An Agent-based Evacuation Model Considering Field Effects and Government Advice

Joel S.E. Teo (Corresponding author)[a]
C1-2-338 Kyotodaigaku Katsura, Nishikyoku, Kyoto 615-8540
Tel: +81-75-383-3231, Fax: +81-75-950-3800
E-mail: joel.teo@kiban.kuciv.kyoto-u.ac.jp

Jan-Dirk Schmöcker[a]
C1-2-436 Kyotodaigaku Katsura, Nishikyoku, Kyoto 615-8540
Tel: +81-75-383-7491, Fax: +81-75-383-3236
E-mail: schmoecker@trans.kuciv.kyoto-u.ac.jp

Florin Leon[b]
Department of Computer Science and Engineering
Bd. Mangeron 27, 700050 Iasi, Romani
Tel: +40-232-278680 ext. 1327
E-mail: fleon@tuiasi.ro

Joe Y-T Li[a]
C1-2-436 Kyotodaigaku Katsura, Nishikyoku, Kyoto 615-8540
Tel: +81-75-383-7491, Fax: +81-75-383-3236
E-mail: joe.liyt@trans.kuciv.kyoto-u.ac.jp

Jun Ji[a]
C1-2-436 Kyotodaigaku Katsura, Nishikyoku, Kyoto 615-8540
Tel: +81-75-383-7491, Fax: +81-75-383-3236
E-mail: jijun@trans.kuciv.kyoto-u.ac.jp

Gabriela Atanasiu[b]
Multidisciplinary Center of Structural Engineering& Risk Management
Bdul D. Mangeron No. 43, 700050 Iasi, Romania
Tel:+40-232-278683 ext.1417 Tel::+40-232-235757
E-mail: atanasiu@ce.tuiasi.ro

Eiichi Taniguchi[a]
C1-2-335 Kyotodaigaku Katsura, Nishikyoku, Kyoto 615-8540
Tel. 075-383-3229, Fax. 075-950-3800
E-mail: taniguchi@kiban.kuciv.kyoto-u.ac.jp

[a]Department of Urban Management, Graduate School of Engineering, Kyoto University
[b]Technical University "Gheorghe Asachi" of Iasi, Romania

Word count: 5,835 words + (6 figures +1 tables) * 250 = 7,585 words
Submission Date: 15 November 2014

ABSTRACT

This research aims to incorporate social capital, which we define as information flow from government to population and information flow within population, into our agent-based evacuation model. We have considered the importance of social capital based on past disaster lessons of broken communication from key decision makers and the effectiveness of crowd influence during evacuation which is vital to future evacuation plans or infrastructure improvements to resolve congestion on critical links or points. The emphasis of the present paper is to describe the modeling framework and implementation into an agent-based modeling framework. We test our software with an illustrative case study. Our key findings demonstrate a higher survival rate if evacuees tend to heed government's evacuation guidance whenever it is available or to follow the neighboring crowd evacuation advice.

Keywords: Social capital, multiagent, simulation, disaster, tsunami

1. INTRODUCTION

In the study of evacuation modeling and analysis, it is suggested that an efficient evacuation planning model should provide evacuation time, locate critical points in the transport network, and be able to assess traffic operations strategies and evaluate policies (*1*). Other main outputs that are of interest to planners and emergency management officials from evacuation studies usually focus on the evacuation times (clearance and average travel times) and network bottlenecks, where the clearance time can be based on reaching an assumed point of safety as compared to the final destination (*1*). In the past, studies of evacuation modeling in the event of a large disaster have been based on evacuees heeding the government's advice for evacuation guidance information, which usually has fixed departure times, designated shelters, and paths (*2*). However, pre-specified decisions may a) not be realistic and b) sometimes lead to reduced efficiency due to uncertain road conditions caused by congestion or hazards during such emergency evacuation (*3, 4*). It was found that pre-planning and government advice are important but under certain circumstances, they are hardly followed or, worse, plans cannot be implemented when the government loses its functionality in a disaster. In disaster situations hence different behavioral rules might apply. A simple rule that seems to be important to describe behavior of evacuees in disaster situations is instead the tendency to follow behavior observed by others. This could lead to congestion and panic, but also to positive effects if those without sufficient knowledge about evacuation options follow others with good advice. The aim of this paper is to describe an agent-based modeling framework that allows quantifying the effects of both field effects and (partially obeying) government advice. We illustrate our model with a small network case study.

The remainder of this paper is organized as follow. Section 2 reviews in more detailed components of evacuation modeling from literatures. Section 3 introduces an overview of our model framework and notations. Section 4 and 5 describes agent behaviors and proposed model. Section 6 demonstrates initial results of the model, comparing one base case with two different evacuation behaviors from scenario. Section 7 concludes this study and discuss future improvements.

2. LITERATURE REVIEW

2.1 General Concept of Evacuation Models

When a large disaster occurs, congestion in affected areas results in loss of efficiency and often creates an excessive load to the network due to traffic primarily out of the hit area but also into or within the hit area (e.g. rescue vehicles, supply of emergency goods, reverse trips to pick-up goods or family members) (*2*). Therefore, better utilization of the available transportation network capacity during disasters is essential to manage traffic and lead people to safety. Church and Cova (*5*) indicated the context of evacuation requires a mode of transit and infers some type of movements. Murray-Tuite and Wolshon (*6*) summarized highway-based evacuation transportation modeling with simulation and its evolution over the past decade. They indicated that evacuation models should include:

- forecasting of evacuation travel demand;
- distribution and assignment of evacuation demand to regional road networks to reach destinations;
- assignment of evacuees to various modes of transportation; and
- evaluation and testing of alternative management strategies to increase capacity of evacuation networks or manage demand.

2.1.1. Evacuation Travel Demand and Trip generation

A number of factors can affect the safety of an evacuation. These factors include the number of people needing evacuation (i.e. demand), the transportation capacity provided for evacuation, the rate at which the demand is exerted, the rate at which capacity is actually provided, the differences between these rates, human behavior, and related to these points, accidents (*7*).

Trip generation approaches generally attempt to capture some of the social and threat factors influencing the decision to evacuate with the goal of producing time dependent demand for traffic simulation. (Time-dependent) evacuation trip generation has been performed with a variety of techniques such as one or two step models (*6*). In the two step approach firstly the number of evacuating households is estimated and subsequently their departure times are obtained, often with a "response curve". In contrast, the one step approach considers both steps simultaneously, i.e. estimates the number of people evacuating in each time-step. It appears further important for evacuation modeling not to ignore some of the other trips happening at the same time. Murray-Tuite and Wolshon (*6*) further note that beside all kind of background traffic, modeling only the "needed" evacuations often ignores a significant number of additional evacuations near the hit area referred to as "shadow evacuations". They further discuss a long list of factors that determine the decision whether and if yes, when to evacuate, showing the complexity of the problem. Therefore they point out that validation of evacuation models is a difficult but important task. Large scale observations are needed to enhance our understanding of the complexities and validate the entire demand modeling process.

2.1.2. Evacuation Mode Choice

As discussed in Murray-Tuite and Wolshon (*6*), a number of factors could be taken into account for mode choice, including, but not limited to, (i) characteristics of the disaster, (ii) required travel distance to reach safety/ shelters, (iii) location of the evacuees at the time an order is given, and (iv) available options. From Wu et al.'s survey after Hurricanes Katrina, they found only 11% of evacuees not taking their own cars, of which "71% rode with someone else and 28% used another form of transportation" (*8*). Therefore they conclude that a person who has access to a car tends to use this for evacuation. This might though not necessarily be the case for more rapid evacuation. Furthermore, the general advice in Japan is to walk during evacuation since many who evacuated by car were stuck in the traffic jams (*9*). For tsunami evacuation modeling furthermore public transport can be largely ignored, as the services are usually suspended after a large earthquake. Obviously this might be different for evacuation due to other causes, such as flooding.

2.1.3. Evacuation Traffic Assignment

To this end, traffic simulation models have been used in the past few decades to investigate traffic flows in emergency evacuation scenarios. Both, user equilibrium and system-optimal assignment as well as non-equilibrated simulation are commonly proposed to estimate flows during the evacuation period. For instance, for a nuclear power plant evacuation scenario, Hobeika and Kim (*10*) compared different traffic assignment procedures that use a traffic simulator and concluded that user equilibrium assignment showed more realistic results than a shortest-path algorithm when traffic management strategies were adopted to improve the vehicular capacity of the highway network. Their results show that the evacuation performance measures are largely dependent on the highway network structure and the number of vehicles produced in an emergency planning zone. With the same objective of minimizing network clearance time, Sattayhatewa and Ran (*11*) proposed an analytical system-optimal dynamic traffic assignment model that allows modeling system degradation in the evacuation process.

Generally government is aiming to move traffic flows closer to system optimal solutions by traffic management measures such as advising certain routes and possibly clearing them from background traffic. In how far route advice is followed though is not very clear. Murray-Tuite et al. (*12*) found that evacuees most often seek familiar routes.

2.2 Social Capital and Evacuation Modeling

As mentioned in the introduction our focus is on modeling field effects and trust in government advise. This is closely related to the concept of "social capital" which has been defined previously as "the resources available to individuals through their social networks" and encompasses trust and norm of reciprocity (*13*). Aldrich claim that "even highly damaged communities with low income and little aid benefit from denser social networks and tighter bonds with relatives, neighbors and extralocal acquaintances" (*14*). The benefits of a resilient social capital include more lives saved through community evacuation, self-organized civilian firefighting corps, community-driven relief distribution etc. (*15*). A strong social capital in the form of stronger community bonds (also known as Kizuna in Japanese) tends to reduce unnecessary frictions, which may happen between victims and unfamiliar volunteers (*16*). In conclusion, a reflection of a society's social capital appears to be important to include in evacuation scenarios, but is extremely difficult to model. We suggest that a) trust in planning authorities and b) field effects among the agents or "compliance behavior" are related to the social capital, though acknowledge that it does not cover all aspects. The following reviews some support for the importance of these two particular effects:

A number of studies found that compliance influences evacuation performance (*17, 18*). Further, from empirical observation and case studies, it is recognized that the population does not automatically follow the advice or orders from officials during evacuation. Rather, evacuees tend to accept advice as additional information when evaluating their decisions on perceived condition. Fu et al. (*18*) proposed hence a framework which integrates a macroscopic traffic simulator with a description of travelers' compliance behavior. From their numerical experiments, departure time and route (destination) compliance has different influences on evacuation efficiency. Mandatory management strategies may lead to low efficiency as drivers' full compliance with non-optimal instructions results in traffic congestion.

Other researchers considered receiving information and intelligence exchange from neighbors and peoples' social network play an important role for evacuating the population (*19, 20, 21*). Among others, the receiving of warnings through media as well as neighbors and the local social network are found to be important factors determining the decision whether to evacuate or not (*20-24*). In particular local neighbors may be the first sources of information about a threat or advice to evacuate (*19*). Also Ranghieri and Ishiwatari reports that the response of family and neighbors in the social network can encourage an individual or a household to evacuate (*9, 21*).

2.3. Multiagent Systems for Evacuation Modeling

We are embedding the above reviewed decision dimensions including our proxies for social capital in an agent based framework. Multiagent systems are suitable for solving problems which are distributed and complex in nature because of their inherent ability to divide the main task into small subtasks handled by individual agents. When the subtasks contain overlapping or conflicting goals, the social aspects of the agent paradigm can be employed, for example by negotiating and constructing cooperative plans.

Evacuation modeling methodology is mainly categorized into optimization, simulation, and risk assessment. Large-scale simulations usually study the evacuation flow due to disasters and identify parts of the environment that are vulnerable to congestion (*25*). Related to our work, Richer et al. (*25*) considered the different levels of spatial knowledge available to each agent. The first level is having perfect information throughout the simulation, the second level is having knowledge of spatial information on the path taken prior to disaster and the third level is the availability of spatial information after a disaster happens. Each of these levels will trigger different wayfinding intelligence either by standard shortest path or random exploration and backtracking. They propose that cooperation (ie. sharing spatial information) improves evacuation performance in decentralized evacuation under imperfect information.

3. FRAMEWORK OVERVIEW AND NOTATION

Above literature review showed that there have been a number of multi-agent based approaches to evacuation modeling already. To the best of our knowledge we believe though our model is unique in including both government advice and field effects. The following describes a general framework that we believe allows reflecting a large number of the findings on factors influencing the various choice dimensions of evacuees. We describe the framework in the following fairly extensively as we believe it allows for easy adaptation and for example some modules such as the modeling of the agent movements on links could be replaced with existing, advanced software.

The simplified structure of the model framework is shown in Figure 1, where government advises the population, sets the capacity of links. Links like bridges and roads are considered passive agents and have limited or residual capacity according to traffic volume. With a set of characteristics parameters describing the population, evacuation decision can be initialized. Shelters with feedback loops to report residual capacity can help improving the flow of evacuees in the network. Table 1 and Table 2 briefly describe the notations for our evacuation model.

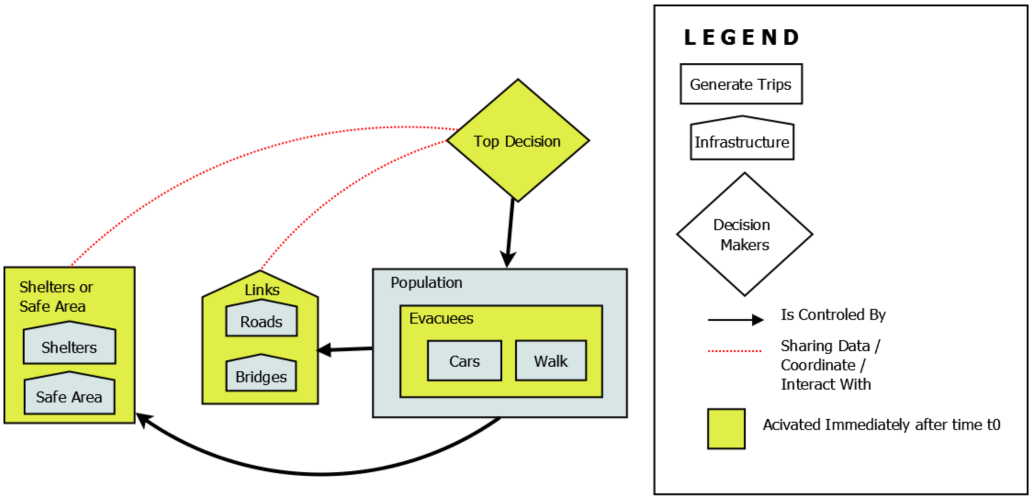


Figure 1 Simplified framework of stakeholders for evacuation simulation

Table 1 Input Parameters and Simulation Outputs

Input Parameters	
Scenario attributes (input)	
τ^0	Time when it is known that the disaster will occur, start of evacuation. Considering a potential Tsunami disaster τ^0 can be clearly defined as the time of the Tsunami triggering earthquake.
τ^z	Targeted time by which evacuation should be completed (assumed to be known to all agents, i.e. population knows when Tsunami will come)
H	Set of zones which the analysis area is split into
d_h^o	Distance of zone h to risk area. Superscript o stands here for ocean, considering a Tsunami evacuation.
Agent 1 (population) attributes, $n_i^p \in N^p$ **agents**	
r_i	Home zone of individual i
$h_i^p(0)$	Location (zone) h of individual i at start of simulation
φ_i	1 if individual i has access to a car, 0 otherwise
ζ_i	Tendency for individual i to follow government advice in his decisions (could be decision specific, i.e. ζ^e_i, ζ^s_i, ζ^p_i)
γ_i	Field effect by surrounding environment: This defines the strength of influence of neighbors and/or family, e.g. if most neighbors/family evacuate, individual i would be more likely to evacuate (could also be decision specific, i.e. γ^e_i, γ^s_i, γ^p_i)
η_i	1 if individual requires "hospital type shelter"
β_i^i, β_i^d	Parameter in utility function
Agent 2 (government) attributes, single agent	
θ	Thresholds to reconsider optimization
Agent 3 (road links) attributes, $n_i^r \in N^r$ **agents**	
$h_k^l(t)$	Zone in which (center of) link k is located
A_k^+, A_k^-	Sets of in and outgoing links (to describe network)
l_k	Length of link k
$c_k(t)$	Travel cost (time) of link k at time t
$\bar{v}_k$	Max speed of link k
ρ_k	Link type / parameter describing speed-density relationship on link k,
$\tilde{\rho}_k$	Also describing link type, but as dummy variable: 1 if link k is a car link, otherwise 0
$\bar{y}_k$	Nominal capacity of link k
$y_k(t)$	Capacity of link k at time t considering earthquake damage or preplanned reduced capacity due to priority reservation for emergency transport (as input of simulation)
Agent 4 (shelter) attributes, $n_i^s \in N^s$ **agents**	
h_j^s	Zone in which shelter j is located
z_j	Capacity of shelter j
ψ_j	Type of shelter: 1 if j is a hospital type shelter, otherwise 0

Derived attributes (simulation output)	
$h_i^p(t)$	Location *h* of individual (persons) *i* at time *t*
$d_i^j(t)$	Distance from current location for individual *i* to shelter *j*
$m^e_i(t)$, $m^s_{ij}(t)$	Number of persons in the neighborhood/ family of individual *i* who have started to evacuate at time *t*, and who have started to evacuate to shelter *j*
$g_{hj}(t)$, $g_{hj}^m(t)$	Predicted shortest travel time from zone *h* to shelter *j* by any mode, with $\mathbf{g}_h$ denoting the set of travel times from *h* to all *j*. Superscript *m* denotes mode specific travel times.
τ^p_i	Time individual *i* reaches shelter
$e_i(t)$	Evacuation decision of individual *i* at time *t* (binary)
$e^a_h(t)$	Evacuation advice for zone *h* at time *t* (binary or possibly some levels of strength of advice)
$s_i(t)$	Shelter chosen by individual *i* at time *t*
$\mu_i(t)$	Mode chosen for evacuation by individual *i* at time *t* (1 if car, 0 for walk)
$S^a_{h(i)}$	Set of shelters which individuals *i* in zone *h* is advised to travel to by top decision maker
$P_i(t)$	Set of links (OD specific path and mode) chosen by individual *i* at time *t*
$P^a_{h(i)}(t)$	Set of links (OD specific path and mode) advised for individuals *i* in zone *h* at time *t*
$q_k(t)$	Flow on link *k* at time *t*
$q_{hs}(t)$, $q_{hsk}(t)$	Flow from *h* to *s* at time *t* (on link *k*)
$q^a_k(t)$,	Amount of demand advised to travel on link *k*
$q^a_{hs}(t)$, $q^a_{hsk}(t)$	Amount of demand advised to travel from *h* to shelter *s* (on link *k*)
$\tilde{z}_j(t)$	Residual capacity of shelter *j* at time *t*
δ_{hj}, δ_{hjk}	Dummy indicating whether demand from zone *h* is assignable to shelter *j*, similarly let δ_{hjk} indicate whether the demand from *h* to *j* can use arc *k*.

4. MODELING AGENT EVACUATION AND GOVERNMENT ADVICE

4.1 Overview of Population Behaviour

The population behavior comprises of five actions. The first three actions are direct decisions by the agents: Firstly, they decide whether to evacuate or not, secondly the choice of shelter and thirdly the mode and path choice. The latter two actions may be described as "forced actions". The forth action describes the movement of the agents based on available link speeds and fifth action removes the agent from the simulation upon arrival at a shelter. We presume that the shelter capacity is not known to the evacuees so that it might occur that a person reaches a shelter that is already fully occupied. In that case the evacuee will decide the next shelter to travel instead. The following sub-sections describe these actions in detail. For generality, the functionalities and the specific implementation of the functions are distinguished.

4.1.1. Evacuation Decision

We presume that not all agents necessarily evacuate immediately upon knowledge that a disaster will occur. As the literature review has shown a number of reasons can deter people living in an endangered area to evacuate at all, or not to evacuate yet. We consider that the population who has not started to evacuate might reconsider their choices at pre-fixed point in times. This is implemented as follows:

<u>A1.1 Determine whether individual is evacuating or not at time t</u>, if agent is not evacuating this action is called periodically, if agent has decided to evacuate, stop calling action for this agent.

We define the utility $u_i^e(t)$ of an agent to evacuate as following functionality:

$$u_i^e(t) = f\Big(\eta_i(need\ for\ hospital\ shelter), d^o_{h_i^p(t)}(distance\ of\ person\ to\ risk\ area),$$
$$\tau^z(Targeted\ time\ to\ evacuate), e^a_{h(i)}(Evacuation\ advice\ from\ government),$$
$$m_i^e(t-1)\ (People\ evacuated\ at\ previous\ time\ step)\Big) \quad (1)$$

The decision whether to evacuate or not is hence a function of whether the agent requires medical aid at the hospital or not, the distance to the risk area, the evacuation target time, the decisions of others and the advice obtained by the government.

Considering additive, linear effects of these five factors leads to following specification:

$$u_i^e(t) = \beta_i^i \eta_i + \beta_i^d d^o_{h_i^p(t)} + \beta_i^u \tau^z + \gamma_i^e m_i^e(t-1) + \zeta_i^e e^a_{h(i)} \qquad (2)$$

where β_i^i, β_i^d and β_i^u describe the relative weight of injury, distance to risk and urgency to evacuate in the utility function. In general we would probably expect that β_i^i is set very high to ensure that those requiring medical help following the initial disaster (earthquake) are evacuating. Finally, γ_i^e and ζ_i^e are the weights of our "social capital" depending factors.

With the above utility function the decision whether to evacuate or not can then be determined deterministically as in (2) where α_i denotes the "utility threshold" for a person *i* to evacuate.

$$e_i(t) = \begin{cases} 1 & u_i^e(t) > \alpha_i \\ 0 & \text{otherwise} \end{cases} \qquad (3)$$

Alternatively, the same parameter can be used for a stochastic approach. Assuming a logistically distributed error term in the perception of utility, one obtains (4) which can be used in the simulation framework to randomly obtain the binary decision for each agent whether to evacuate or not.

$$\Pr\big(e_i(t)\big) = \frac{1}{1+\exp\big(\alpha_i - \mathrm{u}_i^e(t)\big)} \qquad (4)$$

Larger (lower) α_i obviously lead to lower (larger) probabilities for a person to evacuate. For α_i being normally distributed over agents $n_i^p \in N^p$ we expect half the population to evacuate at time $t = 0$ if $\bar{\alpha}$ is equal to the median of $u_i^e(0)$. Note that for $u_i^e(0)$ the median might not equal the mean if large β_i^i values are assumed for injured agents as noted before.

4.1.2. Shelter Choice

Those agents that decided to evacuate will then decide which shelter to evacuate to. In our framework we separate this decision from the mode/ path choice decision, though this might be a simplification or one might even argue that persons first choose the evacuation mode before deciding which shelter to evacuate to. The "term" shelter might be further understood a bit wider as a safe place a person is destined to. Therefore shelter with unlimited capacity at the boundary of the modeled area can also be introduced for people leaving the endangered area altogether.

<u>A1.2 The shelter decision for those persons evacuating</u>, action called either after $e_i(t)$ is updated to yes, or after A1.5.

For the implementation of this activity we define the utility of shelter *j* for person *i* as

$$u_{ij}^s(t) = f\Big(\varphi_i(\mathit{access\ to\ transport\ mode}), \eta_i(\mathit{need\ for\ hospital\ shelter}), S^a_{h(i)}(\mathit{set\ of\ advised\ shelters})\ m_{ij}^s(t-1)(\mathit{People\ evacuated\ at\ previous\ time\ step}), \boldsymbol{g}_{h_i^p(t)}(t)(\mathit{shortest\ travel\ time\ from\ person\ to\ shelter})\Big) \qquad (5)$$

The five terms describe the preference for specific shelters. For those with injury, i.e. shelters with medical facilities, the deterrence for shelters far away from the current zone $h(i)$, whereby evacuees with car access might evaluate distance different to those without car access. The last two factors describe again the social capital factors of shelters chosen by others and shelters advised by the government. Assuming again linearity and additivity we derive

$$u_{ij}^{s}(t) = \beta_i^{i}\eta_i\psi_j + \beta_i^{d}\tilde{g}_{h_i^p(t)j}(t) + \gamma_i^{s}\, m_{ij}^{s}(t-1) + \tilde{\zeta}_{ij}^{s} \tag{6}$$

with $\tilde{g}_{h_i^p(t)j}$ and $\tilde{\zeta}_{ij}^{s}$ being obtained with (7) and (8).

$$\tilde{g}_{h_i^p(t)j}(t) = \begin{cases} g_{h_i^p(t)j}(t) & \text{if } \varphi_i = 1 \\ g_{h_i^p(t)j}^{w}(t) & \text{otherwise} \end{cases} \tag{7}$$

$$\tilde{\zeta}_{ij}^{s} = \begin{cases} \zeta_i^{s} & \text{if } j \in S_{h(i)}^{a} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

Equation 7 denotes that travel time to a shelter which will be the minimum travel time of walk or car for those with car access and the walking travel time for those without car access. Equation 8 modifies the utility for those shelters that have been advised by the government. With (6) to (8) one can then obtain the shelter decision $s_i(t)$ again deterministically or stochastically.

4.1.3. Mode and Path Choice

The third activity follows also straight after the first two, but might be called in addition at different points in time when evacuees want to update their route choice due to congestion or other information becoming available.

A1.3 Mode/Path finding at time t, action called after A1.2 and periodically thereafter, but mode choice only possible at time when $e_i(t)$ is updated to "yes"

To reflect that car users cannot utilize pedestrian links and vice versa for path and mode choice the link cost $c_k^c(t)$ for driving and $c_k^w(t)$ for walking are weighted as follows where *M* is a large number:

$$c_k^c(t) = \frac{l_k}{v_k(t)} + \tilde{\zeta}_{ik}^{p} + (1 - \tilde{\rho}_k)M \tag{9}$$

$$c_k^w(t) = \frac{l_k}{v_k} + \tilde{\zeta}_{ik}^{p} + \tilde{\rho}_k M \tag{10}$$

with

$$\tilde{\zeta}_{ik}^{p} = \begin{cases} \zeta_i^{p} & \text{if } k \in P_{h_i^p(t)}^{a}(t) \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

For walking links one might presume a constant speed, therefore there is no dependency on time *t* in (10). The second term describes again the influence of the government on the decision. $\tilde{\zeta}_{ik}^{p}$ is obtained with (11) where $P_{h_i^p(t)}^{a}$ denote the links advised to be taken by the population. For the combined mode and path choice the shortest paths $P_i(t)$ for both modes are then obtained and the shortest option among the two is chosen (deterministically or stochastically).

We presume that path choice can be updated throughout the journey but mode choice is only possible at the time the evacuation decision is made. Therefore for path choice only we weight link cost $c_k(t)$ as in (12) with δ_{ij} obtained as in (13).

$$c_k(t) = \frac{l_k}{v_k(t)} + \tilde{\zeta}_{ij}^{p} + \delta_{ij}M \tag{12}$$

$$\delta_{ij} = \begin{cases} 1 & \text{if } \mu_i \neq \tilde{\rho}_k \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

4.2. Simulation Dynamics of Population Agent

4.2.1. Population Movement

The previous three activities complete the active decisions made by the agent. Travel speeds are assumed homogeneously equal to the congestion depending on the allowable link speeds. This is denoted by following activity.

A1.4 Agent movement simulation: Update $h_i^p(t)$, action called at each time step
Move agents according to link (Agent 3) speeds

Our simulation might hence be described as "mesoscopic" as we model each agent but do not consider interaction between each agent in the form of car-following approach. We also do not explicitly divide links into "cells" as in cell transmission models but update link positions continuously. An agent is presumed to exit a link and enter the subsequent link on his path to the destination once the time has been sufficient to traverse the link given the congestion level. The link speeds are assumed to be constant over the link length and are obtained from the "road link agents":

A3.1 Obtain $v_k(t)$, the speed on link k at time t, action is called every time step

Link speeds are assumed to be a function of the number of agents on the link, the link capacity and the type of link.

$$v_k(t) = f(q_k(t), \rho_k, y_k(t)) \tag{14}$$

with constraints $v_k(t) \leq \bar{v}_k$ and $q_k(t) \leq y_k(t) \leq \bar{y}_k$.

For simplicity we might presume a continuous function as in (15). Assuming constant pedestrian speeds hence implies $\rho_k = 0$ for walking links. For road links we expect $\rho_k > 0$ with higher ρ_k values possibly for local roads that are interrupted by other road links.

$$v_k(t) = \bar{v}_k \left(1 - \frac{q_k(t)}{y_k(t)}\right)^{\rho_k} \tag{15}$$

4.2.2. Shelter Arrival

Once a population agent reaches a shelter s/he will be removed from the simulation. The possibility that an already full shelter is targeted by the population obviously reflects an "imperfect information scenario". It should be noted though that if all agents follow the government advice such cases should not occur.

A1.5 Removal/reassignment of agent, Action called when agent reaches shelter location.
If $\tilde{z}_j(t)=0$, return to A1.2, else remove agent from simulation and record "end of evacuation for individual i at time t", τ^p_i

Once an agent is absorbed by the shelter the residual capacity of the shelter is accordingly reduced.

A4.1 Obtain the residual capacity of shelter j at time t, action is called at each time step

More formally, we denote the residual capacity at time *t* of shelter *j* as $\tilde{z}_j(t)$ which can be obtained by (16) and (17).

$$\tilde{z}_j(t) = z_j - \sum_{n_i^p \in N^P} \hat{s}_{ij} \tag{16}$$

with

$$\hat{s}_{ij}(t) = \begin{cases} 1 & s_i(t) = j \text{ and } \tau_i^p \leq t \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

4.3. Government Advice

The role of the government is simulated by deriving the optimal assignment of people to shelters, partially similar to research by Nagao et al. (*26*). This results in a set of suggested shelters as well as paths which the population consider in their decision making as described above.

4.3.1. Deriving Advice at Time τ^0

Given the network conditions at time τ^0 following optimization problems are solved.

<u>*A2.1 Advice zone h to evacuate or not*</u>

We define the decision to advice evacuation for an agent as following functionality:

$$e_h^a = f\big(d_h^o(distance\ of\ zone\ to\ risk\ area), \tau^z(Targeted\ time\ to\ evacuate), \boldsymbol{g}_h(shortest\ travel\ time\ from\ zone\ to\ shelter)\big) \tag{18}$$

if $\tilde{e}_h^a$ is larger than a government defined threshold, then increase strength of advice $e^a{}_h$ (or could be binary).

<u>*A2.2 Assign population to shelters*</u>*, by solving a linear optimization problem*

Given the assumption that those who are advised to evacuate will do so and others will not, the demand *w* for shelters of type ψ from zones *j* is obtained as follows:

$$w_j^{\psi}(t) = \sum_i \hat{w}^{\psi}{}_{ij}(t) \tag{19}$$

with

$$\hat{w}^{\psi=0}{}_{ij}(t) = \begin{cases} 1 & h_i(t) = j, \eta_i = 0 \text{ and } e_j^a = yes \\ 0 & \text{otherwise} \end{cases} \tag{20}$$

$$\hat{w}^{\psi=1}{}_{ij}(t) = \begin{cases} 1 & h_i(t) = j, \eta_i = 1\ and\ e_j^a = yes \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

Then the linear program (22) – (26) is solved. Equation 21 denotes the objective function which is here set to minimize the total travel time for all agents. One might denote this as an objective function aiming to minimize "risk exposure" of all agents. Other formulations such as minimization of the time when all agents have entered a shelter could also be considered. Constraint (23) denotes flow conservation considering the type of shelter required by the agents. Equation (24) ensures that shelter capacities are observed. Equation (25) is important in case the network becomes disconnected due to the earthquake. δ_{hj} takes value 1 if shelter *j* can be reached from zone *h* so that the constraint ensures that only shelters that are reachable will be advised. Finally, (26) ensures non-negativity of flows.

$$\min_{\boldsymbol{q}^a} \sum_{h \in H} \sum_{j \in S} g_{hj} q_{hj}^a \tag{22}$$

Subject to

$$\sum_{j \in S^{\psi}} q_{hj}^a = w^{\psi}{}_h \ \forall h, \psi \tag{23}$$

$$\sum_{h \in H} q_{hj}^a \leq z_j \ \forall j \tag{24}$$

$$\left(1 - \delta_{hj}\right) q_{hj}^a = 0 \ \forall h, j \tag{25}$$

$$q^a_{hj} \geq 0 \;\; \forall h, j \tag{26}$$

We presume that it might be difficult for the government to advise people living in the same zone to travel to different shelters. Therefore we simplify the advice, by allowing all people from a zone to travel to any of the shelters that are advised for this zone, as formulated in (27). This might lead though to some issues especially if shelter capacities are limited. The problems associated with this heuristic approach are hence of less importance if a) shelter capacities are large and b) zones are small, so that the above LP will in general not find a large set of shelters between which the demand of the zone should be split.

$$S^a_j(t) = \left\{ \forall_{j \in S} n^s_j \in N^s \,\middle|\, q^a_{hj} > 0 \right\} \tag{27}$$

A2.3 Advice population to take shortest path to shelter

Having obtained the shelter advice, the government might in addition also recommend routes to these shelters from the zones. In the case of Japan, often local governments have pre-designed priority routes which are aimed to be cleared quickly from debris in case of an earthquake. Considering this, and ignoring congestion effects, would hence lead to

$$q^a_{hjk}(t) = \begin{cases} q^a_{hj} & if\ k \text{ is on the shortest path/priority route} \\ 0 & \text{otherwise} \end{cases} \tag{28}$$

Also for advised routes it might be difficult to implement for a government shelter specific advice. Assuming instead simply generic advise for each zone, would lead to (29) where $P^a_h(t)$ denotes the set of links that people from zone *h* are advised to take for evacuation.

$$P^a_h(t) = \left\{ \forall n^r_i \in N^r \,\middle|\, q^a_{hjk}(t) > 0 \right\} \tag{29}$$

4.3.2. Advice Update

Government advice is obtained once at the beginning of the simulation and it is presumed that advice cannot be continuously updated. However, the government might reconsider their advice if the evacuation procedure markedly differs from the ones predicted. Therefore we add following activity:

A2.4 Information processing to reconsider advice, this action is called periodically every x time intervals: Call A2.1. to A2.3 if network situation significantly differs from the predicted one

The definition of "significantly differs" is implemented if either one of the following conditions is true:

a) $\tilde{z}_j(t) = 0$

b) *Link conditions* $\boldsymbol{g}_h$ *significantly deviate from prediction/ priority routes change, e.g. there is a* $g_{hj}(t) / g_{hj}(t\text{-}x) > \theta$

Under a) shelters *j* are full at time *t* and are hence likely approached by more people than advised until time (*t*), this means the population should not be advised to use this shelter anymore. Hence A2.2 is reconsidered without consideration of shelter *j*. The second condition (b) means that significant congestion has occurred so that increased travel times cannot be ignored in the path suggestion. In that case A2.3 is reconsidered taking the current link travel times as basis for the shortest path estimation.

5. MODEL IMPLEMENTATION

Macroscopic modeling focuses on a higher level by studying the behavior on larger entities without taking into consideration each entity and its interactions. In microscopic modeling, each entity (people or vehicle) is modeled individually. Although macroscopic models are ideal for larger regions and are easier to implement compared to microscopic models, they miss important aspects of the simulated behavior, for example the sudden infrastructure changes.

A compromise between the microscopic modeling and macroscopic modeling is the mesoscopic modeling. Mesoscopic model describes the entities with a high level of detail but their behavior and interactions are described at a lower level. The nodes are represented by the intersections, roadblocks, bridges affected or not by the disasters. The links are represented by the roadways/pathways. In the mesoscopic representation each link has two parts: a path and a queue. When vehicles enter a link, they are grouped into packets which are led on the path and then before entering a node, the vehicles are put in a queue. When a vehicle leaves the queue and enters the node, he can choose the next link, this being the only behavior of the entities. Therefore the main activity from the mesoscopic model is to group vehicles into packets which are routed through the network (*27*).

REvaSim, the developed evacuation simulation software in this study belongs to the mesoscopic category, in which the user can define the granularity of the simulation. The simulation works based on groups of people, and the size of the groups is a simulation parameter; it can vary from 1 (fine-grained simulation) to 100 or more (coarse-grained simulation). Figure 2 presents the flowchart of the software solution, represented as a Unified Modeling Language (UML) activity diagram. It closely follows the theoretical framework that was described from sections 3 and 4 that defines the steps of the evacuation and suggests the equations based on results from transportation science.

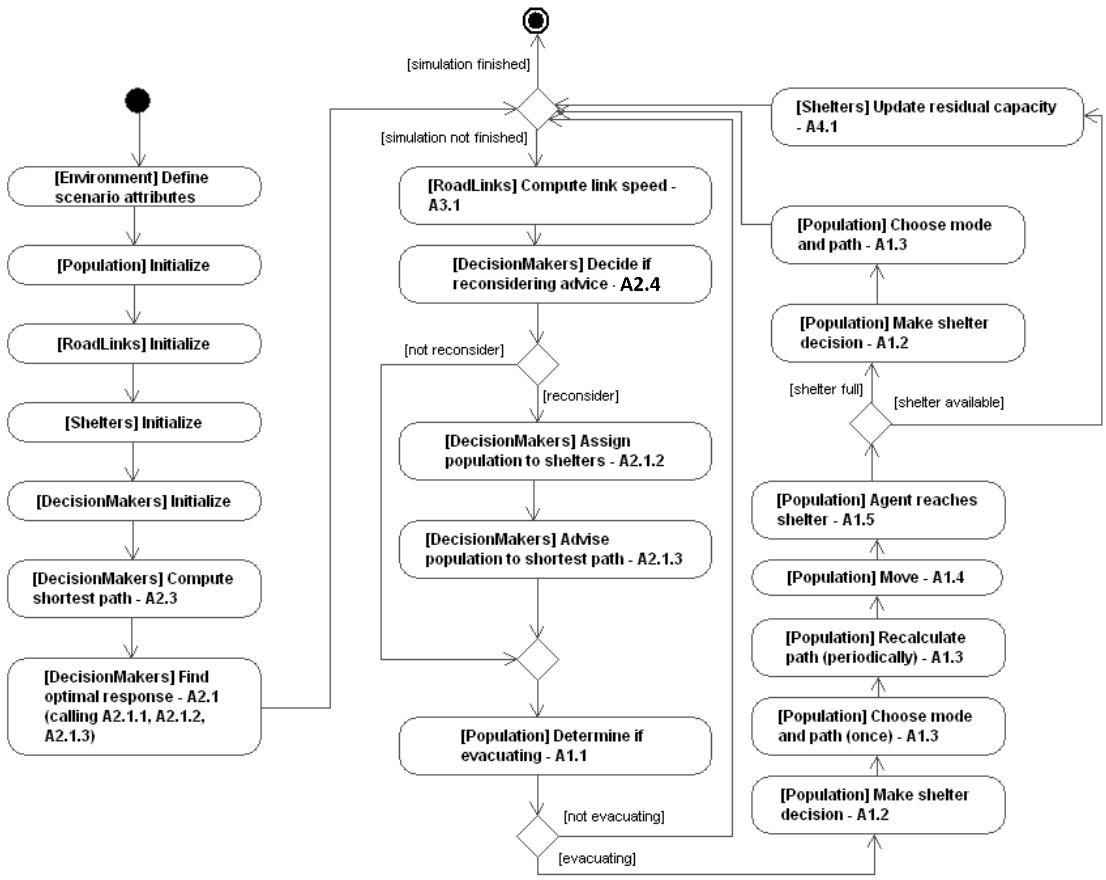


Figure 2 UML activity diagram

6. RESULTS AND DISCUSSION ON HYPOTHETICAL NETWORK

Our multiagent model was first tested on a hypothetical network as shown in Figure 3. For brevity we do not illustrate all model features, but focus on testing the effects that are of main interest in this paper: (*i*) the tendency to follow government's advice and (*ii*) the tendency to follow others. We consider the following parameters for three cases under an earthquake scenario that is supposed to have damaged the bridge of car link F-C, so that the link is only available for walking. To illustrate the effect of limited shelter capacity we further presume that all evacuees have in general a preference for the small shelter at node A, possibly because it appears safer or has more medical facilities (high β_i^i parameters).

Case 1 (Base case):

- tendency to follow others, γ_i = 0
- tendency to listen to government advice, ζ_i^e = 0

Case 2 (Advised case):

- tendency to follow others, γ_i = 0
- tendency to listen to government advice, ζ_i^e = 0.89

Case 3 (Field case):

- tendency to follow others, γ_i = 0.89
- tendency to listen to government advice, ζ_i^e = 0.01

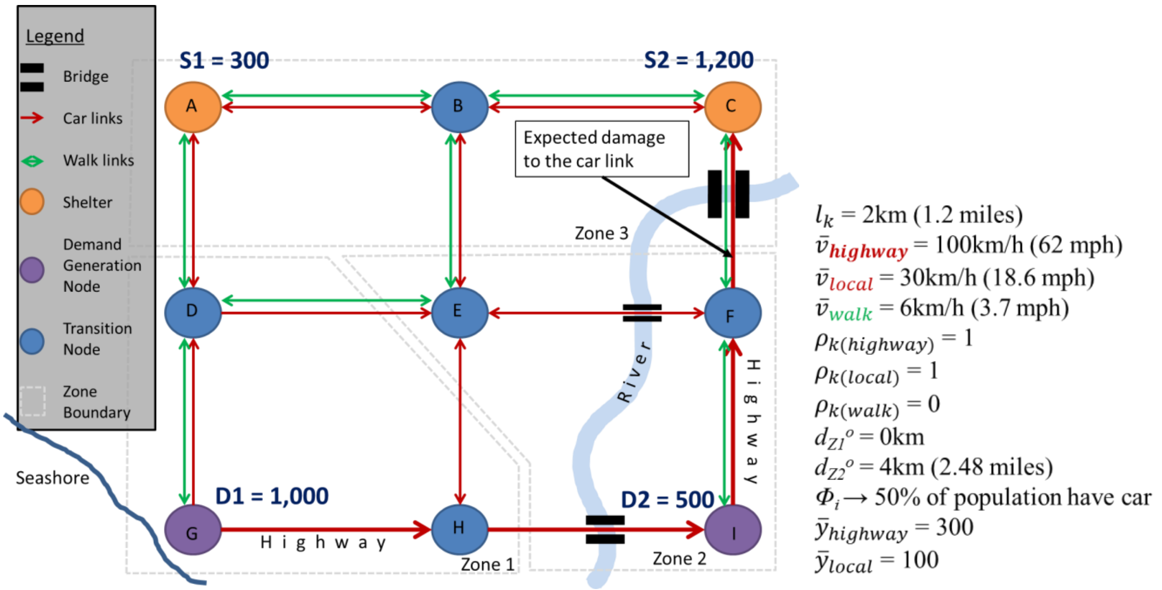
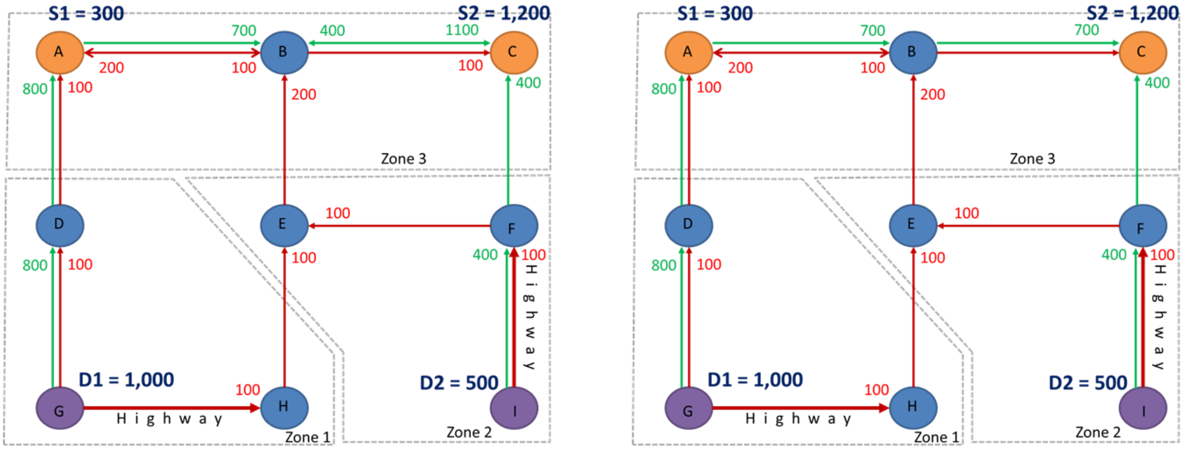


Figure 3 Hypothetical network for analysis

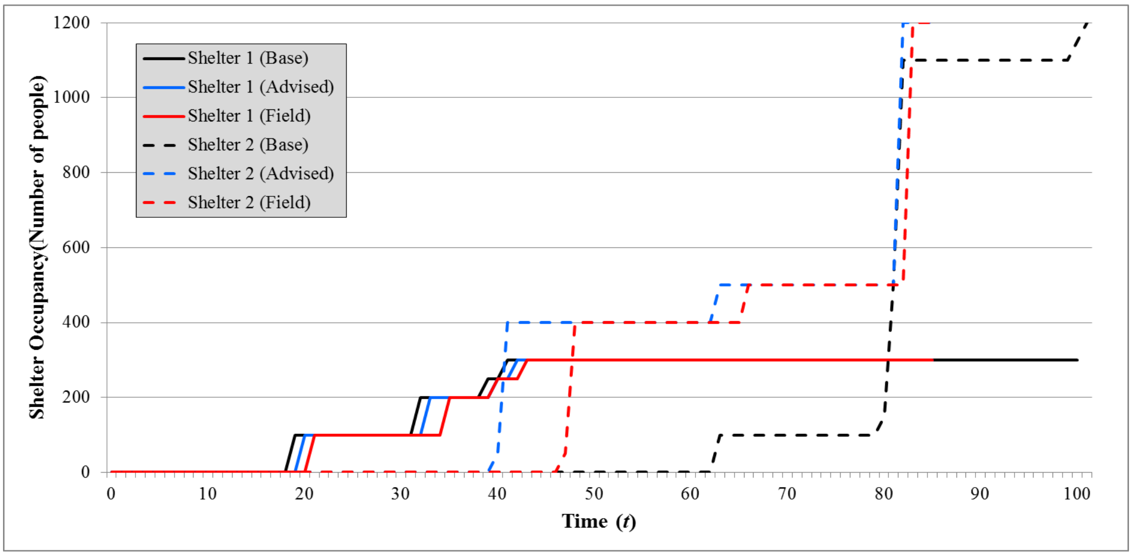
The evacuation flows for the three cases are shown in Figure 4. The overall flow for the cases are generally similar except for the walking population between link B-C. Due to the intensity of the earthquake, a preferred evacuation node was to select Shelter 1 at node A with a high value of η_i. The flow of the evacuee from I-F, F-C, C-B were forced to turn back to Shelter 2 together with evacuees moving from A-B due to the limited capacity at node A as shown in Figure 4a. In contrast, Figure 4b shows the evacuees from I-F, F-C staying at Shelter 2 at node C due to a higher influence from the advised and field effect parameters. The movement of the evacuees from the cases seems to have similarity with the people's behavior during the Great East Japan Earthquake where people escaped as a group even though they were asked to escape individually and some people found that they were in the same shelters as their neighbors (*9*).

The next investigation was to evaluate the time when the two shelters were occupied fully for each case as shown in Figure 5a. Without heeding the government's advice and ignoring the evacuation environment surrounding the agent, the base case showed an early occupancy for Shelter 1 but the overall time taken by evacuees to fill up Shelter 2 was delayed by about 15 time steps compared to the Advised and Field case. Although we could observe from Figure 5b that evacuees started to move out earlier in the base case, the number of people reaching the safe shelter was slower than people in the Field case while people who followed advice reached safety the earliest. In the comparison of time required by the last evacuee to reach a shelter as shown in Figure 6, people who tended to follow others in the Field case required the shortest time for the overall safety of the whole population. Such behavior was similar to the findings by Richter et al. (*25*) where they demonstrated that the sharing of information through local ad hoc peer-to-peer communication may be vital to successful evacuation in the future. With the average evacuation time for the base case being the highest as shown in Figure 6, the evacuees should also be reminded that following government's advice or following others may eventually save their lives especially when long journey time may expose evacuees to potential hazards (*4*).

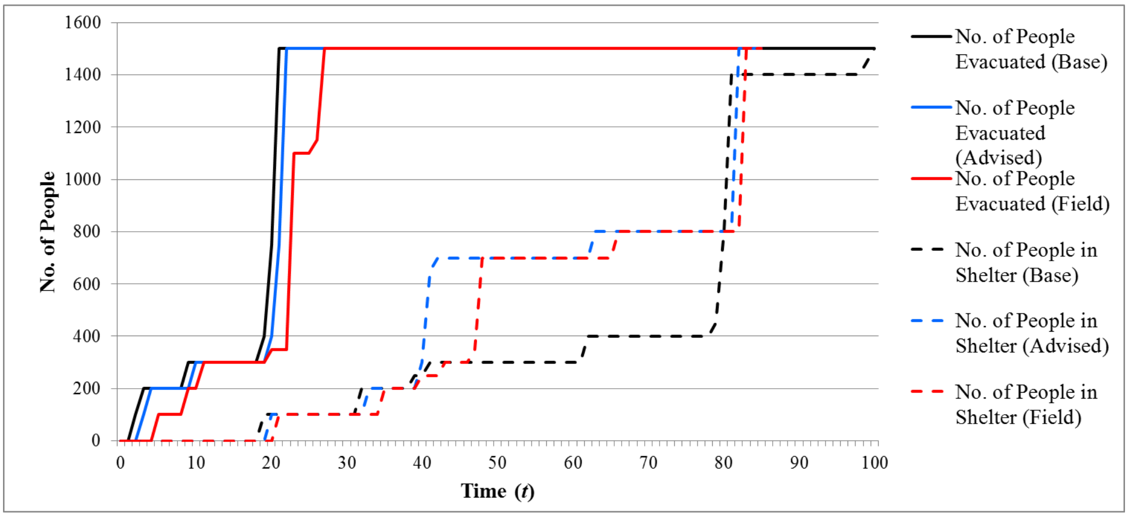


(a) Base case (b) Advised and Field

Figure 4 Evacuation flow at the end of simulation



(a) Shelter occupancy rate at each time step (t)



(b) Number of people evacuating and time of arrival at shelter at each time step (*t*)

Figure 5 Performance measures on shelter occupancy, arrival time and evacuation time

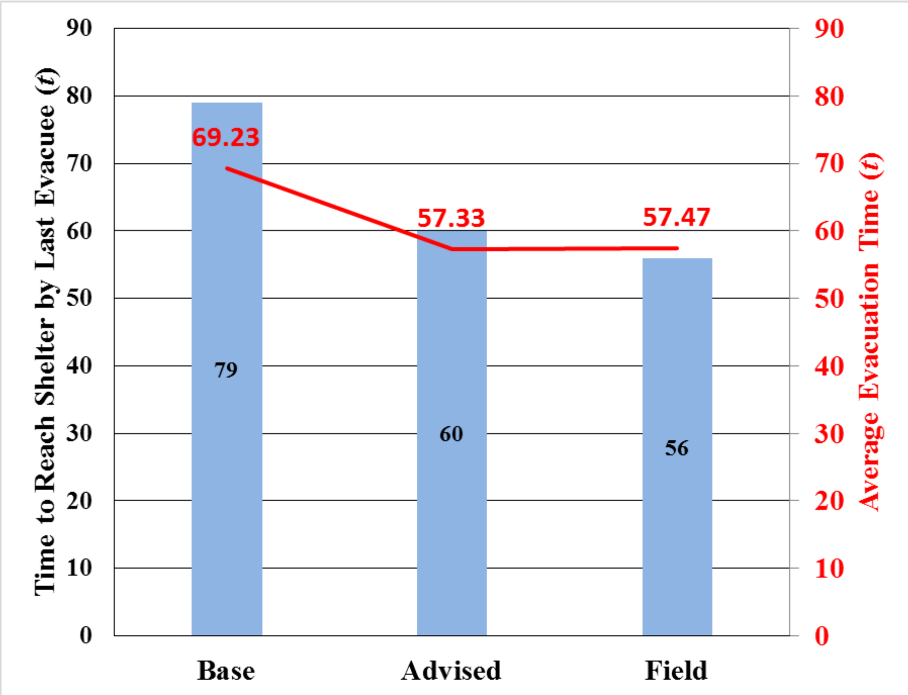


Figure 6 Time steps (*t*) taken for last evacuee to reach shelter and average evacuation time

7. CONCLUSION

In this study, we developed an evacuation model based on by now rich literatures on the topic while considering the additional effect of rising importance on social capital related factors. Especially the tragic events in Japan in 2011 have shown that when there are broken communication links between higher decision makers and the evacuees, some people might follow pre-disaster advice procedures while others might rely more strongly on information obtained via local networks. Both can have positive and negative effects.

The main contribution of this paper has been the framework formulation and development of our mesoscopic multiagent simulation framework that is capable of reflecting these factors. The main purpose of our small case study has been to illustrate some features of the software. Our indicative results emphasized though a point made also in the literature that either following the government's advice or following the evacuation behavior of others will be vital to the success of evacuation or the safety of the evacuees.

In current work we expand the case study to be applied to Tsunami evacuation in Osaka, Japan. Further, the framework presented is flexible to include additional agents to be modeled such as humanitarian logistics related transport. One might also consider adding additional choices to the agent movement in our model, by for example considering the effects of intermediate travels like "return traffic" where evacuees may backtrack to pick-up family or goods, which was not an insignificant amount of traffic during the 2011 Tohoku earthquake in Japan. In future work we hope the model might be useful to assess pre-disaster infrastructure improvement strategies based on the evacuation demand needs from this initial model.

ACKNOWLEDGEMENT

This research is initiated by the CONCERT-Japan pilot joint call on research and innovation for the thematic field of "Resilience against Disasters". The authors wish to acknowledge the support of Japan Science and Technology Agency and Partnership Module of UEFISCDI contract no. 3003/2013 for funding this research initiative.

REFERENCES

1. Ozbay, K., M. A. Yazici, S. Iyer, J. Li., E. E. Ozguven, and J. A. Carnegie. Use of Regional Transportation Planning Tool for Modeling Emergency Evacuation. *Transportation Research Record: Journal of the Transportation Research Board, No. 2312,* Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 89–97.
2. Sbayti, H. and H. S. Mahmassani. Optimal Scheduling of Evacuation Operations. *Transportation Research Record: Journal of the Transportation Research Board, No. 1964,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 238–246.
3. Yuan, F., L. D. Han, S-M. Chin and H. Hwang. Proposed Framework for Simultaneous Optimization of Evacuation Traffic Destination and Route Assignment. *Transportation Research Record: Journal of the Transportation Research Board,No. 1964,* Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 50–58.
4. Robinson, R. M. and A. Khattak. Evacuee Route Choice Decisions in a Dynamic Hurricane Evacuation Context. *Transportation Research Record: Journal of the Transportation Research Board, No. 2312,* Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 141–149.
5. Church, R. L. and T. J., Cova. Mapping evacuation risk on transportation networks using a spatial optimization model. *Transportation Research Part C*, Vol. 8, 2000, pp. 321-336.
6. Murray-Tuite, P. and B., Wolshon. Evacuation Transportation Modeling: An Overview of Research, development, and practice. *Transportation Research Part C*, Vol. 27, 2013, pp. 25-45.
7. Lindell, M.K. and R.W., Perry. Understanding evacuation behavior: an editorial introduction. *International Journal of Mass Emergency and Disasters*, Vol. 9, No. 2, 1991, pp. 133-136.
8. Wu, H.-C., M. K. Lindell, C. S. Prater. Logistics of Hurricane Evacuation in Hurricanes Katrina and Rita. *Transportation Research Part F*, Vol. 15, No. 5, 2012, pp. 445–461.
9. Ranghieri, F., and Ishiwatari, M. Learning from megadisasters: Lesson from the great east Japan earthquake. *The World Bank*, Washington, DC., 2014.
10. Hobeika, A. G., and C. Kim. Comparison of Traffic Assignments in Evacuation Modeling. IEEE Transactions on Engineering Management, Vol. 45, No. 2, May 1998, pp. 192-198.
11. Sattayhatewa, P., and B. Ran. Developing a Dynamic Traffic Management Model for Nuclear Power Plant Evacuation. Presented at 79th Annual Meeting of the Transportation Research Board, Washington, D.C., 2000.
12. Murray-Tuite, P., Yin, W., Ukkusuri, S., Gladwin, H. Changes in Evacuation Decisions Between Hurricanes Ivan and Katrina. *Transportation Research Record: Journal of the Transportation Research Board, No. 2312,* Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 98-107.
13. Lin, N. A Network Theory of Social Capital. In: D. Castiglione, J. W. Van Deth, and G. Wolleb, (Eds.), *The Handbook of Social Capital* (pp.55-69), 2008, New York: Oxford University Press.
14. Aldrich, D. P. (2012). *Building Resilience: Social Capital in Post-disaster Recovery* (p. 232). Chicago and London: The University of Chicago Press.
15. Aldrich, D. P. (2011). The Power of People: Social Capital's Role in Recovery from the 1995 Kobe Earthquake. *Natural Hazards*, 56(3), pp. 595-611.

16. Inagaki, Y. (2013). The Power of Kizuna: Did Social Capital Promote Recovery from the Great East Japan Earthquake? Center for the Study of Social Stratification and Inequality (CSSI) Working Paper Series No. 4, Tohoku University.
17. Pel, A. J., S. P., Hoogendoorn, M. C. J., Bliemer. Evacuation Modeling Including Traveler Information and Compliance Behavior. *Procedia Engineering*, Vol. 3, 2010, pp. 101-111.
18. Fu, H., A. J., Pel, S. P., Hoogendoorn. Optimal Traffic Management to Ensure Emergency Evacuation Compliance. *Proceeding of 13th IEEE International Conference on Networking, Sensing and Control (ICNSC)*, Paris, France, 2013, pp. 532-537.
19. Lindell, M. K. and R. W., Perry. Warning Mechanisms in Emergency Response Systems. *International Journal of Mass Emergencies and Disasters*, Vol. 5, No. 2, 1987, pp. 137–153.
20. Baker, E. J. Predicting Response to Hurricane Warnings: A Reanalysis of Data from Four Studies. *Mass Emergencies*, Vol. 4, No. 1, 1979, pp. 9-24.
21. Anderson, L. R., J. R., Keaton, T. F. Saarinen, W. G., Wells II. *The Utah Landslides, Debris Flows and Floods of May and June 1983*. National Academy Press, Washington, DC., 1984.
22. Baker, E. J. Hurricane Evacuation Behavior. *International Journal of Mass Emergencies and Disasters*. Vol. 9, No. 2, 1991, pp. 287-310.
23. Gladwin, H., and W. G., Peacock. Warning and Evacuation: A Night for Hard Houses. In: Peacock, W.G., Morrow, B.H., Gladwin, H. (Eds.), *Hurricane Andrew: Ethnicity, Gender, and the Sociology of Disasters*. International Hurricane Center, Miami, 1997, pp. 52-72.
24. Perry, R.W. *Citizen Evacuation in Response to Nuclear and Non-Nuclear Threats*. 1981.
25. Richter, K-F., M. Shi, H-S. Gan, and S. Winter. Decentralized Evacuation Management. *Transportation Research Part C*, 31, 2013, pp. 1-17.
26. Nagao, B., Shimamoto, H., Nakamura, T, Uno, N., Schmöcker, J.-D., and Yamazaki, H. Evaluation of Tsunami Evacuation Plans Considering Car Usage and the Starting Time of Evacuation. *JSCE Proceeding of Infrastructure Planning*, Vol. 49, 2014. (In Japanese)
27. Leonard, D. R., Gower, P., Taylor, N. B. (1989) *CONTRAM: structure of the model*, Research report, Transport and Road Research Laboratory, p. 178.