EnDURE: Environmental Disaster Urban Recovery and Evaluation Model

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Abstract

EnDURE is a cellular automata-based multi-agent model to assess and predict the spatial consequences of different decisions for urban recovery after a major natural disaster like Tsunami or Hurricane. We propose that post-disaster recovery processes in urban areas are very complex, involving the damage severity from a specific disaster, the characteristic of geologic and geomorphologic structures over the impacted areas, the preparedness of the affected communities, and the levels of disaster relief efforts from the concerned government agencies and business investors. Urban recovery after disasters represents a surprising and unusual form of urban redevelopment well-matched to processes of land development that are driven from the bottom up but intervened by the higher-level national economy and even international politics in case of a city situated in a developing country. We develop an agent-based conceptual modeling framework that translates these ideas and influencing factors into a formal agent-based model. EnDURE explores fine cell-grained spatial patterns associated with the effects of alternate policy interventions: rehabilitation of structures in moderately damaged areas and new constructions in heavily damaged areas with wide ranges of user-determined factors and their impact intensities as the parameter values. The formal model and illustrative simulations of a prototype EnDURE took the tsunami disaster in Banda Aceh, Indonesia on December 26, 2004 as a case study.

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Introduction

On the morning of December 26 2004, the western-most Indonesian coastal town of Banda Aceh and its environs sustained major damages and losses of life from a massive earthquake and tsunami. The tsunami reached 4 kilometers inland and destroyed or damaged most of the buildings in its path. The central business area of Banda Aceh was almost completely destroyed. The population was reduced from 264,618 to 203,553. The recovery of Banda Aceh has become a project of international efforts as well as various levels of Indonesian governments.

There is growing recognition that the rapid urbanization of Third World countries, especially in the Asia and the Pacific, is resulting in great concentrations of people in unplanned and poorly served communities at high risk from natural and man-made disasters. Today, roughly a billion people (one-third of the world's total urban population) are born into, live in, and die in neighborhoods without benefit for formal planning, landuse regulations, comprehensive infrastructures, or legal land ownership. From the favelas of Brazil to the urban kampongs of Southeast Asia, millions of the Poor illegally occupy and live on land considered too unstable or environmentally contaminated to warrant public investment or even notice. These areas contain the men, women, and children at greatest risk and suffer most grievously in times of disaster. We believe that our efforts to model the vulnerabilities of urban communities and their subsequent recovery after disasters must include representation of the decision processes of the millions of people who occupy the so-called "shadow cities" [Neuwirth, 2004].

Top-down urban planning has little to say about these environments of informal communities found within and around the formal fabric of Third World cities and towns. Few models consider the physical and social issues that confront these, often invisible, people – few provisions for safe water or electricity, roads or sanitation, schools or public order. But bottom-up agent-based models can represent these [Parker et al. 2003] [Xie, Batty, Zhao. 2005], as well as decision-making within the more conventional residential, commercial, and industrial land use representations. Urban dwellers make daily decisions that may be represented, not on the basis of formal hierarchical planning models, but by the decision processes of individual family units occupying small urban parcels. Individual decisions made by millions of well-of but mostly poor residents shape (by default, not planning) their communities and make them vulnerable to natural and man-made disasters.

Why is an agent-based approach to cellular automata modeling likely to produce better simulations of urban disaster recovery responses than conventional top-down policy-driven models? The answer lies with (1) its ability to realistically represent the fine-grained geographical variability of urban environments, (2) the spatially variability of disaster forces, and (3) how urban disaster recovery decisions are actually made. By their nature, urban environmental disasters are geographically selective and variable with respect to their nature and the degree of destruction that actually occurs. Whether by earthquake, tsunami, tornado, flood, landslide, or fire, the extent and severity of damage is controlled by the spatial structure of the disaster force and by the physical variability of the urban terrain and its build environment. To the extent that populations at risk are also of concern, that risk is also spatial variable, which changes over the course of a day.

EnDURE represents these geographical variables on a fine grid and then simulates local decision processes associated with thousands of residents, and with international organizations of varied priorities, and with various levels of governments (all are agents), each one looking at different sets of local variables and external conditions (for instance, investment and donations). While high-level, top-down decision making may direct institutional resources to comprehensive disaster recovery, individual decisions in terms of both organized but varied institutional interests and disorganized spontaneous decisions have significant impacts on the recovery process. Actual overall recovery emanates from the decisions of many thousands of individuals whose lives, property, and communities comprise the urban area affected by the disaster. We will present the formal model of EnDURE and demonstrate a few simulations due to the limit of page length. Please contact the authors if you are interested in implementation and simulation details.

Formal Statement of the Model

At time *t*, the utility score of the i th land cell (the research area is divided into *M*N* cells and thus *i=1, 2, 3, …, M*N*) in township *a* (*a=1, 2,…K,* where *K* is the total number of townships in the research area), denoted by $U(i,t,a)$, is determined by five tuples, where the value of each tuple is determined by its own sub-model.

$$U(i,t,a) = f_u\{E(i,t,a), V(i,t), C(i,t,a), S(i,t,a), N(i,t,a)\} \qquad (1.1)$$

Subject to:

$$\partial U(i,t,a)/\partial E(i,t,a) >= 0;\ \partial U(i,t,a)/\partial V(i,t,a) >= 0;\ \partial U(i,t,a)/\partial C(i,t,a) <= 0;$$

$$\partial U(i,t,a)/\partial S(i,t,a) <= 0;\ \partial U(i,t,a)/\partial N(i,t,a) >= 0.$$

Where $E(i,t,a)$ stands for the cell's economic viability;

$V(i,t,a)$ stands for the cell's vulnerability against disaster;

$C(i,t,a)$ stands for cost of disaster recovery at the cell;

$S(i,t,a)$ stands for the cell's environmental sustainability;

$N(i,t,a)$ stands for the cell's social networking strength.

(1) Economic Viability Sub-Model:

The economic viability of a land cell is influenced by many characters, including its transportation accessibility, original population, economic accessibility and government investment incentives. We represent the economic viability as:

$$E(i,t,a) = g_E\{TA(i,t,a), PO(i), EA(i,t,a), IN(i,t,a)\}; \qquad (1.2)$$

Subject to:

$$\partial E(i,t,a)/\partial TA(i,t,a) >= 0;\ \partial E(i,t,a)/\partial PO(i) >= 0;$$

$$\partial E(i,t,a)/\partial EA(i,t,a) >= 0;\ \partial E(i,t,a)/\partial IN(i,t,a) >= 0.$$

Where $TA(i,t,a)$ reflects the cell's transportation accessibility;

$PO(i)$ is the original population density at the cell before disaster;

$EA(i,t,a)$ reflects the cell's accessibility to economic facilities, which is effected by the economic conditions where the cell is located ;

$IN(i,t,a)$ is the cell's investment attractiveness after a disaster, which bears strong political influences.

The transportation accessibility $TA(i,t,a)$ can be further denoted as the integral of the transportation accessibilities to all modes of transportation.

$$TA(i,t,a) = h_{TA}\{RD(x,y,t), RR(x,y), RV(x,y), CL(x,y)\}; \qquad (1.3)$$

$$= \sum_{p}^{P} \left(\int_{x}^{X}\int_{y}^{Y} Wt_p(x,y) \cdot Rt_p(Va_p(x,y,t)) dxdy \right)$$

Subject to: $x \in X$; $y \in Y$; $p \in P = \{RD, RR, RV, CL\}$.

Where x and y denote the position (x-coordinate and y-coordinate) of a land cell in the township;

p denotes factoring tuples;

$RD(x,y,t)$ is the continuous function showing the distance from the cell to major roads at time t since roads are updated quickly compare with other transportation modes;

$RR(x,y)$, $RV(x,y)$ and $CL(x,y)$ are the continuous function showing the distance from the land cell to railroads, rivers and coastlines, respectively;

$Va_p(x,y,t)$ are the values of tuple p of the cell at time t;

$Rt_p(Va_p(x,y,t))$ are the ratings of tuple p's value;

$Wt_p(x,y)$ are the weightings of tuple p at the cell.

(2) Disaster Vulnerability Sub-Model

After the disaster, the vulnerability to disaster will become more important in site selection process. Based on the analysis to tsunami, the vulnerability level of a land cell is denoted as:

$$V(i,t,a) = g_V(BD(i,t,a), CQ(i,t), GS(i,t), DI(i), TE(i)); \qquad (1.4)$$

Subject to:

$\partial V(i,t,a)/\partial BD(i,t,a) <= 0$; $\partial V(i,t,a)/\partial CQ(i,t) >= 0$; $\partial V(i,t,a)/\partial GS(i,t) >= 0$;

$\partial V(i,t,a)/\partial DI(i) <= 0$; $\partial V(i,t,a)/\partial TE(i) <= 0$.

Where $BD(i,t,a)$ is the building density at the cell;

$CQ(i,t)$ is the construction quality at the cell;

$GS(i,t)$ reflects the geological stability at the cell;

$DI(i)$ reflects the former disaster influence at the cell;

$TE(i)$ reflects the topographic impact to disasters at the cell.

(3) Recovery Cost Sub-Model

The cost to reconstruct or rehabilitate is also an important factor in agents' decision making. It is denoted as:

$$C(i,t,a) = g_C(EC(i,t), SC(i,t,a)); \qquad (1.5)$$

Subject to:

$\partial C(i,t,a)/\partial EC(i,t) >= 0$; $\partial C(i,t,a)/\partial SC(i,t,a) >= 0$.

Where $EC(i,t)$ reflects economic cost of new constructions and rehabilitation at the cell;

$SC(i,t,a)$ reflects the social cost at the cell and is denoted as:

$$SC(i,t,a) = h_{SC}(EQ(i,t,a), TA(i,t,a), SW(i,t,a)); \qquad (1.6)$$

Where $EQ(i,t,a)$ stands for social equity condition;

$TA(i,t,a)$ stands for the transparency of the political system;

$SW(i,t,a)$ stands for the social well-beings.

(4) Environmental Sustainability Sub-Model:

This will evaluate how the development on the land cell will meet the environment sustainability criteria as well as how well the land development meet people’s aesthetic expectation:

$$S(i,t,a) = g_S(ES(i,t,a), AS(i,t)); \qquad (1.7)$$

Subject to:

$$\partial S(i,t,a)/\partial ES(i,t,a) >= 0; \ \partial S(i,t,a)/\partial AS(i,t) <= 0.$$

Where $ES(i,t,a)$ is the environmental sustainability criteria of the cell;

$AS(i,t)$ is the resident aesthetic value of the cell;

(5) Social Networking Strength Sub-Model:

Social networking is treated as macro-level control of the post-disaster recovery process. Influences from five types of stakeholders, who may have different preferences on various recovery plans, are considered in the sub-model.

The probability of land cell *i* following the recovery plan *rp* at time *t* is denoted as:

$$PROB(i,rp,t) = \frac{\sum_{h}^{H} PREF(i,rp,t,h)}{\sum_{p}^{P}\sum_{h}^{H} PREF(i,rp,t,h)} \qquad (1.8)$$

Subject to: $h \in H = \{IO, NG, PG, LG, NO, RS\}$ and $rp \in P = \{Possible\ recovery\ plans\}$.

Where $PREF(i,rp,t,h)$ reflects stakeholder *h*’s preference over plan *rp* on cell *i* at time *t*;

IO reflects the influence from international organizations;

NG reflects the influence from national government;

PG reflects the influence from provincial government;

LG reflects the influence from local government;

NO reflects the influence from non-government organizations (NGOs);

RS reflects influence from local residents.

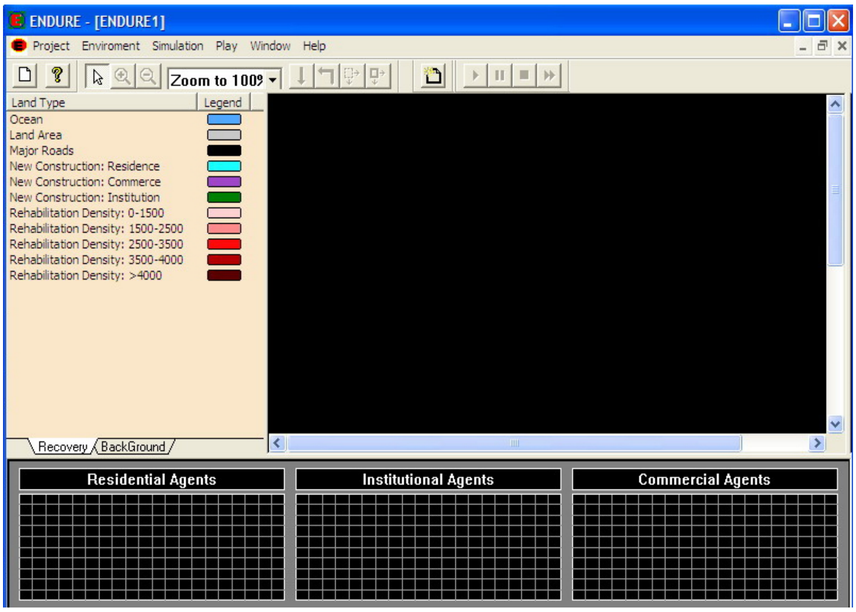

Figure 1 The graphic user interface of EnDURE

Figure 2 Simulation legend

Preliminary Simulations

(1) Planned recovery – maximize rehabilitation of existing structures (Figure 3)

Rehabilitation is treated as primary growth in this case; Damage is heavily weighted; Density has high weight (mid-high densities have higher ratings) and higher density is preferred; Accessibilities and Environments are somewhat important. Construction is considered for completely damaged areas. Zoning is considered (50%) and planning is important (high cut-off value). Accessibilities are slightly favored over Environments.

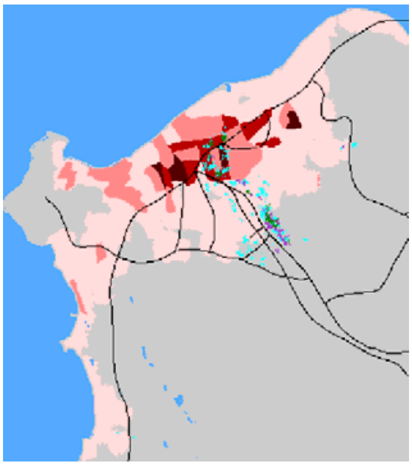

Figure 3

(2) Planned recovery – to maximize new construction (Figure 4)

Rehabilitation is treated as secondary growth in this case; Damage is greatly considered; Density has high weight (mid-high densities have higher ratings) and high density is preferred; Accessibilities are slightly favored over Environments. Construction is considered as primary recovery effort (including moderately damaged areas). Zoning is considered (50%) and planning is important (high cut-off value). Accessibilities are slightly favored over Environments.

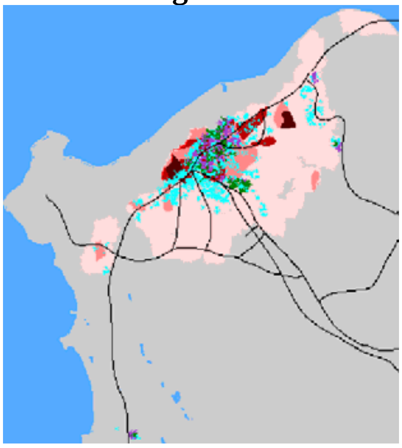

Figure 4

(3) Planned 10 year fast recovery with strict zoning ordinance (Figure 5)

Rapid growth of Banda Aceh's population happens due to immigration and reproduction; Funds and construction materials are available to rebuild and add new housing; Rehabilitation is treated as secondary growth in this case; Damage is less considered; Construction is considered as primary recovery effort (including moderately damaged areas); Zoning ordinance is strictly enforced (100%); Planning is important (high cut-off value); Accessibilities and Environments are equally important.

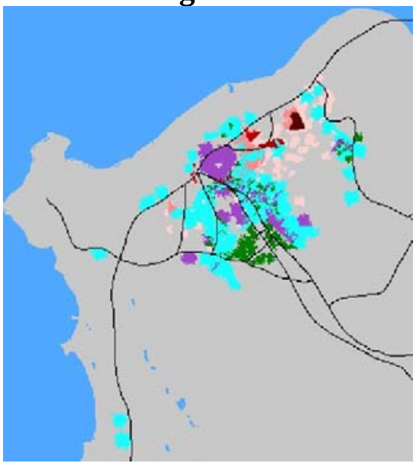

Figure 5

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