**Urban Vulnerability**

**OVERVIEW**

**Purpose and patterns**

This model is inspired by water governance problems in cities around the world. Investments need to be made to reduce the damage from extreme events (droughts, floods, polluted water) at different spatial scales and severity. Individuals can contribute to infrastructure by adjustments to their property. Public authorities invest in public infrastructure and they need to make decisions where they invest their limited resources.

The overall purpose of the stylized theoretical model is to understand how assumptions of decisions making by households and public authorities impact the spatial vulnerability of the urban system. Questions to explore are: what leads to inequality of vulnerabilities? Will different disturbance regimes require different governance priorities to derive sustainable and fair outcomes?

**Entities, state variables and scales**

Agents representing residents are located in one of M neighborhoods. Each resident agent has a certain income Y, private infrastructure, a memory of past damage from events, and the level of damage from events experienced in the current time step.

A neighborhood consists of a patch with a maximum number of residents that can occupy the neighborhood. The cost of living in the neighborhood relates to the mean income of resident agents in the neighborhood. When more agents with high income enter a neighborhood this will increase the cost of living. The figure below shows the default setting of 49 neighborhoods and a maximum of 36 residents in each neighborhood. The neighborhood also has a public infrastructure.

Background pattern

Description automatically generated

The public authority that makes decisions on where to invest in public infrastructure, is operating at the observer level. This agent has a budget and a priority criterium on how to rank neighborhoods for investments. The priority criterium can change based on the outcomes of voting from residents.

The model will move forward in time tick by tick, not representing a specific time unit. Every 50 ticks the resident agents can vote and a change of priorities of the investments in public infrastructure. The agents keep track of 10 ticks of historical data that could impact decisions they make.

**Process overview and scheduling**

Each tick the information is updated in the following order:

1. Events: random events at the individual, neighborhood, and city-wide level causes damage.
2. Movement of residents. Residents who experience relatively large damage check whether it is possible to move to another location, and do so if possible.
3. When voting happens in a time step, agents will vote whether to increase or decrease the budget for public works.
4. The residents make decisions about whether to invest in their private infrastructure.
5. The public authority ranks neighborhoods in order of importance and invests in public infrastructure until the budget runs out.
6. Update metrics and visualization.

**DESIGN PRINCIPLES**

**Basic principles**

This is a stylized model based on experience in developing a model on water governance for Mexico City (Baeza et al. (2019), Bojórquez-Tapia et al. (2019), Shelton et al. (2018)) and aims to capture the spatial vulnerabilities in a city as a consequence of decisions made by different levels of society (Eakin et al. 2017). The model is also an example of implementing a coupled infrastructure system capturing different types of infrastructure (Anderies et al., 2016). Public infrastructure providers and resource users make decisions on the creation and maintenance of infrastructure.

**Emergence**

A possible emergence are spatial patterns of vulnerability of neighborhoods to external disturbances.

**Adaptation**

Residents can adapt by moving to another neighborhood, investing in private infrastructure and vote to change the priority setting of public infrastructure investments.

Neighborhoods adapt due to investments, by the public authority.

The public authority changes it’s priority of investments if this is an outcome from the elections.

**Objectives**

Residents try to reduce the damage to their properties due to external events.

**Learning**

There is no fundamental learning by the agents.

**Prediction**

Agents do not explicitly predict the future. If making assessment on benefits of investing in private infrastructure, they use historical observations as the best guess for the future.

**Sensing**

Agents keep perfect records of past events within the whole city, and know the damage function.

**Interaction**

There is no direct interaction between residents. They indirectly compete for spots in neighborhoods, impact the cost of living for each other.

**Stochasticity**

Stochasticity is included mainly by the external events, but also due to the random order in which agents update their decisions (like movements).

**Collectives**

Collectives in their model are neighborhoods, which are patches with a certain number of residents.

**Observation**

Each tick we calculate the gini coefficient about the cost of living among neighborhoods to get a sense of inequality between neighborhoods. We also update the locations of agents on the screen. This is for visualization only and needed to show the consequences of movements. The colors of patches and agents are also updated.

**DETAILS**

**Initialization**

We assume initial levels of 1 for the private and public infrastructure. The income of the residents is randomly assigned to be between 1 and 10. The intensity of past events is assumed to be 0.1 for the different types of events. However, we assume that the damage levels in the working memory of the agents are 0 at the start of the simulation.

**Input data**

Parameters used in the model

|  |  |  |
| --- | --- | --- |
| Parameter | description | value |
|  | Probability that an event happens at the resident level | 0.1 |
|  | Probability that an event happens at the neighborhood level | 0.1 |
|  | Probability that an event happens at the city level | 0.1 |
|  | Maximum level of the damage for an event at the resident level | 0.3 |
|  | Maximum level of the damage for an event at the neighborhood level | 0.3 |
|  | Maximum level of damage for an event at the city level | 0.3 |
|  | Parameter that defines the shape of damage function | 2 |
|  | Parameter of exponential distribution for resident level events | 0.5 |
|  | Parameter of exponential distribution for neighborhood level events | 0.4 |
|  | Parameter of exponential distribution for city level events | 0.3 |
| , | Parameters of Cobb Douglass function | 0.4, 0.4 |
|  | Decay rate of private infrastructure | 0.03 |
|  | Decay rate of public infrastructure | 0.02 |
| budget | Budget of public authority to invest in public infrastructure | 5 |

**Submodels**

*Events*

Each tick we check whether there are events happen at the individual, neighborhood and city level, and if so with what level of intensity. The damage caused by an external event depends on the intensity of the events, using a general damage function (Prahl et al., 2012).

Where is the relative damage of the property of agent i in neighborhood j to event type z. The parameter is the maximum value of the damage for event type z. The default model has event types: individual, neighborhood and city level. The parameter defines the shape of the damage function. The variable defines the intensity of the event and is an outcome from an exponential distribution. The variable is the infrastructure level for the property of agent i in neighborhood j that protect the property from damage.

The infrastructure reducing property loss is a combination of private and public investments. For simplicities sake, we assume that they are two somewhat complementary stocks that generate via a Cobb-Douglas function a total infrastructure level

The level of public and private infrastructure declines each tick with a decay rate or and increases if agents have invested in the infrastructure.

The total damage that an agent experience relates to the cost of living in the neighborhood. We multiply the damage level with the Price of living in neighborhood j.

Events not only lead to damage to the property of the agents, but also reduce the infrastructure. Hence private infrastructure is multiplied with and public infrastructure is multiplied with

*Movement of residents*

Agents may look for better places to live. If damage as a fraction of income is higher than , the agent explores whether there is a better option.

Especially agents who of lesser means are considering to leave due to high damage levels. They can only leave if there is another neighborhood with open spots and for which the price is equal or lower than the income of the agent. Would there be a better location (low damage levels related to income), and can you afford it?

*Voting*

Residents check, using the historical data, whether increasing the public infrastructure leads to a relative beneficial increase. If the mean annual damage prevented is bigger than 1 / income agents will vote to increase the budget, otherwise they vote to decline the budget. Hence for wealthier residents a higher relative benefit is needed before they vote to increase the budget, which is paid from tax money (and those with more income will pay more tax).

*Investments in private infrastructure*

Agents make each time step a decision to invest in private infrastructure. They use records of the events of the last 10 timesteps to calculate what the expected benefit of increasing the private infrastructure with one unit. If this higher than the expected costs the agent will invest in the private infrastructure.

*Investments in public infrastructure*

The investments in the public infrastructure is defined by a governmental authority who has a budget B and has to make decisions which neighborhoods to invest. How does the water authority make it’s allocation decisions? We assume that the water authority ranks the neighborhood according to one of the following criteria:

* Neighborhoods with a lower level of infrastructure will get higher priority.
* Neighborhoods with a higher total damage in the last 10 time-steps get a higher priority
* Neighborhoods with a higher relative damage to income get a higher priority

**Some results**

We will first do analysis when events can happen only at neighborhood level, and infrastructure is only at the neighborhood level too.

Parameters used in the model

|  |  |  |
| --- | --- | --- |
| Parameter | description | value |
|  | Probability that an event happens at the neighborhood level | 0.1 |
|  | Maximum level of the damage for an event at the neighborhood level | 0.3 |
|  | Parameter that defines the shape of damage function | 2 |
|  | Parameters of Cobb Douglass function | 0.4 |
|  | Decay rate of public infrastructure | 0.02 |
| budget | Budget of public authority to invest in public infrastructure | 5 |

Below are some illustrative results of 1000 runs of 500 ticks for different priorities of allocating investments in public infrastructure and different values of the threshold and different frequencies in which neighborhoods experience events to evaluate the impact how quickly residents move to another neighborhood.

In the figure below we see that a higher threshold to move leads to a lower level of inequality since agents were initially randomly allocated and are less likely to move and sort themselves. Prioritizing the state of the infrastructure leads to less inequality. More frequent events lead to move inequality.



Figure 2: The Gini coefficient of prices of property values in neighborhoods for different values of and different frequencies (0 to 100%) of the ticks an event may happen at the neighborhood level.

When there are more events the cost of events increases (Figure 3). We see that there is a slight benefit of a high threshold of agents to move, which may lead to more consistent investment in private infrastructure (instead of leaving the neighborhood).



Figure 3: Relative damage from events.

Figure 4 demonstrates that if it is easy for agents to leave, they do not invest in private infrastructure (that they cannot take with them).



Figure 4: Level of relative private infrastructure.

Figure 5 shows that more frequent events lead to more investments in public infrastructure, and a higher threshold for agents to leave towards another neighborhood lead to higher investment in public infrastructure.



Figure 5: Level of public infrastructure.

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