Integrated Land Market and Hazard Consequence Model

# Overview

This document describes in detail the integrated land market and hazard consequence model in this repository. The ABM is written in Julia using Agents.jl (Datseris *et al.*, 2022). IN-CORE is used to model damage and losses resulting from natural hazards (<https://incore.ncsa.illinois.edu>; van de Lindt et al., 2018).

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# Running the Model

## Code versions

## Example of running the model

# ODD Protocol

The ODD (Overview, Design concepts, and Details) protocol is commonly used to describe agent-based models (Grimm et al., 2006). This section describes the integrated land market and hazard consequence model in this repository following the ODD protocol.

## Overview

### Purpose

The purpose of this model is to explore the risks that emerge with respect to acute natural hazards as a result of planning policies. Modeling and simulation are commonly used to inform disaster theory and understand emerging phenomena. However, many modeling efforts of infrastructure damage, societal loss, and mitigation plans associated with natural hazards often consider static representations of communities despite their dynamic and complex nature. Homeowners, urban planners, and policy makers can influence changes to the built environment, but no single entity has autonomous control over a community and outcomes of policy are difficult to fully envision. The model described herein is an integrated urban change and hazard consequence model with consideration given to population growth, a changing built environment, natural hazard mitigation planning, and future acute hazards

### State Variables and Scales

Agents in the model represent entities that own and modify the built environment. There are six agents and six land uses in the model. The model operates at the community level with each time step representing one year. The model is intended to be ran for about 30-timesteps. The model is driven by supply and demand for places of residence for both full time residents and visitors. The figure below shows how each agent is related to the land uses. Arrows denote that the agent occupies a parcel, whereas colors indicate that an agent owns a parcel.



The six agents are as follows:

* *Unoccupied Owner*: These agents are associated with unoccupied parcels and act as “sellers” in the model. As other agents bid on their parcel, they review the bids selecting the maximum if it exceeds their willingness to accept the price.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| id | Unique identifying number for agent |
| pos | Position in model space; string that is either the unique id of a parcel or “none” indicating the agent is not associated with a parcel |
| pos\_idx | position index; used to quickly identify agent location in model |
| WTA | willingness to accept price |
| prcl\_on\_mrkt | Boolean indicating whether the parcel is on the market for agents to buy |
| prlc\_on\_visitor\_mrkt | Boolean indicating whether the parcel is on the market for visitor agents to occupy |
| AVG\_bldg\_dmg | average building damage for parcel that agent is in (if applicable) |
| MC\_bldg\_dmg | monte-carlo sample of building damage for parcel that agent is in (if applicable) |

* *Household*: These agents are associated with full-time residents. They either reside in a parcel or are searching for a place to live. They can either own an “owned residential” property (*i.e.*., a single-family home), or reside in a rental or high occupancy residential property (*i.e.*, a rental home or apartment respectively). The number of people associated with newly added household agents are randomly drawn from a Gamma distribution. A household will randomly gain or lose one person following a Poisson process. A single age is randomly assigned to represent the head of the household following a Gamma distribution and increasing at each time step. Once the head of the household turns 80 years of age, the agent is removed and their place of residence becomes vacant.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| id | Unique identifying number for agent |
| pos | Position in model space; string that is either the unique id of a parcel or “none” indicating the agent is not associated with a parcel |
| pos\_idx | position index; used to quickly identify agent location in model |
| alpha1 | agent preference for distance to coast; weighted from 0-1 |
| alpha2 | agent preference for distance to community asset; weighted from 0-1 |
| alpha3 | agent preference for distance to CBD; weighted from 0-1 |
| alpha4 | agent preference for market pressure; weighted from 0-1 |
| budget | budget assigned to agent; sampled from normal distribution |
| price\_goods | price representing other goods that agents buys; used in bid formulation |
| number\_prcls\_aware | number of parcels the agent is aware of in search; bounds agent rationality |
| looking\_to\_purchase | Boolean indicating whether the agent is looking to purchase a property |
| WTA | willingness to accept price |
| age | age of agent |
| own\_parcel | Boolean indicating whether the agent owns the parcel |
| num\_people | number of people associated with agent |
| utility | utility gained from parcel |
| utility\_cst | utility deaggregated by distance to coast |
| utility\_cms | utility deaggregated by distance to community asset |
| utility\_cbd | utility deaggregated by distance to CBD |
| utility\_mkt | utility deaggregated by market pressure |
| household\_change\_times | vector developed from Poisson process representing when number of people in household increase/decrease by one. |
| AVG\_bldg\_dmg | average building damage for parcel that agent is in (if applicable) |
| MC\_bldg\_dmg | Monte-Carlo sample of building damage for parcel that agent is in (if applicable) |

* *Landlord*: These agents own parcels and rent them to household agents as “rental residential” or to visitor agents as “low occupancy seasonal rentals” (*i.e*., vacation homes). At any point in the simulation, landlord agents can choose to switch between these two land uses based on a net utility gain. Like household agents, landlord agents are removed from the model when they turn 80 and their property becomes vacant. Landlord agents do not reside in parcels.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| id | Unique identifying number for agent |
| pos | Position in model space; string that is either the unique id of a parcel or “none” indicating the agent is not associated with a parcel |
| pos\_idx | position index; used to quickly identify agent location in model |
| alpha1\_RR | agent preference for distance to coast for rental residential; weighted from 0-1 |
| alpha2\_RR | agent preference for distance to community asset for rental residential; weighted from 0-1 |
| alpha3\_RR | agent preference for distance to CBD for rental residential; weighted from 0-1 |
| alpha4\_RR | agent preference for market pressure for rental residential; weighted from 0-1 |
| alpha1\_LOSR | agent preference for distance to coast for low occupancy seasonal rental; weighted from 0-1 |
| alpha2\_LOSR | agent preference for distance to community asset for low occupancy seasonal rental; weighted from 0-1 |
| alpha3\_LOSR | agent preference for distance to CBD for low occupancy seasonal rental; weighted from 0-1 |
| alpha4\_LOSR | agent preference for market pressure for low occupancy seasonal rental; weighted from 0-1 |
| budget | budget assigned to agent; sampled from normal distribution |
| price\_goods | price representing other goods that agents buys; used in bid formulation |
| number\_prcls\_aware | number of parcels the agent is aware of in search; bounds agent rationality |
| looking\_to\_purchase | Boolean indicating whether the agent is looking to purchase a property |
| WTA | willingness to accept price |
| age | age of agent |
| own\_parcel | Boolean indicating whether the agent owns the parcel |
| transition\_penalty | float representing penalty cost of landlord agent transitioning between rental residential and low occupancy seasonal rental; used to keep all landlords from transitioning every time step |
| utility | utility gained from parcel |
| AVG\_bldg\_dmg | average building damage for parcel that agent is in (if applicable) |
| MC\_bldg\_dmg | monte-carlo sample of building damage for parcel that agent is in (if applicable) |

* *Firm*: These agents purchase properties for development as either “high occupancy rental” (*i.e.*, apartments) or “high occupancy seasonal rental” (*i.e*., hotels). Firm agents cannot switch between these land uses during the simulation. After a parcel is developed into one of these land uses, it remains as such for the remainder of the simulation. Firm agents do not age and are not removed from the model at any point. Firm agents do not reside in a parcels.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| id | Unique identifying number for agent |
| pos | Position in model space; string that is either the unique id of a parcel or “none” indicating the agent is not associated with a parcel |
| pos\_idx | position index; used to quickly identify agent location in model |
| alpha1\_HOR | agent preference for distance to coast for high occupancy residential; weighted from 0-1 |
| alpha2\_HOR | agent preference for distance to community asset for high occupancy residential; weighted from 0-1 |
| alpha3\_HOR | agent preference for distance to CBD for high occupancy residential; weighted from 0-1 |
| alpha4\_HOR | agent preference for market pressure for high occupancy residential; weighted from 0-1 |
| alpha1\_HOSR | agent preference for distance to coast for high occupancy seasonal rental; weighted from 0-1 |
| alpha2\_HOSR | agent preference for distance to community asset for high occupancy seasonal rental; weighted from 0-1 |
| alpha3\_HOSR | agent preference for distance to CBD for high occupancy seasonal rental; weighted from 0-1 |
| alpha4\_HOSR | agent preference for market pressure for high occupancy seasonal rental; weighted from 0-1 |
| budget | budget assigned to agent; sampled from normal distribution |
| price\_goods | price representing other goods that agents buys; used in bid formulation |
| number\_prcls\_aware | number of parcels the agent is aware of in search; bounds agent rationality |
| looking\_to\_purchase | Boolean indicating whether the agent is looking to purchase a property |
| WTA | willingness to accept price |
| own\_parcel | Boolean indicating whether the agent owns the parcel |
| utility | utility gained from parcel |
| AVG\_bldg\_dmg | average building damage for parcel that agent is in (if applicable) |
| MC\_bldg\_dmg | monte-carlo sample of building damage for parcel that agent is in (if applicable) |

* *Visitor*: These agents represent a transient seasonal visitor or portion of the tourist population and temporarily reside in either “low occupancy seasonal rental” (*i.e.*, vacation homes) or “high occupancy seasonal rental” properties (*i.e.*, hotels). The number of people associated with a visitor agent is sampled from a Gamma distribution. At the start of each time step, all visitors in the model are removed and new visitor agents are reassigned to vacant low occupancy or high occupancy seasonal rental parcels.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| id | Unique identifying number for agent |
| pos | Position in model space; string that is either the unique id of a parcel or “none” indicating the agent is not associated with a parcel |
| pos\_idx | position index; used to quickly identify agent location in model |
| num\_people | number of people associated with agent |
| number\_prcls\_aware | number of parcels the agent is aware of in search; bounds agent rationality |
| alpha1 | agent preference for distance to coast; weighted from 0-1 |
| alpha2 | agent preference for distance to community asset; weighted from 0-1 |
| alpha3 | agent preference for distance to CBD; weighted from 0-1 |
| alpha4 | agent preference for market pressure; weighted from 0-1 |
| utility | utility gained from parcel |
| utility\_cst | utility deaggregated by distance to coast |
| utility\_cms | utility deaggregated by distance to community asset |
| utility\_cbd | utility deaggregated by distance to CBD |
| utility\_mkt | utility deaggregated by market pressure |
| AVG\_bldg\_dmg | average building damage for parcel that agent is in (if applicable) |
| MC\_bldg\_dmg | monte-carlo sample of building damage for parcel that agent is in (if applicable) |

* *Real estate*: This agent sets the market value of every parcel throughout the simulation. This market value is used to inform both the unoccupied owner agents’ willingness to accept price and the cost of structural retrofits. The market value of a parcel is based on a user-defined base price of land, the maximum expected utility that either household or visitor agents will get from the parcel, and the overall demand for parcels. The Real Estate Agent is not associated with any parcel.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| id | Unique identifying number for agent |
| pos | Position in model space; string that is either the unique id of a parcel or “none” indicating the agent is not associated with a parcel |
| pos\_idx | position index; used to quickly identify agent location in model |
| LandBasePrice | base price of land in model; modified based on general land market |

The six land uses are in the table below:

|  |  |
| --- | --- |
| **Land use** | **Description** |
| Unoccupied | Parcels that are marked as unoccupied are available for agents to bid on and purchase. Parcels become unoccupied if an agent is removed from the model. |
| Owned Residential | These parcels are associated with household agents and represent single-family homes. As such, only on household agent can reside in an owned residential property. |
| Rental Residential | These parcels are owned by landlords and occupied by households. At each time step, landlords can decide to switch between rental residential properties and low occupancy seasonal rental based on demand for each. |
| Low Occupancy Seasonal Rental | These parcels are owned by landlords and occupied by visitor agents. At each time step, landlords can decide to switch between rental residential properties and low occupancy seasonal rental based on demand for each. |
| High Occupancy Residential | These parcels are owned by firms and occupied by households. 20 household agents can occupy a single high occupancy residential property |
| High Occupancy Seasonal Rental | These parcels are owned by firms and occupied by visitors. 45 visitor agents can occupy a single high occupancy seasonal rental property |

### Process overview and scheduling

#### Process Overview

The figure below shows a flowchart representation of the modeling framework. The urban change model is shown with the grey dash-dot box on the left, whereas the hazard consequence model, IN-CORE, is shown with the blue dash-dot box on the right.



Figure 1: Flowchart representation of the coupled urban change (grey dash-dot box on left) and hazard consequence model (blue dash-dot box on right)

The model begins with the identification of natural hazard mitigation policies (b). A population allocation is called once per iteration to initially assign population characteristics to each tax-lot (c). The population growth model (d) then updates the number of full-time residents and visitors in the model to match input population growth trajectories. A land market is simulated with agents bidding on parcels and the highest bidder obtaining ownership of a parcel (e). The land market results in an updated community description (f) with parcel owners, seismic codes, and land uses. This process repeats until a user defined time of hazard event in the simulation. Each step represents one year.

When the model is at the time step of the hazard occurring, the community description is passed to the hazard consequence model. Here IN-CORE is used to determine damages to the built environment. Hazard models (g) represent spatially explicit hazard intensity measures. Damage models (h) are fragility functions that map a hazard intensity measure to damages to each building. The fragility functions return the probability of exceeding a given damage state based on the hazard intensity measure, representing damage to the built environment (i). This overall process is then repeated for a user-defined number of iterations.

#### Scheduling

Each time steps in the model represent one year and consists of the following processes:

* Population Growth (*PopulationGrowth!*): The number of household, visitor, landlord, and firm agents that are searching for parcels are updated. These agents are added to the general model space (*i.e.*, not associated with a parcel) based on a user defined constant number of agents searching for parcels. The model updates parcel and agent counts after this step.
* All Agents Step (*AllAgentsStep!*): All agents take an individual step. Stepping is ordered based on ID (not randomized) and the agents do not interact with each other during this step. This step is used to age agents (Household and Landlord agents), model the number of people in a household (if applicable; Household agents), check to switch land use (Landlord agent) and update land prices (Real Estate agent).
* Simulate Visitor Market Step (*SimulateVisitorMarketStep!*): This step identifies all properties that can host visitors and simulates visitor agents being assigned to parcels for the iteration. The order of visitor agents in this market are randomized for each time step. Visitor agents search for parcels that meet their preferences. This market is first-come-first-served in that visitor agents are not bidding against each other but occupy the parcel that is available and meet’s their preferences. The model updates parcel and agent counts after this step.
* Simulate Market Step (*SimulateMarketStep!*): This step simulates the land market for agents looking to purchase properties (Household, Landlord, and Firm). The order of these agents are randomized. Buyers formulate bids based on utility and budget. Sellers (unoccupied owner agents) receive the bids and select the one that is the highest. IF the bid price is larger than the unoccupied owner’s WTA price, the successful bidder become the new owner of the parcel. The land use is then updated based on the owner.
* Population Out Migration (*PopulationOutMigration!*): This step is used to represent out-migration from the community. If the number of full-time residents or visitors are larger than the input population trajectories, then out migration occurs. This constrains the population to the input population trajectories. The model updates parcel and agent counts after this step.

## Design Concepts

Design concepts are outlined below:

* *Emergence*: Aggregate counts of the number of parcels and people in each land use under different policy scenarios emerge from the urban change model. The coupled hazard consequence model allows for the number of people in damaged buildings to emerge.
* *Fitness*: Agents calculate the utility of parcels based on heterogeneous preferences. Utility is calculated using the Cobb-Douglas utility function.
* *Prediction*: Landlord agents make predictions about whether to put their property on the market as rental residential or low occupancy seasonal rental based on immediate demand for full time residents and visitor agents respectively. Firms apply the same prediction to high-occupancy residential and seasonal rental based on immediate demand for full time residents and visitors.
* *Sensing*: agents know both how many other agents are in the market searching for parcels and how many available parcels there are.
* *Interaction*: agents interact with each other when submitting bid prices and reviewing incoming bids.
* *Stochasticity*: Agent preferences and budgets are heterogeneous and modified for each iteration. Initial land uses are stochastic from the housing unit allocation. Building damages are returned as the probability of being in different damage states. These probabilities are used to both: (1) compute the expected damage state, and (2) sample a random damage state once per iteration.
* *Observation*: Data is collected at three scales: (1) agent, (2) space, and (3) model. The data is output as CSV files.

## Details

### Initialization

The model is initialized with spatial representations of: (1) parcels in a community, (2) pertinent features such as the coastline, central business district, community assets, and greenspaces, and (3) a zoning layer. With this information, an initial parcel data frame is constructed that represents the parcels and contains spatial information such as the distance to pertinent features and the zone that the parcel is in. A population and housing unit allocation (c in the flowchart representing model processes) stochastically assigns individuals to each parcel using US Census data (Rosenheim et al., 2019). All of the features in this initial data frame are provided in the table below.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| guid | Globally unique identifier for the parcel; if an agent is in a parcel, this is the same as the agent’s “pos” |
| struct\_typ | Structure type; Hazus fragility curves are used for the damage and loss analysis and therefore the structure types are from Hazus; for this work, these include W1 (light-frame wood), W2 (mid-rise wood), C1L (low-rise concrete) and C1M (mid-rise concrete). |
| year\_built | Year of construction or year built |
| no\_stories | Number of stories |
| dgn\_lvl | Design level representing the seismic code the building; units of meters |
| d\_commasst | Distance to community asset; units of meters |
| d\_coast | Distance to coast; units of meters |
| d\_cbd | Distance to central business district; units of meters |
| zone | Unique identifier for the zone that the parcel is in |
| zone\_type | Type of zone that the parcel is in; options considered here include: open space (OS), residential (R), residential-high density (R\_HD), seasonal rental (SR), and commercial (C); additional zones can be considered by modifying the input zoning layer and zoning\_params file |
| numprec | Number of people in the parcel from the housing unit allocation |
| landuse | Initial land use of the parcel inferred from the housing unit allocation |
| owner\_type | Type of agent that owns the parcel |
| max\_n\_agents | Maximum number of agents that can occupy the parcel |
| x | x-location of the parcel; EPSG:26910 – NAD83/UTM zone 10N is used here |
| y | y-location of the parcel; EPSG:26910 – NAD83/UTM zone 10N is used here |

### Input

Input to the model consists of both shapefiles and CSZ files. The table below describes the shapefiles.

|  |  |  |
| --- | --- | --- |
| **Shapefile** | **Attribute** | **Description** |
| Beach.shp | ID | ID for beach |
| Buildings.shp | Guid | Globally unique identifier for the parcel; if an agent is in a parcel, this is the same as the agent’s “pos” |
| Struct\_typ | Structure type; Hazus fragility curves are used for the damage and loss analysis and therefore the structure types are from Hazus; for this work, these include W1 (light-frame wood), W2 (mid-rise wood), C1L (low-rise concrete) and C1M (mid-rise concrete). |
| Year\_built | Year of construction or year built |
| No\_stories | Number of stories |
| Dgn\_lvl | Design level representing the seismic code the building; units of meters |
| CBD.shp | ID | ID for central business district |
| CommunityAssets.shp | ID | ID for community assets |
| Type | Type of community asset (e.g., school, library, hospital) |
| Name | Name of community asset (e.g., SeasidePostOffice, SeasideFireDepartment) |
| Greenspace.shp | ID | ID for greenspace |
| Zoning.shp | guid | Globally unique identifier for zone |
| zone\_abbr | Zone abbreviation; must also be in the zoning\_param.csv input file |
| ZONING | Description of zone |

The following CSV files are also read as input to the model.

*Input.csv:* Provides general input to the model.

|  |  |  |
| --- | --- | --- |
| **Variable** | **Default Value** | **Description** |
| n\_years | 30 | number of years to simulate per iteration; time of hazard occurring |
| n\_sims | 50 | number of simulations/iterations |
| hazard\_recurrence | 500 | hazard recurrence interval (100, 250, 500, 1000, 2500, 5000, 10000) |
| seed | 1337 | seed for simulations |
| distance\_decay\_exponent | 0.0008 | Used to parameterize distance decay function |
| max\_n\_LOSR | 100000 | cap on number of low occupancy seasonal rentals |
| age\_alpha | 15 | Alpha term for parameterizing gamma distribution for sample of agent age |
| age\_theta | 2.667 | Theta term for parameterizing gamma distribution for sample of agent age |
| nhousehold\_alpha | 5 | Alpha term for parameterizing gamma distribution for sample of number of people in household |
| nhousehold\_theta | 0.44 | Theta term for parameterizing gamma distribution for sample of number of people in household |
| nvisitor\_alpha | 10 | Alpha term for parameterizing gamma distribution for sample of number of people in visitor group |
| nvisitor\_theta | 0.4 | Theta term for parameterizing gamma distribution for sample of number of people in visitor group |
| Household\_budget\_mean | 800 | Household agent budget mean; used to parameterize normal distribution |
| Household\_budget\_std | 200 | Household agent budget standard deviation; used to parameterize normal distribution |
| Household\_price\_goods | 70 | Cumulative price of other goods that agent considers when making bid (food, education, entertainment, etc.). Parameterizes WTP |
| Household\_number\_parcels\_aware | 10 | number of parcels agent is aware of when searching market |
| Household\_number\_searching | 400 | Constant number of households in model space searching for parcel |
| Household\_change\_rate | 5 | Average number of years that parcel household has same number of people |
| Landlord\_budget\_mean | 800 | Landlord agent budget mean; used to parameterize normal distribution |
| Landlord\_budget\_std | 200 | Landlord agent budget standard deviation; used to parameterize normal distribution |
| Landlord\_price\_goods | 70 | Cumulative price of other goods that agent considers when making bid (food, education, entertainment, etc.). Parameterizes WTP |
| Landlord\_number\_parcels\_aware | 20 | number of parcels agent is aware of when searching market |
| Landlord\_number\_searching | 200 | Constant number of landlords in model space searching for parcel |
| Landlord\_transition\_penalty | 0.35 | Penalty for landlord transitioning from one state to another |
| Firm\_budget\_mean | 2000 | Firm agent budget mean; used to parameterize normal distribution |
| Firm\_budget\_std | 50 | Firm agent budget standard deviation; used to parameterize normal distribution |
| Firm\_price\_goods | 70 | Cumulative price of other goods that agent considers when making bid (food, education, entertainment, etc.). Parameterizes WTP |
| Firm\_number\_parcels\_aware | 20 | number of parcels agent is aware of when searching market |
| Firm\_number\_searching | 3 | Constant number of firms in model space searching for parcel |
| Visitor\_number\_parcels\_aware | 10 | number of parcels agent is aware of when searching market |
| RealEstate\_LandBasePrice | 150 | Real estate agent base price for land |
| AllowNew\_OwnedRes | 1 | Boolean for allowing new owned residential development |
| AllowNew\_RentalRes | 1 | Boolean for allowing new rental residential development |
| AllowNew\_LOSR | 1 | Boolean for allowing new LOSR development |
| AllowNew\_HOR | 1 | Boolean for allowing new HOR development |
| AllowNew\_HOSR | 1 | Boolean for allowing new HOSR development |

*Zoning\_params.csv:* Maps the zoning abbreviations to the different land uses. The zoning abbreviations must match those in the Zoning.shp file. Each row corresponds to a zone, and each column to a land use. Default values are provided below. Boolean values are represented as 1 (True) and 0 (False).

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | unoccupied | owned\_res | rentl\_res | ho\_res | losr | hosr | comm |
| OS | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| R | 1 | 1 | 1 | 0 | 1 | 0 | 1 |
| R\_HD | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| SR | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| C | 1 | 0 | 0 | 1 | 0 | 1 | 1 |

*BuildingCodes.csv:* Input file describing mandatory building codes when a new change of hands occurs.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| from | Initial land use before change of hands |
| to | New land use that the new owner is considering updating the parcel to |
| percent\_cost | Percent of base price that the building code costs. This is used in the owner WTP calculations. |
| to\_code\_level | The code level that the building must go to. |
| Required | Boolean indicating whether the change is required. Boolean values represented as True/False |

*PopulationGrowth.csv:* Input file describing deterministic population projections. These are provided for both full time residents and visitors

|  |  |
| --- | --- |
| **Variable** | **Description** |
| Tick | Time step in model. Starts at 0; must be in 5-year increments |
| FullTimeResidents | Number of full time at the time step |
| Visitors | Number of visitors at the time step |
| Year | Year in actual model; this column is not used in the model, but rather provided for the user |

*PreferenceMatrix.csv:* Matrix describing preferences. If a standard deviation is provided, the preferences are sampled from a normal distribution parameterized on a mean and standard deviation. An example preference matrix is provided below. In this case, a household agent’s preference for parcels near the coast will be sampled from a normal distribution with N(0.3, 0.2).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **household** | **visitor** | **Landlord - rentl\_res** | **Landlord - losr** | **Firm - hor** | **Firm - hosr** |
|  | 0.3 | 0.7 | 0.2 | 0.4 | 0.15 | 0.15 |
|  | 0.7 | - | 0.4 | - | 0.15 | - |
|  | - | 0.3 | - | 0.2 | - | 0.15 |
|  | - | - | 0.4 | 0.4 | 0.7 | 0.7 |
|  | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 |

*TaxLot2Bldg.csv:* Optional input file that maps tax-lots to a single building. This is provided because some tax-lots in Seaside are contained within a single building (a condo containing multiple tax-lots). In the model, one building is represented as a parcel rather than the many tax-lots located therein. If not using, leave this file blank with the columns provided.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| guid | Globally unique identifier for the parcel |
| rep\_guid | Representative GUID that all parcels in the GUID column will be mapped. |
| max\_n\_agents | Maximum number of agents in the building; that is, the number of tax-lots that are represented. |

*DataAxelCommercialBuildingMapping.csv:* Optional file describing which parcels are commercial buildings in the community. These are assumed static and do not change with this version of the model. If unknown, leave this file blank with the column provided.

|  |  |
| --- | --- |
| **Variable** | **Description** |
| guid | Globally unique identifier of the parcels that are commercial buildings |

### Submodels

The figure below shows a flowchart representation of the modeling framework. The urban change model is shown with the grey dash-dot box on the left, whereas the hazard consequence model, IN-CORE, is shown with the blue dash-dot box on the right. This section describes each submodel of the flow chart in more detail.



1. *Start:* The model starts here

Relevant functions:

*main*()

1. *Natural Hazard Mitigation Policies:* This is a set of policies that are imposed on the modeling environment and constrains the overall model. By simply modifying the input outlined above, policies to consider could include caps on the number of low occupancy seasonal rental parcels, enforced building codes, relocating community assets, creating new green spaces, rezoning, and limiting new development of particular land uses. The user could also modify the source code to include additional policies outside of those that are controlled by input files.
2. *Population Allocation:* This submodel represents the housing unit allocation algorithm in IN-CORE (Rosenheim et al., 2019; <https://incore.ncsa.illinois.edu/doc/pyincore/modules.html#analyses-housingunitallocation>). This submodel takes publicly available US Census data and stochastically downscales it to the parcel-level. This results in the number of people in each parcel. From the housing unit allocation, the initial land uses are inferred.

Relevant functions:

*housing\_unit\_allocation*()

*assign\_property\_types*()

1. *Population Growth Model:* The population growth submodel adds more agents to the model based on the values provided in the input file. Note that this submodel adds agents to the general model space. That is, they are not assigned to a parcel yet, but are in the market looking to purchase a parcel. In this submodel, the household, visitor, landlord, and firm agents are increased. In addition, this submodel represents population outmigration. Population outmigration occurs if the number of people in parcels exceed the values provided in the input file PopulationGrowth.csv.

Relevant functions:

PopulationGrowth!()

PopulationOutMigration!()

1. *Land Market Simulation:* Household, landlord, and firm agents are competing in a landmarket attempting to purchase parcels that meet their preferences. The landmarket is an extension of the ALMA and ALMA-C models (Filatova et al., 2009; Filatova et al., 2011). The model presented herein considers six agents whereas ALMA only considers two agents: buyer and seller. As in ALMA, agents competing in the land market compute their willingness to pay (WTP) for a parcel. Here, the WTP is modified to account for structural retrofits as:

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

Where is the agent budget sampled from a normal distribution, is the utility of the parcel, represents costs of other goods, and where is computed as , with NB number of buyers and NS number of sellers. The final two terms of equation (2) were not in the ALMA model formulation and were added to account for costs associated with structural retrofits. Here, is a constant between 0 and 1 parameterized on the transition between retrofit levels, *e.g*., low- to moderate-seismic code vs. low- to high-seismic code (see BuildingCodes.csv), and is the market value of the parcel provided by the real estate agent. This term is subtracted to account for the additional costs an agent would incur if retrofits were mandatory.

The utility, *U*, is computed using a Cobb-Douglas utility function as:

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

Where is a normalized value (0-100) representing either proximity to a particular feature or market pressure, weights the importance of this feature to the agent representing preferences, and *n* are the number of features considered. The preference weights, , for each agent are sampled from a normal distribution and rescaled such that they sum to 1. Proximity is computed using a scaled distance decay function, , with *d* being distance to the feature and *k* being a tunable parameter. The market pressure is based on the number of buyers and sellers, .

Relevant functions:

*SimulateVisitorMarketStep*!()

*SimulateMarketStep*!()

1. *Community Description at Time t:* The community description at time *t* includes the structural properties, seismic codes, land uses, parcel owners, and number of people in each parcel.

Relevant functions:

*UpdateModelCounts*!()

1. *Hazard Models:* Hazard models are spatially explicit representations of natural hazards. For the Seaside testbed tehse were previously developed as a part of a probabilistic seismic and tsunami hazard analysis (Park et al., 2017; Cox et al., 2022). The PSTHA resulted in hazard maps for seven recurrence intervals (100, 250, 500, 1000, 2500, 5000, and 10000-year). The user can select which hazard recurrence interval to consider as input to the model in Input.csv. The hazard maps are available in the IN-CORE data service which is called at runtime. No hazard layers need to be provided locally.
2. *Damage Models:* Damage models are fragility functions that describe the probability of exceeding a damage state given a hazard intensity measure. Here Hazus seismic and tsunami fragility curves are employed. The fragility curves are represented as lognormal distribution functions parameterized on a median and dispersion. The fragility curves are mapped to each buildng type and seismic-code level. The fragility curves are available on the IN-CORE data service which is called at runtime and thus not needed locally. The figure below shows an example of seismic fragility curves for a light-frame wood structure for different seismic-code levels.



1. *Damage to Physical Infrastructure:* Damage to physical infrastructure is modeled using IN-CORE. IN-CORE maps the spatially explicit hazard intensity measures of (g) to the community description of (f) using the damage models of (h). The hazard occurs in the model at the time step specified by the user in Input.csv. When this step occurs, the model constructs the building data frame necessary to be provided as input to IN-CORE. Using the fragility curves of (h), the probability of each parcel being in different damage states is provided. The expected damage state is computed using these probabilities and one random sample of damage state is computed. Examples of damage to infrastructure include: Park et al., 2019, Kameshwar et al., 2019, and Sanderson et al., 2021.

Relevant functions:

*csz!*()

*pyincore\_CSZ*()

*bldg\_dmg\_eq*()

*bldg\_dmg\_tsu*()

*bldg\_dmg\_cmltv*()

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