interactions with each other as well as the environment can affect these rules and in turn influence agents' behaviors (Macal and North 2010). By modeling agents' behaviors and interactions individually, the behavior of the entire system can be revealed.

Nevertheless, the ABM is seldom used in hurricane related studies. Chen et al. (2006) developed an agent-based hurricane evacuation model for the Florida Keys using survey data. This model was able to estimate not only the minimum clearance time of the evacuation, but also the accommodations needed if the evacuation is interrupted by a landfall hurricane. A dynamic ABM system was developed by Dawson et al. (2011) for flood incident management. This system is able to estimate the vulnerability of individual agents in coastal communities, subject to different flood conditions, defense scenarios, warning times and evacuation strategies. The flood inundation, traffic condition, flood risk, agent's vulnerability and agent's behavior were modeled to evaluate the effectiveness of different FIM measures.

One of the key challenges in the ABM is the modeling of individual agent (Crooks et al. 2008). Specifically, it is the modeling of agent's demographic and psychological attributes, and their relations with agent's behaviors. The psychological attributes usually include risk perception, subjective knowledge, hazard experience, etc. Using data from the 2003 Hurricane Loss Mitigation Baseline Survey (HLMBS) (Peacock 2003b), Peacock et al. conducted three studies in analyzing the influences of Florida residents' demographic and psychological characteristics on (1) the status of hurricane mitigation (Peacock 2003a), (2) the hurricane risk perception (Peacock et al. 2005), and (3) the household responses to hurricane mitigation incentives (Ge et al. 2011). The influences were modeled using probabilistic models through logistic regressions. The outcomes of their studies are valuable resources for the modeling of agents' behaviors in hurricane mitigations.

In this study, an agent-based hurricane mitigation framework was developed for the purpose of evaluating the effectiveness of different incentives for mitigating the combined effects of hurricane wind and flood hazards. A case study hurricane mitigation domain (Miami, Florida) was constructed to mimic the real configuration of the existing building stock and the attributes of residents in the study domain. The occurrence of the new building constructions, demolitions and hurricane hazards over time was modeled using historical data. Agents' responses to hazards and incentives for retrofitting their homes, and decision-makings with regard to building retrofits were modeled using the survey data. Finally, the combined wind and flood loss estimations were performed to evaluate the cost-benefit of the hazard mitigation incentives.

This paper is organized such that an overview of the agent-based hurricane mitigation framework is presented in Section 1, followed by a case study in Section 2, and preliminary findings and conclusions are given in Section 3.

1. OVERVIEW OF THE AGENT-BASED HURRICANE MITIGATION FRAMEWORK

The proposed framework for agent-based regional hurricane mitigation is presented in
. This framework, which is composed of six modules, accounts for agents' responses to incentives and natural hazards in hurricane mitigations through modeling of agents' behaviors. The six modules are Buildings, Agents, Retrofits, Hazards, Constructions & Demolitions, and Incentives (see
). The behaviors of the six modules are defined individually and the connections between them are defined using a set of rules or functional relationships. These connections are marked as arrows, which indicate directional impacts from one module to the other, in

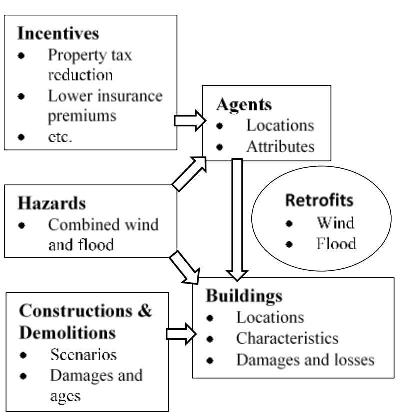

Figure 1: Framework for agent-based regional hurricane mitigation

. For instance, hazards can impart damages to buildings and cause losses, and hazards are also able to influence agents' psychological attributes or behaviors. The Retrofits module, marked as a circle, requires agents' decision making, which is affected by both hazards and incentives.

In this hurricane mitigation framework, the initial locations and characteristics of individual buildings as well as the initial locations and attributes of individual agents were first determined using historical survey data. Then, given selected incentives, simulations were performed at a fixed time interval (e.g. one month) to evaluate the performance of the entire system (i.e. all six modules and the connections). At every time step, the building characteristics and the agent attributes were updated. Agents responded to incentives and hazards, and decided if they wanted to retrofit their buildings. New constructions and demolitions occurred at every time step as well. When affected by a hurricane in a time step, the combined wind and flood losses was computed using a loss estimation framework adapted from the HAZUS-MH methodology. The updates of building characteristics, including demolitions, and agent attributes were simulated after the hurricane. The following sub-sections are organized to describe this process in detail.

1.1. Building locations and characteristics

As mentioned above, a key feature of the agent-based modeling is to model each individual from the bottom. This requires specific modeling of each individual building that exists in the study domain. For simplicity and as an illustrative example, only residential buildings were taken into account in this study. Buildings were modeled as individual dots (dimensionless) on a map (see Figure 2) containing location and characteristic information, which are adequate for regional hurricane mitigations

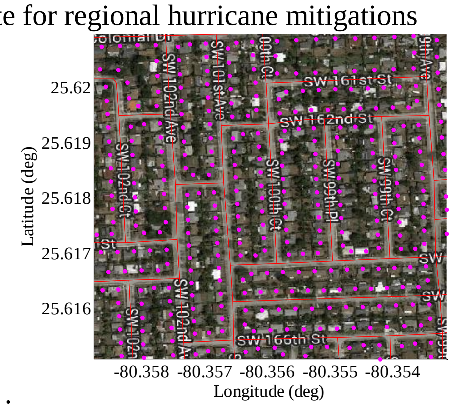

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Figure 2: Comparison between modeled and actual

locations of buildings

1.1.1. Locations of buildings

The numbers of buildings in each Census block were first determined using the 2010 U.S. Census (U.S. Census Bureau 2010) and the 2011 American Community Survey (ACS) (U.S. Census Bureau 2011) data through a probabilistic method. Then, the buildings were placed along the roads but with a distance to the roads in the Census blocks. A comparison between the modeled building locations and their actual locations on a Google map is presented in Figure 2. It can be clearly seen that the modeled locations (solid circles) agree well with their actual locations.

1.1.2. Characteristics of buildings

After the locations of buildings were determined, their characteristics could be assigned. The 20 building characteristics considered in this study include year structure built, household income, building square footage, number of stories, flood zone, base flood elevation, foundation type, foundation height, building replacement value, corresponding wind and flood damage functions, etc. These characteristics were selected because they are essential in hurricane loss estimation and hazard mitigation.

It should be noted that these characteristics were assigned to every building using survey data. Among others, the ACS data, which is a typical source available, only provides data at Census block group (i.e. a group of Census blocks) level. Therefore, in order to assign characteristics to each individual building, we used the probability mass functions (PMFs) obtained from the survey data (e.g. ACS data) at the Census block group level. The PMF for a particular characteristic represents the discrete probability of every category in that characteristic. For instance, there are 9 categories for year structure built (2005-2010, 2000-2004, 1990-1999, …, 1940-1949, 1910-1939). Each of them is associated with a distribution probability corresponding to a Census block group. For each building in that Census block group, the year built was randomly sampled following the PMF.

In this framework, similar concept was utilized in the assignment of characteristics. The correlations between characteristics were also considered. Because the assignments heavily rely on the above-mentioned probabilistic method, statistics of the assigned characteristics were checked to ensure the accuracy in terms of capturing the trends of the PMFs used to develop the mitigation framework. PMFs were checked for the entire hurricane mitigation domain and all of them agreed well with the assigned statistics. One example is given in Figure 3.

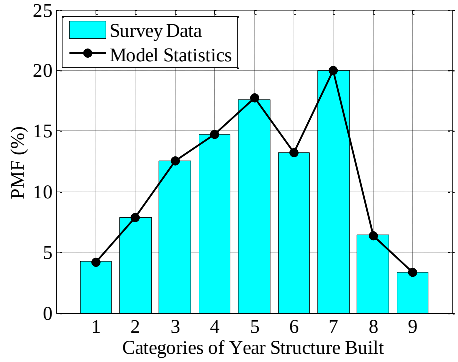

Figure 3: Comparison between PMF from survey data and model statistics for characteristic – year structure built

1.2. Agent attributes

Agent is the most critical part in this agent-based hurricane mitigation framework. Agents make decisions and they connect all other portions in the system as a whole. Like the buildings, agents were modeled from the bottom as well, which includes their locations and attributes. In current version of the model, only householders were modeled as agents and the movements of agents were not considered. Therefore, the locations of agents are the same as the building locations. The attributes, which include both demographic and psychological attributes, of each individual agent were assigned using the same probabilistic method discussed in the previous sub-section. These attributes are income, age, gender, race, education, years in residence, with child under 12 in home, hurricane knowledge, hazard intrusiveness, hurricane experience, and damage experience. The last four are psychological attributes and the rests are demographic attributes. The ACS and the HLMBS data were used to develop the PMFs for the assignments of the demographic and psychological attributes, respectively. Like the building characteristics assignments, the comparisons between the PMFs from the survey data and the assigned statistics for agent attributes were also performed, and good agreements were observed.

1.3. Details of retrofit measures

A key component of the agent-based hurricane mitigation framework is the Retrofits. We considered different wind and flood retrofit measures for different building types. Some common ones include installing secondary water resistance, updating roof deck attachment (e.g. from 6d@6/12 to 8d@6/6), enhancing roof-wall connection (toe-nail to strap), installing shutter, adding wet flood-proofing, adding dry flood-proofing, elevating first floor, constructing levees or floodwalls, etc.

In the hurricane mitigation framework, agents are able to respond to incentives and decide which retrofit measure they want to take. The decision module is introduced in Sub-section 1.6. The cost effectiveness of incentives can also be analyzed. The costs associated with wind retrofit measures came from the Federal Emergency Management Agency (FEMA) P-804 (FEMA 2010b) and the RSMeans Building Construction Cost Data (RSMeans 2011). The costs for flood retrofit measures were from the FEMA P-499 (FEMA 2010a). All costs were converted into 2011 U.S. Dollars using consumer price index inflation factors.

1.4. Combined hurricane wind and flood

Another critical component in this hurricane mitigation framework is the Hazards. Both hurricane wind and flood hazards were taken into consideration. The combined hurricane wind and flood loss assessments were performed using the HAZUS-MH (Hazards U.S. – Multi-Hazards) combined wind and flood loss estimation methodology (FEMA 2012a,b). Note that the wind and flood hazards can affect both the building inventory and the agents' responses to incentives (see Figure 1).

1.4.1. Modeling hurricane wind and flood

A database of 50,000 years of full-track synthetic hurricanes was constructed using a stochastic hurricane simulation program (Liu and Pang 2014). The surface wind speeds at 10m elevation and the corresponding flood elevations were computed using a wind field model (Georgiou 1985) along with a boundary layer model (Vickery et al. 2009), and the SLOSH (Sea, Lake and Overland Surges from Hurricanes) program (Jelesnianski et al. 1992). Details of this hurricane wind and flood modeling procedure can be found in Pei et al. (2014a, 2014b). The surface wind speeds and flood elevations were pre-calculated and ready to be used in the hurricane loss estimation.

1.4.2. HAZUS-MH combined wind and flood loss estimation

The HAZUS-MH combined wind and flood loss estimation methodology was implemented in this hurricane mitigation framework. Using pre-defined loss/damage functions, the HAZUS-MH program estimates the combined losses due to wind and flood by first analyzing the "wind-only" and "flood-only" losses separately and then combines them (FEMA 2012a,b). These damage and loss functions were assigned to each building in Sub-section 1.1. Using these damage and loss functions, once the wind speed and flood elevation on a specific building was determined, the "wind-only" and the "flood-only" damage and loss could be easily obtained. The determined damage state (i.e. minor, moderate, severe, and destructive) was next used to decide if a building needs to be demolished or not (see Sub-section 1.5); while the estimated "wind-only" and "flood-only" losses were utilized to compute the combined wind and flood losses. To estimate the monetary loss of a building, its replacement value (also assigned in Sub-section 1.1) was required.

1.5. New construction and demolition of buildings

To account for the building inventory change over time in the study domain, new constructions and demolitions of buildings were considered. The new constructions were modeled through adding new buildings to the hurricane mitigation domain. The demolitions of buildings were achieved by demolishing not only the old buildings, but also the buildings destructively damaged after a hurricane.

1.5.1. New construction of buildings

In this paper, only one scenario was considered to model the new constructions that might possibly occur over time. It assumed that the inventory change in the future would follow the same pattern as what happened in the past. To mimic the growth of the cities, any Census block closer to those with previously constructed new buildings had a much higher chance to be selected to locate new constructions than those that were further away with only older constructions. For each new construction, the building characteristics (see Sub-section 1.1) and agent attributes (see Sub-section 1.2) were assigned accordingly using the aforementioned data and methods.

1.5.2. Demolition of buildings

As mentioned above, demolition of a building occurs either when the building is too old to be used or when it is destructively damaged after a hurricane. The determination of building damage state was discussed in Sub-section 1.4. Since the damage function only provides the probability to a damage state, a random number (1 or 0) was generated to decide if the building reached that state or not. If the building reached destructive damage state, the building would be demolished. The buildings might also be demolished due to age. The building demolition rate as a function of age was obtained from the 2012 U.S. Census Housing Unit Estimates (U.S. Census Bureau 2012). Again, random numbers were generated to decide the demolition of each building.

1.6. Agents' behaviors

Since the movements of agents are not considered in the current version of the hurricane mitigation framework, agents' behaviors were only modeled as their responses to incentives and natural hazards. The way how agents' psychological attributes change due to encountered hazards are discussed in the coming sub-section, followed by the implementation of statistical models on the modeling of agents' responses to incentives.

1.6.1. Agents' responses to hazards

Agents' responses to natural hazards were modeled in such a way that their psychological attributes, including hurricane knowledge, hazard intrusiveness, hurricane experience, and damage experience, might increase once they encountered hurricane hazard or decrease if they did not encounter hurricane hazard for a relatively long time. To achieve this, the encountered hurricane hazards were classified into 7 categories using experienced peak wind speeds. The change of hazard intrusiveness of an agent due to the change of wind speeds from the simulated hurricane hazards are plotted in Figure 4. As can be clearly seen, the model captures the dynamic change of the hazard intrusiveness due to the variation of the simulated hurricane hazards. This mimics the reality that, agents are more risk aware or intrusive right after hazard events. However, their intrusiveness fades as time passes.

1.6.2. Agents' responses to incentives

Statistical models were used to model agents' responses to multiple incentives. The incentives that can be considered in this hurricane mitigation framework include property tax reduction, lower insurance premium, lower-interest loan, and forgiveness loan. Similar methodology was used to model the agents' responses to these incentives. The property tax reduction is used hereafter as an example to illustrate the methodology. As mentioned before, a study was performed by Ge et al. (2011) in the modeling of agents' responses to hazard mitigation incentives. In this hurricane mitigation framework, agents' responses to incentives were modeled using their equation:

$$\ln\left(\frac{P}{1-P}\right) = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n,\ i = 1 \sim n \quad (1)$$

where, x_i are the independent variables, β_i are the coefficients, and P is the probability of accepting any particular incentive. The scaled (e.g. 1, 2, 3, etc.) demographic and psychological attributes (see Sub-section 1.2) were modeled as independent variables, and the β coefficients were adopted from Ge et al. (2011), which were computed through logistic regression. Once the P value was calculated, the respective probability of accepting the incentive could be obtained. A random number (1 or 0) was then generated to check the decision of the agent on the acceptance of the incentive. "1" means acceptance, while "0" means rejection.

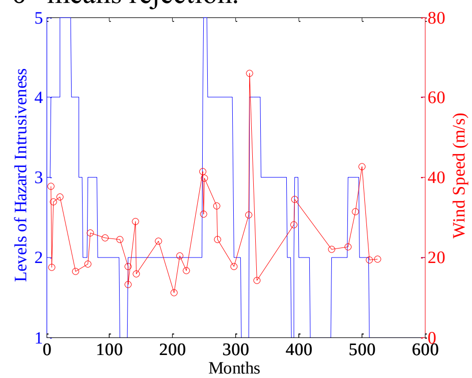

Figure 4: Modeled change of agent's hazard intrusiveness due to variation of encountered hurricane hazards

Once the agent decided to accept the incentive, one or more measures were selected to retrofit the building. The probability of selecting specific retrofit measures depends on the relative cost of the retrofit measures to the benefit the agent can get from the incentive and the risk perception of the agent. The agent has a higher chance of selecting retrofit measures that have the closest total price to the benefit he/she can get from the incentive, and the agent with a higher risk perception tends to spend more money on his/her retrofit measures. Agent's risk perception was modeled using a similar method as the one proposed in Peacock et al. (2005).

2. CASE STUDY

A case study was performed for Miami-Dade County, FL using the proposed agent-based hurricane mitigation framework. Per the 2010 U.S. Census and the 2011 ACS data, the total population in this area was around 2.5 million with a five-year averaged housing unit count of nearly 987,000 and a median household income of $43,957 (2011 USD). The major task of this case study is to investigate the impacts of incentives on the cost reductions of hurricane hazards. These costs include repair costs (hurricane losses), retrofit costs, and demolition costs.

2.1. Hurricane selection

Instead of using the full time history of the 50,000-year simulated hurricanes, an ensemble of carefully selected hazard-consistent hurricane scenarios were implemented in this hurricane mitigation framework. The methodology used for the selection of the hazard-consistent hurricane scenarios came from a previous study of the authors (Pei et al. 2014b). The hurricane scenarios were selected for 300-yr mean recurrence interval (MRI) considering the joint occurrence of hurricane wind and flood. The tracks of the selected hurricane scenarios are plotted in Figure 5. Only three representative hurricane scenarios were utilized in this study, but they produce spatially and temporally different wind speeds and flood elevations.

Once a hazard-consistent hurricane scenario was selected, a 25-year window centered by the selected hurricane scenario was picked as the time period for one simulation (see next sub-section for details). The selected hurricane scenario also needed to ensure that all other hurricane events occurred within the timeframe had MRIs much less than the MRI level (i.e. 300 years in this case) associated with the selected scenario. If so, the selected hurricane scenario was deemed as a representative scenario and it was used in the subsequent hurricane mitigation simulations along with other events occurred within that time period; otherwise, reselection was required.

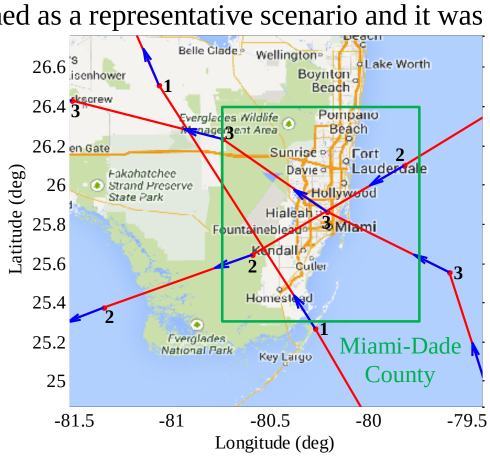

Figure 5: Tracks of selected representative hurricane scenarios

2.2. Simulation procedure

Using the 3 groups of carefully selected synthetic hurricane events (25 years each), 18 agent-based hurricane mitigation simulations were performed. Details of these simulations are tabulated in Table 1. Different combinations of the selected hurricane groups and incentive levels (in this case, only property tax reduction) were considered.

Table 1: Simulation details

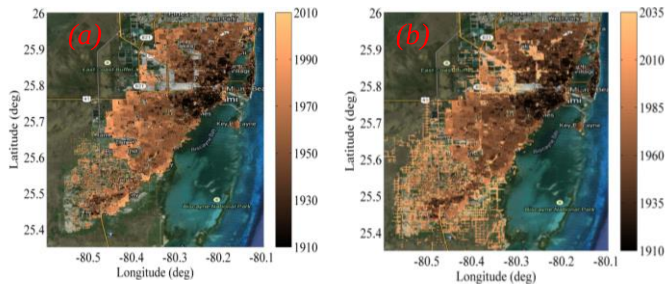

Figure 6: Geographic distribution of characteristic – year structure built at (a) beginning and (b) end of the 25-year simulation period

Simulation Number	Hurricane Group	Incentive Level (% PTR*)
1,2,3	1/2/3	0
4,5,6	1/2/3	15
7,8,9	1/2/3	25
10,11,12	1/2/3	35
13,14,15	1/2/3	50
16,17,18	1/2/3	75

* PTR = Property Tax Reduction

In every simulation time step (i.e. one month), new constructions were assumed to occur first, followed by the updates of agents' demographic and psychological attributes. Agents' demographic attributes (e.g. age, years in residence, etc.) were updated in the very first month of every year. Agents' psychological attributes were updated right after a hurricane or six months after a hurricane if there was no event occurred during that period of time. To be more realistic, the incentive was assumed to last for only five years starting from the beginning of the simulation time period (i.e. 25 years) and agents were allowed to take the benefit of incentive only once in the first five years. After the first five years, agents were still able to retrofit their buildings but with no incentive. To avoid over-decision, we assumed that agents' retrofit decisions were made only once when there was an incentive or when their buildings were severely damaged after a hurricane. Hurricane hazards occurred over time identical with the patterns of those pre-selected synthetic hurricane events. If a building was destructively damaged after a hurricane, it was demolished right away. Buildings also had chances to be demolished due to their ages. The building inventory, hurricane losses, retrofit costs, and demolition costs obtained at every modeling time step were recorded for further analyses.

2.3. Simulation results

The assigned characteristic – year structure built along with the building locations in Miami-Dade County, FL at both the beginning and the end of the 25-year simulation period are plotted in Figure 6. Different colors represent different categories in the characteristic. For example, darker colors represent older buildings and lighter colors represent newer buildings. Older buildings were built closer to the City of Miami area, and newer buildings were constructed further away. Besides, new constructions were simulated as well. Road networks were generated artificially in empty Census blocks for the purpose of locating new constructions using the methodology discussed in Sub-section 1.1.

To evaluate the effectiveness of different incentive levels on the reduction of hurricane related costs (HRC), Figure 7 was generated. In this figure, hurricane cost reduction was defined as the absolute difference between the total HRC with incentives and those without incentives in the 25-year simulation period. The total HRC were calculated as a summary of the regional (i.e. Miami-Dade County) building retrofit costs (partially or fully paid by incentives), hurricane repair costs (i.e. hurricane losses), and building demolition costs due to destructive damages. As can be clearly seen from Figure 7, in general, the hurricane cost reduction increases with the increase of the incentive level. However, its increasing rate significantly decreases as the incentive level reaches 50%. Therefore, a property tax reduction between 50% and 75% may be a reasonable incentive to reduce the regional hurricane loss at Miami-Dade County for 300-year MRI events within a 25-year timeframe.

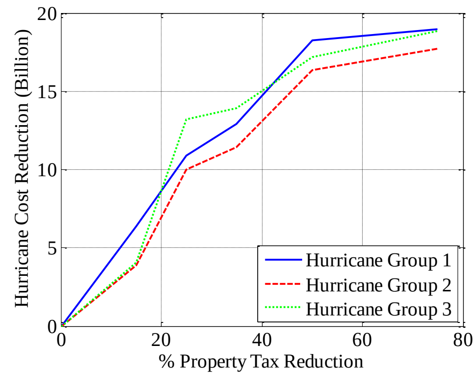

Figure 7: Relationship between hurricane cost reduction and percentage property tax reduction for 3 groups of simulated hurricanes

3. CONCLUSIONS

For the first time, an agent-based hurricane mitigation framework was developed to evaluate the effectiveness of incentives on mitigating regional hurricane hazards. Even though the case study was only carried out for Miami-Dade County, FL and the simulations were only performed for 300-year MRI hurricane events in a 25-year timeframe. The proposed framework is flexible and it can be applied to anywhere for any hazard level with any simulation time period.

The framework developed in this study can be used by coastal jurisdictions who make decisions on hazard mitigation or city planning, and insurance companies that are interested in setting up incentive-based insurance premiums, which account for the stakeholders' points of view.

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