Optimizing Sign Placements for Crowd Evacuation on Road Network in Case of Tsunami Alert

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***Abstract*- In recent years, the number of people affected by natural disasters and in particular tsunamis has been increasing. Artificial Intelligence and Operation Research approaches to simulate crowd evacuation and prepare cities for Tsunamis are of critical interest. Given an extremely simple model of human behavior, i.e. a memory-less stochastic agent, we address the problem of optimizing the placement of Tsunami evacuation signs with respect to evacuation time and casualties. Moreover, we formalise this optimisation problem as a Mixed Integer Linear Programming (MILP) problem and we ran some experiments with a MILP solver to give an early warning for the evacuation of the road network of Nhatrang city in Vietnam.**

***Keywords*- Agent Based Model;Optimization Sign Placement;Mixed Integer Linear Programming;Simulation**

INTRODUCTION

Tsunamis have appeared frequently in recent years and have led to huge losses. On December 25, 2004 a tsunami in the Indian Ocean caused an earthquake of magnitude 9 on the Richter scale leading to approximately 230 000 deaths and on March 11, another tsunami in Tohoku, Japan caused an earthquake of magnitude 9 on the Richter scale leading to approximately 20 000 deaths [12]. Tsunamis lead to particularly severe damages when they occur near crowded residential areas or urban centres located on coastal zones. Since urban areas include complicated road networks, crowd evacuation on these networks requires identifying paths to safe locations [10, 7]. Although each urban area has its own peculiarities due to its topology, its infrastructure, its road network and even its cultural habit, the problem remains to escape to shelters as fast as possible. If a Tsunami alert is raised in the Philippines in the direction of Vietnam for example, the population of a coastal city like Nhatrang only has two hours to evacuate. In developing countries, the means to support evacuation include simple road signs since everyone cannot afford a smartphone with 3G capabilities that would support the reception of personalized evacuation routes as available in Japan for example. Furthermore, even in Japan, there are Tsunami route signs that support the evacuation and increase the awareness of Tsunamis. The problem of placing signs in cities to minimize casualties and evacuation time is thus critical. In this paper, we specifically address the problem of minimizing the average evacuation time by placing signs. This problem raises two research issues.

The first issue is to accurately model a crowd and simulate it on a road network. As real road networks of many cities are now available in Geographic Information Systems (GIS), it becomes possible to simulate crowds over these networks of routes, and to assess the quality of a given sign placement in accordance. A number of crowd modeling approaches have been already applied separately or in combination to solve evacuation problems. Such approaches include cellular automata, lattice gas, social force, fluid dynamics, agent based approaches, game theory and experiments with animals [18, 8, 9, 10]. In these models, apart from Agent Based Models (ABM), the agents are always homogeneous and have similar behaviors. On the contrary, ABM considers each agent with its individual behavior and perception. Although ABM [4, 6, 16] are very flexible, they often require a lot more computation than their counterparts that may accommodate very large populations.

The second issue is how to place signs and analyze the impact of such placements on the crowd behavior. This is mainly an optimization problem, which cannot usually be solved exactly. Earlier approaches involved in solving this optimization problem using heuristics, using the crowd simulator as a black-box to assess the performance of the candidate sign placements [18, 11]. This approach has two drawbacks: first, the simulator usually requires a lot of computation power, and the optimization process cannot thus explore the space of candidate solutions in depth. Also, even if we could explore sufficiently many solutions, nothing would guarantee us that we did not fall in a local minimum.

In this paper, we tackle these two issues at once. By choosing a very simple model of crowds where the human behavior is modeled as memory-less stochastic agent, we can avoid the explicit use of a simulator. Instead, we formulate the optimization problem as a Mixed Integer Linear Program (MILP), in such a way that the dynamics of the agents are embedded inside this linear program. Then, the optimization problem can be solved using any state-of-the-art MILP solver. With this approach, we can either find optimal solution or get approximate solutions with some guarantees on the quality of the approximation, when applied to problems of larger scale. This of course is not possible with complex crowd models.

The main motivation of this work is to bring an answer to the concrete problem of making Vietnamese coastal cities safer with respect to Tsunamis. Many American cities or Japanese cities are already considered Tsunami ready but much work remains to do for cities such as Nhatrang (a

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touristic city, located in the middle of Vietnam) known to be vulnerable to tsunamis as it is on the path of possible tsunamis resulting from earthquakes generated within the Philippine islands.

The paper is organized in four sections. Section II presents our formulation of this problem as an optimization problem. In Section III we show how the problem can be formalized as a MILP. In Section IV, our approach is applied to compute sign placements on the road network of Nhatrang city to improve its evacuation. Finally, Section V concludes and gives some discussion and perspectives for future works.

THE EVACUATION TIME OPTIMIZATION PROBLEM

A. Modelling Agents Behaviors as Semi Markov Chains

Let a graph $G=(V,E)$ represent the city in which $V=\{1,2,...,n\}$ is a set of junctions and $E=\{(i,j),i,j\in V\}$ is a set of edges representing roads connecting vertices. Each edge is associated with a weight c_{ij} representing the time required by an agent to move from vertex i to vertex j. Also, the set of neighbors of the vertex i is referred to as $N(i)=\{i:(i,j)\in E\}$. Among all vertices, some of them are referred to as shelters. Let $X\subseteq V$ denote the set of shelters that assumed place in the vertices of the graph $G=(V,E)$. If an agent reaches a shelter, then it is considered a out of danger.

One of the simplest ways to represent a non-deterministic behavior of agents on a graph G is to use a semi-Markov chain. Informally, semi-Markov chains generalize Markov chains by allowing the transitions to take various amounts of time. In our case, we assume that moving an agent from vertex i to vertex j will require exactly c_{ij} units of time.

Consider agents behaving according to a semi-Markov chain. At time $t=0$, we assume that these agents are distributed randomly on the graph with respect to a given distribution $\mu=\{\mu_i, i\in V\}$. At time $t>0$ an agent positioned on vertex i will move towards vertex $j\in N(i)$ with probability P_{ij}, where $\mathbf{P}$ is a stochastic matrix such that if $(i,j)\in E$, then $P_{ij}=0$ and such that $\sum_{j\in V} P_{ij}=1$. Finally, if vertex i is a shelter, then $P_{ij}=1$. The resulting semi-Markov chain describes the behavior of the all agents: For any agent, its probability distribution over V after t movements is given by $P^t\mu$. Note that it is an absorbing chain, as shelters are absorbing states.

Formally, a quadruplet $(\mathrm{G,X},\mu,\mathbf{P})$ will completely define the territory and the behavior of agents when no signs are placed on the network. Let us introduce some definitions relative to the placement of signs.

Definition 1 A sign placement is a subset $S\subseteq E$ such that if $(i,j)\in S$ then for all $j'\neq j,(i,j')\in S$. Informally, $(i,j)\in S$ means that we place a sign on the vertex i pointing towards the vertex j. Also, $V(S)=\{i:\exists j,(i,j)\in S\}$ refers to the set of vertices on which signs are placed.

After some signs have been placed, the behavior of the agents will change. Intuitively, when an agent is on a signed vertex, it will always follow the sign. Formally, a set of signs induces a new stochastic matrix.

Definition 2 For a given sign placement S and a stochastic matrix $\mathbf{P}$, we define the induced stochastic matrix P^S over the set of vertices as follows: for all $(i,j)\in S$ and for all $j'\neq j$, we have $P^S{}_{ij}=1$ and $P^S_{ij'}=1$. Also, for all $i\in V\setminus V(S)$ and all $j\in V$, we have $P^S{}_{ij}=P_{ij}$.

Given a sign placement S, the probability distribution of agents over V after t movements is given by $\left(P^S\right)^t\mu$.

B. Formalizing Sign Placement as an Optimization Problem

Definition 3 Given a graph G, a stochastic matrix P, a sign placement S, a set of shelters $X\subseteq V$ and an initial state $i_0\in V$, the average evacuation time $AET(S,i_0)$ is defined as the average time needed by an agent before it reaches a shelter, given that:

•At time $t=0$, the agent is located on vertex i_0.

•The behavior of the agent is dictated by the stochastic matrix P^S.

•The time required by an agent to cross any edge $(i,j)\in E$ is c_{ij}.

In case agents are distributed randomly across the graph, we have the following definition:

Definition 4 Given a quadruplet $(\mathrm{G,X},\mu,\mathbf{P})$ and a sign placement S, we define the Population Average Evacuation Time as $\boldsymbol{PAET(S)=E_{i\sim\mu}(AET(S,i))=\sum_{i\in V}\mu_i.AET(S,i)}$.

We note that $PAET(\varnothing)$ is the average rescue time without any sign. An ideal formulation of our problem is:

Definition 5 Evacuation Time Optimization Problem (ETOP). Given a quadruplet $(\mathrm{G,X},\mu,\mathbf{P})$ and an integer k, the ETOP problem consists in finding the best sign placement S containing at most k signs minimizing PAET(S).

Unfortunately, unless P=NP there are no polynomial time algorithm able to solve this problem. More precisely:

Theorem 1 The decision version of the ETOP problem is NP-complete.

The proof, which is rather involved, will appear in a longer version of this paper. It is based on a reduction from the minimum vertex cover problem.

In the next section, we will see that the ETOP problem can be formalized as a Mixed Integer Linear Programming problem (MILP).

A MIXED INTEGER PROGRAMMING FORMULATION

Because the ETOP problem is NP-complete, we either need carefully crafted heuristics to solve it in a reasonable amount of time, or we can formulate this problem as a Mixed Integer Linear Programming (MILP) Problem which will allow us to use powerful MILP solvers such as CPLEX (being an optimization software package and named for the simplex method implemented by language C) to solve exactly or approximately our problem in a reasonable amount of time.

To formulate this problem as a mathematical programming problem, we need to define a few variables, as well as a set of constraints. Variables a_{ij} will be binary variables, and all other variables will be real-valued.

- For each edge (i, j), the variable $a_{ij} \in \{0,1\}$ indicates whether we should place a sign on edge (i, j) (in which case $a_{ij} = 1$) or not (in which case $a_{ij} = 0$). Variables a_{ij} naturally induce the sign placement $S = \{(i, j) \in E : a_{ij} = 1\}$. To ensure that there is at most one sign per vertex, we set the constraints $\sum_{j \in N(i)} a_{ij} \le 1$ for all $i \in V$. To ensure that there are at most k signs in the whole network, we add the single constraint $\sum_{(i,j)\in E} a_{ij} \le k$.
- For each edge (i, j), let us define q_{ij} as the Average Evacuation Time of an agent starting at vertex i, moving towards vertex j, and then behaving according to the transition matrix $\mathbf{P}^S$. Formally, we have $q_{ij} = c_{ij} + AET(S, j)$.
- For each vertex i, let us define $q_i = AET(S, i)$. Naturally, if i is a shelter then $q_i = 0$.
- For each vertex i, let us define $q'_i = 0$ as the Average Evacuation Time for an agent starting at vertex i, ignoring any sign on vertex i if such a sign exists, and then behaving normally according to the transition matrix $\mathbf{P}^S$ for all other time steps. Formally, $q'_i = E_{j\sim P_i}\{c_{ij} + AET(S, j)\} = \sum_{j\in N(i)} P_{ij}\{c_{ij} + AET(S, j)\}$.

Note that these real valued variables share some similarities with the usual Q-values used to solve in Markov decision processes.

Finally, we can see that q_i, q'_i and q_{ij} are linked together in the following way: If there is no sign placed on vertex i, then $q_i = q'_i$. On the contrary, if a sign is placed on edge (i, j), we get $q_i = q'_i$. So we get the following mathematical program:

$$
\begin{aligned}
&\min \sum \mu_i q_i \text{ such that} \\
&\forall i \in X,\ \ q_i = 0, \\
&\forall i \in V,\ \ q'_i = \sum_{j\in N(i)} P_{ij}\{c_{ij} + AET(S, j)\}, \\
&\qquad q_i = q'_i \text{ if } \sum_{j\in N(i)} a_{ij} = 1, \\
&\forall (i, j) \in E,\ q_i = q_{ij} \text{ if } a_{ij} = 1, \\
&\qquad q_{ij} = c_{ij} + q_j, \\
&\forall i \in V,\ \sum_{j\in N(i)} a_{ij} \le 1, \\
&\qquad \sum_{(i,j)\in E} a_{ij} \le k.
\end{aligned}
$$

where $X \in V$ is the set of the shelters.

Domain constraints must be added to this set of constraints: for all $(i, j) \in E$, $a_{ij} \in \{0,1\}$ and $q_{ij} \in \mathbf{R}_+$. Also, for all $i \in V$, $q_i \in \mathbf{R}_+$ and $q'_i \in \mathbf{R}_+$. If there exists a sign placement with at most k signs leading to finite average evacuation times (note that this is not always the case) then solving this program will yield the best one.

This set of constraints does not constitute a MILP, because there are conditional constraints (e.g. $q_i = q_{ij}$ if $a_{ij} = 1$). Our goal will thus be to convert these constraints into linear inequalities. For this purpose, let us define a constant $Q_{\max}$ with an arbitrary value at least as high as the highest average evacuation time. Then, we can replace $q_i = q_{ij}$ if $a_{ij} = 1$ by $q_i \ge q_{ij} - Q_{\max}.a_{ij}$. Note that if $a_{ij} = 0$, because the objective is to minimize the q_i, this inequality will imply that $q_i = q_{ij}$. On the contrary, if $a_{ij} = 1$ then this inequality will not constrain q_i in any way. Thus, this inequality is strictly equivalent to the original formulation. The same holds for the other conditional constraint. Thus, the above mathematical program can be written as follows:

$$
\begin{aligned}
&\min \sum \mu_i q_i \text{ such that} \\
&\forall i \in X,\ \ q_i = 0, \\
&\forall i \in V,\ \ q'_i = \sum_{j\in N(i)} P_{ij}\{c_{ij} + AET(S, j)\}, \\
&\qquad q_i \ge q'_i - \mathrm{Q}_{\max} \cdot \left(\sum_{j\in N(i)} a_{ij}\right), \\
&\forall (i, j) \in E, q_i \ge q_{ij} - Q_{\max} a_{ij}, \\
&\qquad q_{ij} = c_{ij} + q_j, \\
&\forall i \in V,\ \sum_{j\in N(i)} a_{ij} \le 1, \\
&\qquad \sum_{(i,j)\in E} a_{ij} \le k.
\end{aligned}
$$

Adding the same domain constraint as before, we get a MILP, whose solution gives us an optimal sign placement.

RESULTS AND EXPERIMENTS

A. *Experiments*

When tsunamis occur, pedestrians must be very quickly informed of the incoming danger to begin the evacuation. For coastal areas of central Vietnam, whether the source of the tsunami is located offshore or near shore, evacuation time is very short. So to get ready for a tsunami warning, each coastal city needs to plan to evacuate the area safely. One important component of the tsunami response is the design of evacuation maps and other specific scenarios in coastal areas situated near the tsunami threat.

We chose to focus on urban areas of the coastal Nhatrang city, which is composed of 11 wards, a population of 163,885 and a total surface of (Fig. 1) [12]. This area is highly touristic, often crowded, and a tsunami may yield the greatest damages. In Nhatrang city, shelters are buildings that satisfy some design requirements. More generally, shelters must meet some specific criteria with respect to their heights, their structural foundations and the purpose of buildings (schools, government buildings or military buildings). The city is divided into several parts and each part has a shelter. In the next subsection, ETOP is applied to two scenarios. In the first scenario, only a small part of the city is considered, while in Scenario 2 the whole city is investigated. Alert sign placement in the road network isplaced according to the solution to the ETOP problem.

Figure 1 The pedestrians distribution in the Nhatrang city, this data give the initial population distribution $\boldsymbol{\mu}=\{\mu_i, i \in V\}$

Figure 2 The road network in Nhatrang city

As shown in [11], the population distribution in this city highly depends on the time of the day and on the season. The distribution of the population in different wards of Nhatrang city can be found in the Vietnamese statistic yearbook [12]. This data described the people distribution in the night or not during tourist seasons. In [1, 2], a model of the distribution of Nhatrang population was proposed. In this work, we will use this model to compute our initial distribution μ (Fig. 1).

B. *Application*

According to the literature, an earthquake of magnitude 8.4 on the Richter scale occurring in deep sea through Manila and can yield a 1.9 m high tsunami in Nhatrang and up to 4 m if an earthquake with magnitude 8.8 on Richter scale appears in the same area[11]. The tsunami propagation time from the source region to the sea near Nhatrang is approximately 2 hours [11, 12]. Based on these studies, two levels of emergency following were selected as the basis for building evacuation plans:

- Scenario 1 (evacuating the part of Nhatrang city which is less exposed to the tsunami): Allows pedestrians evacuate in time: t≤30 minutes (Fig. 3).
- Scenario 2 (evacuating the whole Nhatrang city): Allows pedestrians evacuate in time: 30 minutes≤t≤2h (Fig. 4)

Figure 3 Scenario 1: Allows pedestrians evacuate in time: t≤30 min. The costal divided by three zones according to dangerous level and the criteria of the shelters that are high buildings

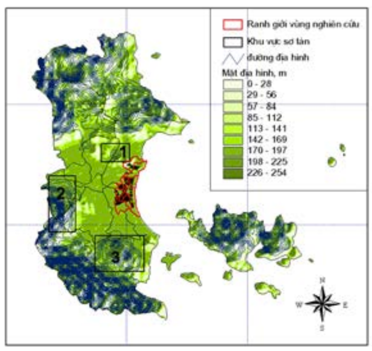

Figure 4 Scenario 2: Allows pedestrians evacuate in time: 30 min≤t≤2h. Pedestrian evacuated on the high land mountain position in 1,2 or 3 in the figure

Based on these two evacuation scenarios, the tsunami evacuation was classified into two types. For Scenario 1, the evacuation time for implementation in only 30 minutes, so the shelter was selected as the high buildings have sustainable structures adjacent to the coast in the study area (Fig. 3). For Scenario 2, the evacuation time is longer, up to a two hours, so the evacuation of selected areas may be located further inland on the condition that the terrain must be high enough to avoid the impact of the tsunami such as position 1,2 or 3 in (Fig. 4).

Experiments on a Small Area:

For these first experiments, we chose a small part of Nhatrang city, which can be represented as the directed graph as (Fig. 5) follows:

Figure 5 Part of the road network in Nhatrang city

We use platform GAMA [17] being platform of agent based model simulation to transfer GIS data to the direct graph (Figs. 5, 6) and applying the results of ETOP to the GIS to simulation evacuation (Fig. 7), described detail in [1,2].

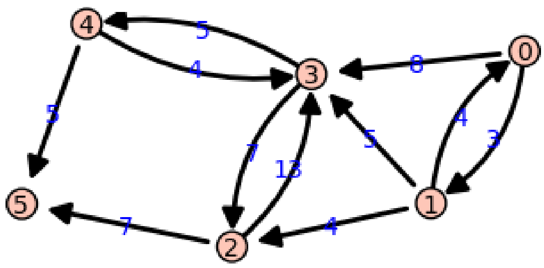

Figure 6 The GIS data is converted in a directed graph

Figure 7 The sign placements are set up based on the ETOP results

In our methodology, we made the assumption that the behavior of all agents can be represented by a stochastic matrix P. In these experiments, we further assumed that an agent located on vertex i has an equal probability to reach any vertex j∈N(i). Of course, this is a very preliminary assumption which will need to be refined later on.

We ran the CPLEX which is a well known MILP solver on the two scenarios.

The result of the number of signs in the small area effect on the evacuation is described in (Fig. 8). We see that there are only 5 vertices if the sign at all the vertices than the evacuation time is around 350 minutes. However, if we do not have any alert sign, the evacuation time is approximately 900 minutes in (Fig. 8).

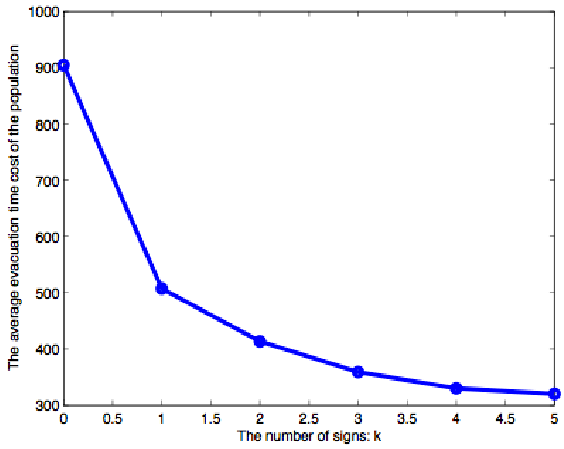

Figure 8 The average evacuation time of pedestrians w.r.t. the number of signs

Experiments on the Whole Nhatrang City:

This experiment is based on the second scenario, where the whole city has to be evacuated. The main roads of Nhatrang city whose widths are larger or equal to 15 meters are shown in (Fig. 9). The shelters are the vertice13,14 that is high land showed in (Fig. 4). As for Scenario 1, we ran the solver on this problem with various values of k. We were able to plot the optimal average evacuation time as a function of the number of signs k (Fig. 10). A surprising result here is that adding more than 7 signs does not bring much improvement to the evacuation process. In addition, we draw the optimal sign placement with the k=10 in Fig. 9.

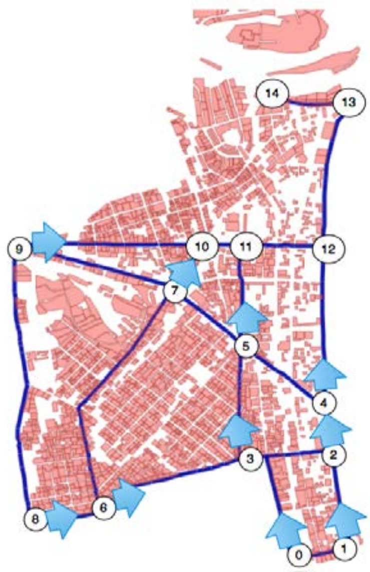

Figure 9 The main road of Nhatrang city that have their width are larger than 15 meters. The blue arrows are signs that is the result of the ETOP with the number of signs k=10

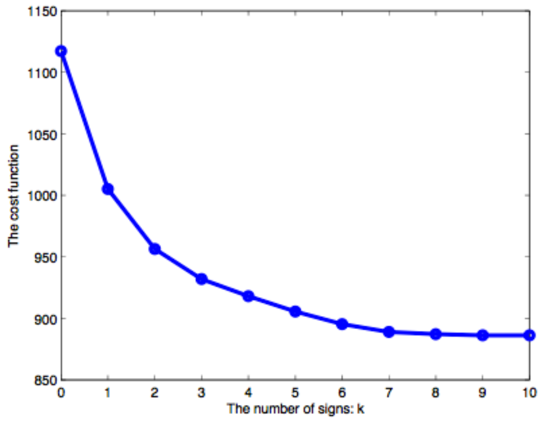

Figure 10 The cost function of average evacuation time (the unite of cost function is the number pedestrians times minutes) of pedestrians respective with the number of signs of the main roads of Nhatrang

CONCLUSION AND DISCUSSION

Optimizing the sign placement to evacuate coastal cities in case of Tsunami alert is the main purpose of this work. In this paper, we proposed to model human behavior as semi-Markov chains. Based on this model, we proposed an original formulation of the sign placement problem, which we called the Evacuation Time Optimization Problem. Then, we showed that this problem could be represented as a Mixed Integer Linear Programming problem (MILP). Using powerful open-source MILP solvers, we could compute optimal sign placements for Nhatrang city.

In future work, we will need to try CPLEX, which is a much more powerful (but commercial) MILP solver, with which we may solve much larger problems.

This work has been conducted as cooperation between the Institute of Geophysics and Vietnam Academy of Science and Technology. However, the validation of this model is the limitation of this work. Eventually, comparing the alert signs using ETOP and other approaches is among possible future work that we want to investigate.

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