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The MATSim network flow model for traffic simulation adapted to large-scale emergency egress and an application to the evacuation of the Indonesian city of Padang in case of a Tsunami warning

Gregor Lämmel (1), Hubert Klüpfel (2), Kai Nagel (1)

1. Transport Systems Planning and Transport Telematics – TU Berlin
Salzufer 17-19 – 10587 Berlin – Germany
Contact address, e-mail: *laemmel@vsp.tu-berlin.de*
2. TraffGo HT GmbH Bismarckstraße 142a – 47057 Duisburg – Germany

Gregor Lämmel1, Hubert Klüpfel2, Kai Nagel1

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Abstract

The evacuation of whole cities or even regions is an important problem, as demonstrated by recent events such as the evacuation of Houston in the case of hurricane Rita or the evacuation of coastal cities in the case of tsunamis. This paper describes a complex evacuation simulation framework for the city of Padang, with approximately 1,000,000 inhabitants. Padang faces a high risk of being inundated by a tsunami wave. The evacuation simulation is based on the MATSim framework for large-scale transport simulations. Different optimization parameters like evacuation distance, evacuation time or the variation of the advance warning time are investigated. The results are given as overall evacuation times, evacuation curves and detailed GIS analysis of the evacuation directions. All these results are discussed with regard to their usability for evacuation recommendations.

1 Introduction

The evacuation of whole cities or even regions is an important problem, as demonstrated by recent events such as the evacuation of Houston in the case of hurricane Rita or the evacuation of coastal cities in the case of tsunamis. As a consequence of these events, disaster and evacuation planning has become an important topic in science and politics.

Congruent with the importance of the topic, there is a large body of research regarding emergency evacuations. As a first classification, one may differentiate between two situations: (i) evacuation from within buildings, ships, airplanes, etc.; (ii) large-scale citywide or regional evacuations, e.g. because of nuclear power plants failures or because of hurricanes. Case (i) usually concerns pedestrian evacuation; case (ii) usually uses traffic-based evacuation.

A good overview of pedestrian evacuation modeling and software can be found in the books of the bi-annual conference series "Pedestrian and Evacuation Dynamics" (Schreckenberg and Sharma, 2002; Galea, 2003; Gattermann et al., 2006). Pedestrian evacuation simulations can be classified into microscopic and macroscopic ones. Microscopic models represent space, time, and persons on a fine-grained level. Possible microscopic approaches are Cellular Automata (CA) (Klüpfel et al., 2003), discretized differential equations ("molecular dynamics (MD)") (Helbing et al., 2002, Helbing et al., 2005), or movement rules based on random utility modelling (Bierlaire et al., 2003). Examples of software packages based on microscopic models are Exodus (Galea, 2002), Myriad (www.crowddynamics.com), Egress (www.aeat-safety-and-risk.com/html/egress.html), and PedGo (Klüpfel, 2006). Macroscopic models use the analogy of flows of pedestrians and liquids. Examples of software packages based on macroscopic models are Aseri (Schneider and Könnecke, 2002) and Simulex (www.iesve.com). See Refs. (Jafari et al., 2003) and (Kuligowski, 2004) for surveys. Compared to what is known in terms of field measurements (e.g. (Predtetschenski and Milinski, 1978; Weidmann, 1993)), most if not all packages lead to similar results (Rogsch, 2005).

Once the pedestrian movement model is selected, it is necessary to define the evacuation directions. For more complex geometries, this is no longer a single movement towards one or two exits, but may involve rather complex movements in a building or in a street network. The arguably simplest solution is a grid-based potential function where the "uphill direction" leads to the nearest exit (Nishinari et al., 2004). The

same can be done using essentially continuous spatial variables, at the expense of much larger computing times (Hoogendoorn et al., 2002). Alternatively, routing can be done along graphs (Hamacher, 2001; Gloor et al., 2004*a*), which is a much faster technique when the abstraction to a graph is possible.

Another line of research concerns citywide or regional evacuations, i.e. case (ii). The development of these tools was much influenced by the development of tools in the areas of transport planning and traffic management. At the core of many of these methods is a static assignment routine (e.g. (Sheffi, 1985; Ortúzar and Willumsen, 1995)). A typical example for traffic-based evacuation simulation based on static concepts is MASSVAC (Hobeika and Kim, 1998) although later versions contain dynamic aspects.

A severe shortcoming of static assignment is that it does not possess any consideration of the time-of-day dynamics. Dynamic traffic assignment (DTA) is defined as a distribution of time-dependent trips on routes. A typical approach to implement DTA is day-to-day re-planning: The traffic flow simulation (also called network loading) is run with pre-specified routes, route costs are extracted, some or all of the routes are modified, the traffic flow simulation is run again, etc., until some stopping criterion is fulfilled. Examples of stopping criteria are that either every trip uses a route which minimizes expected travel time (time-dependent Nash equilibrium), or it selects between different route alternatives following a pre-specified distribution function (time-dependent SUE).

Many DTA packages have been tested in the evacuation context: MITSIM (Jha et al., 2004), Dynasmart (Kwon and Pitt, 2005, Chiu et al., 2005), PARAMICS (Chen and Zhan, 2004), and VISSIM (Han and Yuan, 2005). Oak Ridge National Laboratory has a package named "OREMS" (cta.ornl.gov/cata/One_Pagers/OREMS.pdf) explicitly for evacuation traffic. Publications stressing dynamic aspects of traffic-based evacuation as a novelty can be found as recent as 2000, e.g. (Sattayhatewa and Ran, 2000; Barrett et al., 2000). For a review, see (Alsnih and Stopher, 2004).

A further distinction is if travelers can re-route while they are on their way (within-day re-planning; en-route re-planning), or only before their trip (day-to-day re-planning; pre-trip re-planning) (Cascetta and Cantarella, 1991). Clearly, en-route re-planning capability is more realistic. It is, however, also more demanding: Adaptation of the plans needs to be called frequently from within the network loading, rather

than only having to alternate between the network loading and the mental layers as one does in day-to-day re-planning.

A large body of work (e.g. (Theodoulou and Wolshon, 2004, Lim and Wolshon, 2005)) uses microsimulation to investigate the issues of contraflow evacuation, i.e. the reversal of inbound lanes of a freeway in order to obtain additional outbound capacity.

To our knowledge, none of the above approaches is able to simulate large-scale scenarios (with millions of entities) while remaining microscopic:

- With a CA model, an area of $40\,km \times 40\,km$ translates into   cells. Even if every cell only needs 1 Byte, this still translates into 10 GByte of memory, resulting in large simulation times.

- For the MD approach, the problems are the sub-second time resolutions that are typically used (Farkas, accessed 2008).

- DTA approaches seem the most likely candidates, but to our knowledge their implementation of the traffic flow dynamics usually is still too time-consuming for scenarios of that size: Ref. (Sbayti et al., 2007) reports a study using Dynasmart-P consisting of 1347 nodes and 3004 links. 200,000 vehicles were loaded onto the network. The runtime for about 30 iterations of 2 hours of simulation was almost 8 hours. This means running one iteration with this 1347 nodes/ 3004 links scenario takes about 16 minutes. If the runtime scales with the scenario size it would be very time consuming to run larger scenarios. In Ref. (Wen et al., 2006), the DynaMIT framework was applied to a real-time scenario but on a small network (243 nodes and 606 links). In that study a rolling horizon approach was chosen to have a 5 min estimation and 30 min prediction on that network. Two iterations of estimation and two iterations of prediction took about 1 min. If the runtime scales with the size of the network the performance is comparable to the Dynasmart-P approach and again too slow for large-scale scenarios.

One way to achieve faster computation with a microscopic model is to use a model with deliberately large time steps and to computationally concentrate on those areas (links) where the pedestrian movement actually takes place (Gloor et al., 2004b). Another approach is based up on a modified queuing model (Gawron, 1998, Simon et al., 1999). The queuing model simplifies streets to edges and crossings to nodes; the difference to standard queuing theory is that agents (particles) are not dropped but spill back, causing congestion. This graph-oriented model

is defined by lengths/widths, free speed and flow capacity of the edges. This simplification leads to a major speedup of the simulation while keeping results realistic. The combination of these two approaches (switching off unused links; queue model) is used in this paper.

A robust simulation framework will help to find feasible solutions for arbitrary evacuation scenarios. The aim of this work is to find feasible evacuation solutions for an evacuation of large cities or regions by foot. This means we are looking for solutions from which it is possible to derive recommendations for the real world. This work is part of the current multi-disciplinary project "Last-Mile" (Birkmann et al., 2007). The overarching goal of "Last-Mile" is to develop jointly with local partners a numerical last mile tsunami early warning and evacuation information system on the basis of detailed earth observation data and techniques as well as hydraulic numerical modeling of small-scale flooding and inundation dynamics of the tsunami including evacuation simulations in the urban coastal hinterland for the city of Padang, West Sumatra, Indonesia. It is well-documented that Sumatra's third largest city with one million inhabitants is located directly on the coast and partially sited beneath the sea level, and thus, is located in a zone of extreme risk due to severe earthquakes and tentatively triggered tsunamis.

To develop an evacuation simulation for such a big city one needs much preparatory work, i.e. one needs detailed picture of the walkable area of the city, the socio-economic profile and of the expected extension of the inundation. In this article we will not go into detail how this information was explored. The interested reader is referred to (Lämmel et al., 2008) for more information about how to get the necessary input data.

2 Simulation framework

The simulation framework is based on the MATSim framework for transport simulation (MATSIM www page, accessed 2008). Since MATSim is focused on simulation of motorized traffic, several adaptations were necessary. The key elements are:

- The agent database, where every agent represents one evacuee.
- The simulation network, based on links and nodes.
- The traffic flow simulator, where all the agents plans are executed.
- The plans generator, which generates an escape plan for every agent.

- There is a mechanism that allows improving the performance of the agents' plans by repeatedly trying to find faster evacuation routes.

2.1 Synthetic population, plans, agent database

MATSim always start with a synthetic population of all involved individuals. A synthetic population is a randomly generated population of individuals which is based as much as possible on existing data such as census data. For evacuation, the synthetic population is the collection of all synthetic individuals that are involved in the evacuation.

Every synthetic individual possesses one or several plans. These plans are "intentions" of the synthetic individuals, to be tested in the traffic flow simulation described later, and scored afterwards. For evacuation, the plans are evacuation strategies. For example, such a strategy may be to leave the building 5 minutes after a second warning, and follow a predetermined route to safety. The collection of agents together with their plans is sometimes called an agent database.

People can have different positions within the city when a warning occurs. For example, they can be at home or at work. Therefore, also in the evacuation context it makes sense to consider MATSim plans in their more conventional meaning, as a description on what a synthetic traveler intends to do during a normal day. One can then run a regular traffic flow simulation with these plans, stop it at the time of an evacuation warning, and use the positions of all agents at the time of that warning as the initial condition to the evacuation.

2.2 Simulation network

The simulation network represents the area that is accessible by the evacuees. In the case of a vehicular evacuation this network consists of all accessible streets. Each street segment defines a link. The parameters of the links are the length, capacity and the free flow speed. For a pedestrian evacuation the links in the simulation network also consist of squares and sidewalks. The flow capacity is given by the width of a link as described in the next section. A good way of creating the simulation network is by extracting the needed information from satellite imagery.

In the case of an evacuation simulation the network has time dependent attributes. For instance large-scale inundations or

conflagrations do not cover all the endangered area at once. In fact the spreading of the threat could be seen as a function of time. One solution would be by modeling this as a time variant network. This means streets, bridges etc. will be blocked as soon as they no longer passable. In MATSim time variant aspects of the network are modeled as network change events. A network change event modifies parameters of a link in the network (e.g. free speed or flow capacity). As soon as a link is no longer passable its free speed will be set to zero.

2.3 Traffic flow simulator

The traffic flow simulation is implemented as a queue simulation, where each street (link) is represented as a FIFO (first-in first-out) queue with three restrictions (Gawron, 1998). First, each agent has to remain for a certain time on the link, corresponding to the free speed travel time. Second, a link flow capacity is defined which limits the outflow from the link. If, in any given time step, that capacity is used up, no more agents can leave the link. Finally, a link storage capacity is defined which limits the number of agents on the link. If it is filled up, no more agents can enter this link. The difference to standard queueing theory is that agents (particles) are not dropped but spill back, causing congestion.

An illustration of the queue model is shown in Fig. **1** a). The parameters of the model are:

- Link minimum width w

- Link area A

- Link length l

- Flow capacity $FC = w * C_{max} = w * 1.3 \dfrac{p}{m * s}$

- Free flow speed $v_{max} = 1.66 \dfrac{m}{s}$

- Storage capacity $SC = A * D_{max} = A * 5.4 \dfrac{p}{m^2}$

where   is the maximum flow capacity per unit width, and   is the maximum density per unit area.

The parameters have been chosen to approximate Weidmann's fundamental diagram (Weidmann, 1993).[1] He pointed out that the relation between density and velocity is adequately captured by the so-called Kladek-formula:

$$v_{F,hi}(D) = v_{F,hf} \times [1 - e^{-\gamma \times (\frac{1}{D} - \frac{1}{D_{max}})}]$$

With:

- $v_{F,hi}$ the velocity at a particular density $[m/s]$,

- $v_{F,hf}$ the velocity at free flow $[m/s]$,

- γ a free parameter $[persons/m^2]$,

- D the actual density $[persons/m^2]$ and

- D_{max} the density at which no flow occurs $[persons/m^2]$.

Empirical studies showed the best results with $\gamma = 1.913$, $v_{F,hf} = 1.34 m/s$ and $D_{max} = 5.4 \frac{persons}{m^2}$.

Our study uses the same maximum density, but the free flow speed was set to *1.66 m/s*. This value is slightly higher then the *1.34 m/s* used by Weidmann, but the values presented by Weidmann reflect the pedestrian flow under normal conditions and not in a case of emergency.

Our queuing model, however, generates a speed-density relationship of the form $v = min[v_{max}, FC/D]$ (Simon and Nagel, 1999). The flow capacity *FC* is a free parameter that has to be chosen to fit the desired fundamental diagram. Even if a complete agreement is not possible, with $FC = 1.3 \frac{p}{m*s}$ the flow dynamics produced by our queue model is not too far away from Weidmann's fundamental diagram (cf. Fig. **1** b)). Furthermore, Predtechenskii's and Milinskii's (Predtetschenski and Milinski, 1978) empirical study supports a value of approx. $1.3 \frac{p}{m*s}$ for the flow capacity.

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[1]   Newer studies (Schadschneider et al. , to appear) imply other fundamental diagrams then those from Weidmann. An adaptation of these values could, in consequence, become necessary in future.

2.4 Plans generation

Initial plans use the shortest path (according to free speed travel time) out of the evacuation area for all agents. Within the MATSim framework a shortest path router based on Dijkstra's shortest path algorithm (Dijkstra, 1959) has been implemented. This router finds the shortest path in a weighted graph from one node to any other, whereby the actual weights for a link are defined by a time- and distance-dependent cost function. Since we want to evacuate the city as fast as possible, the weights represents the (expected) travel time. There is, however, no particular node as the target of the shortest path calculation, as the evacuees have more than one safe place to run to. Instead, in the underlying domain every node outside the evacuation area is a possible destination for an agent that is looking for an escape route. To resolve this, the standard approach (e.g. (Lu et al., 2005)) is to extend the network in the following way: All links which lead out of the evacuation area are connected, using virtual links with infinite flow capacity and zero length, to a special "evacuation node", and all paths are routed to that special evacuation node. Doing so, Dijkstra's algorithm will always find the shortest route from any node inside the evacuation area to this evacuation node and, in consequence, to safety.

2.5 Agents learning

After an execution of the traffic flow simulation, every agent will score the performed plan. The score of a plan is calculated by a scoring function as it is described later. The scored plans remain in the agents' memory for further executions. For the learning procedure two different learning strategies were used. The `ReRoute` strategy generates new plans with new evacuation routes based on the information of the experienced travel times from the last run. This uses the router described in the previous section, but using time-variant link travel times as link costs. The other strategy is called `ChangeExpBeta`. This strategy decides if the just performed plan should be used again, or if a random plan out of the memory should be selected for the next iteration. The probability to change the selected plan is calculated by

$$p_{change} = \min(1, \alpha * e^{\beta * (s_{random} - s_{current})/2})$$

With:

- α : The probability to change if both plans have the same score
- β : A sensitivity parameter

- $s_{\{random,current\}}$: The score of the current/random plan

If the system is "well-behaved", this set-up converges to a steady state where the probability that agent a uses plan i is

$$p_{a,i} = \frac{e^{\beta * s_{a,i}}}{\sum_j e^{\beta * s_{a,j}}}$$

i.e. the standard multinomial logit model (e.g. (Ben-Akiva and Lerman, 1985)).

The plans score (utility) is determined by the scoring function:

$$U_i = \beta_{tr} t_{tr,i} + \beta_{dist} d_i$$

where is the (dis)utility of plan i, is the marginal utility (in $1/h$) for travel (normally negative), is the experienced travel time for plan i, represents the marginal utility (in $1/km$) of distance (normally negative), and the distance covered by executing plan i.

Each strategy is selected with a certain probability. These probabilities are assigned before the simulation starts, but they can be varied during the iterations. Typically, `ReRoute` is called with a relatively small probability, say 10%, and `ChangeExpBeta` is called in the remaining cases.

After re-planning every agent has a selected plan that will be executed in the next iteration. Repeating this iteration cycle of learning, the agentsâ™ behavior will move towards a Nash equilibrium. If the system were deterministic, then a state where every agent uses a plan that is a best response to the last iteration would be a fixed point of the iterative dynamics, and at the same time a Nash Equilibrium since no agent would have an incentive to unilaterally deviate. Since, however, the system is stochastic, this statement does not hold, and instead we look heuristically at projections of the system. From experience it is enough to run 100 iterations until the iterative dynamics has reached a steady state. In most (but not all) evacuation situations, the Nash equilibrium leads to a shorter overall evacuation time than when everybody moves to the geographically nearest evacuation point. On the other hand, a Nash equilibrium means that nobody has an incentive to deviate. The Nash equilibrium in an evacuation situation can therefore be considered as a solution that could be reached by appropriate training.

3 Scenarios

The aim of this work is to find feasible solutions for the evacuation of the city of Padang in the case of a tsunami. There are several aspects that have to be taken into consideration. At first one needs a synthetic population for the agent database. In the studies described in this paper it is assumed that all people are at home. The information about the distribution of the population was derived from existing census data (BPS, 2005). The agent database consists of about 320,000 agents living in the endangered area.

Another important aspect is the information about safe places. In the future it is planned to identify buildings that are suitable for a vertical evacuation. For the time being we use a simpler approach: All areas with an elevation of more than 10 *m* above sea level are defined as safe. Fig. **2** shows an image of the city with the endangered area.

However, just evacuating the so-defined endangered area as quickly as possible is not necessarily the best solution: Based on models of small-scale flooding and inundation dynamics of the tsunami (Goseberg et al., in press) it is not expected that all the area below 10 *m* will be flooded. Based on these simulations, one also learns that the estimated time between the earthquake and the inundation of the city is about 28 *min*. The results are backed by the results of large-scale tsunami simulations for the west coast of Sumatra Island (McCloskey et al., 2008). Making all links impassable after they are flooded makes the agents learn a more risk averse behavior: they are not only trying to reach the safe area as fast as possible, but they also try to avoid the flooding. Since this is an additional constraint, this will in general *increase* the evacuation time of the full "endangered" area.[2]

But even in this setup the learned behavior is not necessarily plausible: One can still find simulated people who flee for a long time in parallel to the shore line, turning inland only shortly before the tsunami approaches. One way to get a more risk averse behavior is given by the fact that a solution for a scenario where the tsunami reaches the shore line earlier (e.g. after 10 *min*) is also a solution for the "28 *min*" scenario. At the same this solution is more risk averse because the agents are forced to leave the flooding area earlier. Once more, in general this will increase the the evacuation time for the full endangered area.

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[2] We say "in general" since our Nash equilibrium (NE) solution is not the system optimum (SO), and it may happen that the additional constraint pushes the NE towards the SO. The interpretation of the NE is discussed in more detail in Sec. 5.

Another important aspect is the large number of bridges in the city. Bottlenecks often emerge at bridges. The local non profit organization KOGAMI (tsunami alert community http://kogami.or.id) suggests to avoid all the bridges in the inner city during an evacuation (cf. Fig. **2**).

As discussed in 2.5, the agents in the simulation improve their plans by iterative learning. After a simulation cycle is finished all the agents plans will be scored. The scoring function takes both, evacuation time and covered distance, into account. The evacuation time should be the major criterion for the plans scoring. But also the distance costs can important. For example, there could be situations, where two evacuation routes have equal travel time but one route is substantially longer then the other. If the scoring function only took the travel time into account, then both routes would get the same score. In the real world one would recommend the shorter route even if there is a bit more congestion then on the longer one.

Taking this all together we define seven different scenarios:

run	warning time	bridges blocked	β_{tr}	β_{dist}
1	28	no	-6	0
2	8	no	-6	0
3	28	yes	-6	0
4	8	yes	-6	0
5	8	no	-6	1
6	8	no	-6	5
7	8	no	-6	10

4 Results

For each run 100 iterations of learning were performed. As expected the evacuation time decreases significantly with the iterations. Fig. **3** compares the initial iteration (top) and the last iteration (bottom) of run 2. It shows the area that has been evacuated after 30 *min* of evacuation and the maximum expansion of the inundation. In the initial iteration all agents are on the shortest path, while in the last iteration the system has converged towards Nash equilibrium and the agents are on the fastest path under the given circumstances. It is clearly shown that with the Nash equilibrium approach considerably more agents manage to escape in the given time than in the shortest path solution.

In all runs, the evacuation of all areas below 10 *m* took at least one hour. Nevertheless, in all runs the highly endangered coastal strip,

which is expected to be flooded, was evacuated before the tsunami waves reach the shore line. However, the runs perform differently in terms of the evacuation progress. Fig. **4** shows the evacuation curves for run 1 to run 4. While avoiding potentially flooded areas early (run 2 vs. run 1) makes little difference, it is clearly visible that blocking the bridges during evacuation slows down the evacuation of the full endangered area. Still, even if the bridges are blocked, there seems to be enough time to evacuate the highly endangered area at the coastal strip.

Adding distance costs (runs 5 to 7 vs. run 2) results in longer evacuation times. Fig. **5** compares the evacuation curves. The more distance costs are added, the longer the evacuation takes. This result is not unexpected, because the agents now have to optimize another criterion. They do not only try to find the fastest evacuation route, but a trade-off between fast and short.

But even if the additional distance costs increase the evacuation time, there are also advantages. Without distance costs, an agent chooses with equal probability between two equally fast evacuation routes even if one of the routes is substantially longer than the other. Not only is this counterintuitive, but from those results it is difficult to derive specific recommendations for the real world: It is, for example, not realistic that people living in the same street or even the same household would follow completely different evacuation routes. In emergency situations, people tend to be irrational and to display herd behavior (Helbing et al., 2000). From this point of view it is better to recommend people living next to each other the same evacuation route. Adding additional distance costs helps to find those solutions. This is shown in Fig. 6.

Fig. 6 compares the evacuation destinations between run 2 and run 7. The arrows in this figure point towards the place where the people flee to. Each arrow represents the home location of one person. Arrows pointing to the same destination have the same shade of gray. For run 7 this destination depended colorization is much more grouped and not so mixed up as it is for run 2. The only difference in the setup was the additional distance costs for run 7. This means that from simulation runs with additional distance costs it is easier to derive recommendations for the real world, at the cost of a slower evacuation procedure, as shown in Fig. **5**.

5 Discussion

5.1 Nash equilibrium vs. other solutions

The Nash equilibrium (NE) approach is used as a first benchmark: As can be seen from Fig. **3**, the approach allows to evacuate a much larger critical area than with an approach where everybody takes the geometrically shortest path to safety. This is clearly a consequence of congestion on *some* of the geometrically shortest paths, making evacuees caught in congestion better off if they use a different, geometrically longer path. This is confirmed by the fact that adding distance into the cost function makes the evacuation take longer again.

Many people argue that the NE approach is not appropriate for evacuation since people will not evacuate often enough for this solution to be plausible. We would argue that the NE approach could, if designed correctly, established by appropriate training of the population, in particular for a nighttime situation as discussed here, where families can be assumed to be united from the start. Then, the NE solution would have the advantage that nobody in the population would have an incentive to deviate from this solution.

This is in contrast to a system optimal solution, which might be even better than the NE solution, but which might give individuals incentives to deviate.

Nevertheless, it is nothing but a possible benchmark. It may be unrealistic or problematic at least for the following reasons:

- It is probable that people will also display other types of behavior, such as herd behavior, or uniting the family (possibly causing counterflows) before evacuating. In fact, personal interviews show that at this point many people do not have the intention to evacuate at all (Hoppe, 2007).

- The NE solution for Padang is most probably not a confluent flow solution (see, e.g., (Chen et al., 2004)). This means that the "correct" direction from any intersection is not always just a single link that remains fixed over time. Instead, the simulation shows that it is quite common in the NE solution that flows split at intersections, or move into different downstream links at different times.

- Although evacuation flows of pedestrians are reasonably stable and thus predictable (Rogsch, 2005), there are still many reasons why the simulation could be wrong: parked cars or other obstacles could reduce the minimum width of links; some people

might have difficulty walking; some people might use other means of transport, thus leading to a mix of different vehicles rather than a homogeneous pedestrian population; cars might even be abandoned (and thus convert to obstacles) in the course of an evacuation. Note that pedestrian evacuation reaches a flow rate of 1.3 pedestrian per second per meter cross section; the use of individual vehicles (cars, motorcycles, bicycles) will probably *reduce* that flow rate, increasing congestion.

Overall, we believe that it is plausible to say that the simulation at this point is rather a "good case" than a bad case scenario. Still, the fact that one seems to be able to evacuate the "flooded areas" with 30 *min* to spare (Fig. **3**) gives hope that one may be able to construct a workable solution.

5.2 Risk exposure over time

Our simulation has so far been defined in terms of a "minimal time to evacuate": Given the network, the initial distribution of the population, and pre-defined safe areas, the simulation attempts to answer the question which times are plausibly needed in order to get everybody into the safe areas. Yet, it is not clear which exactly are the safe areas:

- In the case of an actual warning, neither tsunami wave heights not wave patterns nor the time until the wave reaches the shore line will be known. Therefore, it is impossible to define a "minimal" dangerous area. On the other hand, it would be quite difficult to establish a solution where people need to walk for 30 *min* or more, especially since it is probable that there will be a fair number of false alarms. – At this point, we are considering to take an "envelope" of the inundation (see Fig. **3**) from a number of worst case scenarios computed by (Goseberg et al. , in press). In addition, there will eventually be special "shelters", buildings marked as safe, etc.

- It is unclear how to proceed with the time-dependence of the problem. Clearly, bridges will eventually be unsafe. But so will be certain other streets, and it might be better to use a bridge to get into safety right afterwards than to stay on risky streets for a much longer time. This problem is apparent in all of our situations: Given a certain warning time, it makes sense for some of the evacuees to take a path that increases their risk temporarily in order to be really safe much earlier.

This problem is confounded by the "minimal time to evacuate" approach: There will eventually be a warning time which cannot be reduced any further without accepting loss of life in the simulations. If this, however, is the minimal warning time ever used in the simulations, the simulated agents can assume that all of the city is safe for that amount of time, and route themselves accordingly. If then, in reality, the warning time is even shorter, such routes might not be advantageous.

Our current plan is to investigate approaches where we designate different "risk levels" to different links, and devise evacuation paths where agents always reduce risk. This will avoid the situation described above, but will result in a less efficient evacuation. This efficiency reduction will be tested and quantified by the simulation.

- It is not possible to designate non-flooded areas directly as "safe", since evacuees both in the simulation and in reality would stop there, causing congestion for evacuees that follow.

6 Conclusion

This paper describes a microscopic evacuation simulation based on the MATSim framework for transport simulation. The key elements of MATSim are the synthetic population, the simulation network, the traffic flow simulator, and a mechanism that lets the members of the synthetic population improve their evacuation plans. The scenario for this study is the Indonesian city of Padang with approximately 1,000,000 inhabitants. The city faces a high risk of being inundated by a tsunami wave. About 320,000 people live in a highly endangered area. The simulation runs were performed with 320,000 agents forming a corresponding synthetic population.

In this study, seven different runs with different parameters were conducted. Parameters that were varied are the advance warning time, blocking of the bridges, and the distance cost for traveling. With the variation of these parameters the system moves towards different Nash equilibria. Results regarding the overall evacuation time, evacuation curves and evacuation directions are given. Sec. 5 discusses under which circumstances a Nash equilibrium would be a good solution for the evacuation problem. Some points that are presently not covered by the simulation framework are also addressed (e.g. abandoned cars in the streets as obstacles). Finally problems with a definition of safe areas are discussed.

In future work we are going to integrate tsunami proof shelters into the simulation framework as additional safe areas. This is of particular interest because in currently running studies the buildings in the city will be classified regarding their usability as shelters. Furthermore we are currently investigating methods for risk averse evacuations. This will be done by adding additional risk costs to links depending on their direction. Overall we have shown in this paper that the MATSim framework is a good analysis tool for evacuation scenarios, especially if they are large-scale.

Acknowledgements

References

Alsnih, R. and Stopher, P. (2004), "A review of the procedures associated with devising emergency evacuation plans", Working Paper ITS-WP-04-04, Institute of Transport Studies, The University of Sydney and Monash University. See `http://www.itls.usyd.edu.au/publications/working_papers/wp2004/its_wp_04-04.pdf`

Barrett, B., Ran, B. and Pillai, R. (2000), "Developing a dynamic traffic management modeling framework for hurricane evacuation", Paper 00-1595, Transportation Research Board Annual Meeting, Washington, D.C.

Ben-Akiva, M. and Lerman, S. R. (1985), *Discrete choice analysis*, The MIT Press, Cambridge, MA.

Bierlaire, M., Antonini, G. and Weber, M. (2003), "Behavioral dynamics for pedestrians", *in* K. Axhausen (Ed.), Moving through nets: The physical and social dimensions of travel, Elsevier, pp. 1-18. `http://infoscience.epfl.ch/record/86990/files/Bierlaire2003_283.pdf`

Birkmann, J., Dech, S., Hirzinger, G., Klein, R., Klüpfel, H., Lehmann, F., Mott, C., Nagel, K., Schlurmann, T., Setiadi, N., Siegert, F. and Strunz, G. (2007), "Numerical last-mile tsunami early warning and evacuation information system", *in* L. Stroink (Ed.), GEOTECHNOLOGIEN Science Report No. 10: Early Warning Systems in Earth Management, Die Deutsche Biliothek, Vol. 10

pp. 62-74
`http://www.geotechnologien.de/Download/pdf/S cience_Report/SR10.pdf`

BPS (2005), *Kecamatan Dalam Angka - Subdistricts in Numbers*, Statistical bureau (BPS) Kota Padang, Padang, Indonesia.

Cascetta, E. and Cantarella, C. (1991), "A day-to-day and within-day dynamic stochastic assignment model", *Transportation Research A,* Vol. 5 No. 25 A, pp. 277–291.

Chen, J., Kleinberg, R. D., Lovász, L., Rajaraman, R., Sundaram, R. and Vetta, A. (2004), "(Almost) tight bounds and existence theorems for confluent flows", *in* László Babai (Ed.), STOC '04: Proceedings of the thirty-sixth annual ACM symposium on Theory of computing, ACM, New York, NY, USA, pp. 529–538.

Chen, X. and Zhan, F. (2004), "Agent-based modeling and simulation of urban evacuation: Relative effectiveness of simultaneous and staged evacuation strategies", Paper 04-0329, Transportation Research Board Annual Meeting, Washington, D.C.

Chiu, Y.-C., Korada, P. and Mirchandani, P. (2005), "Dynamic traffic management for evacuation", Paper 05-2369, Transportation Research Board Annual Meeting, Washington, D.C.

Dijkstra, E. (1959), "A note on two problems in connexion with graphs", *Numerische Mathematik,* Vol. 1 , pp. 269–271.

Farkas, I. (accessed 2008), "`pedsim` source code". See `http://pedsim.elte.hu`

Galea, E. (2002), "Simulating evacuation and circulation in planes, trains, buildings and ships using the EXODUS software", *in* Schreckenberg and Sharma (Ed.), *Pedestrian and Evacuation Dynamics*, Springer, Berlin, pp. 203–225.

Galea, E., (Ed.) (2003), *Pedestrian and Evacuation Dynamics*, Proceedings of the 2nd international conference, London, CMS Press, University of Greenwich, UK.

Gattermann, P., Waldau, N. and Schreckenberg, M., (Eds.) (2006), *Pedestrian and Evacuation Dynamics*, Proceedings of the 3rd international conference, Vienna, Springer, Berlin.

Gawron, C. (1998), "An iterative algorithm to determine the dynamic user equilibrium in a traffic simulation model", *International Journal of Modern Physics C,* Vol. 3 No. 9, pp. 393–407.

Gloor, C., Stucki, P. and Nagel, K. (2004*a*), "Hybrid techniques for pedestrian simulations", *in* Sloot, P., Chopard, B. and Hoekstra, A. (Eds.), Cellular automata, Proceedings, *in* Lecture Notes in Computer Science, Vol. 3305, Springer, Berlin Heidelberg,

pp. 581–590.
`http://www.springerlink.com/content/ng75m5ly`
`yd8b617p/`

Gloor, C., Stucki, P. and Nagel, K. (2004*b*), "Hybrid techniques for pedestrian simulations", *in Proceedings of Swiss Transport Research Conference (STRC)*, Monte Verita, CH. See *http://www.strc.ch*

Goseberg, N., Stahlmann, A., Schimmels, S. and Schlurmann, T. (in press), "Highly-resolved numerical modeling of tsunami run-up and inundation scenarios in the city of Padang, West Sumatra", *in* Procceedings of the Interantional Conference on Coastal Engineering, Hamburg.

Hamacher, H. and Tjandra, S. (2001), "Mathematical modelling of evacuation problems: A state of art", *Berichte des Fraunhofer ITWM*, Vol. 24, pp. 1–38.

Han, L. and Yuan, F. (2005), "Evacuation modeling and operations using dynamic traffic assignment and most desirable destination approaches", Paper 05-2401, Transportation Research Board Annual Meeting, Washington, D.C.

Helbing, D., Buzna, L., Johansson, A. and Werner, T. (2005), "Self-organized pedestrian crowd dynamics: experiments, simulations and design solutions", *Transportation Science*, Vol. 39, pp. 1–24.

Helbing, D., Farkas, I., Molnar, P. and Vicsek, T. (2002), "Simulation of pedestrian crowds in normal and evacuation situations", *in* Schreckenberg and Sharma (2002), pp. 21–58.

Helbing, D., Farkas, I. and Vicsek, T. (2000), "Simulating dynamical features of escape panic", *Nature*, Vol. 407, pp. 487–490.

Hobeika, A. and Kim, C. (1998), "Comparison of traffic assignments in evacuation modeling", *IEEE Transactions on Engineering Management*, Vol. 2 No. 45, pp. 192–198.

Hoogendoorn, S., Bovy, P. and Daamen, W. (2002), "Microscopic pedestrian wayfinding and dynamic modelling", *in* Schreckenberg and Sharma (2002), pp. 123–154.

Hoppe, M. (2007), Early warning experiences in Padang after first Bengkulu earthquake on 12 september 2007, Technical report, GTZ-International Services.

Jafari, M., Bakhadyrov, I. and Maher, A. (2003), Technological advances in evacuation planning and emergency management: Current state of the art, Final Research Reports EVAC-RU4474, Center for Advanced Infrastructure and Transportation (CAIT), Rutgers University, NJ.

`cait.rutgers.edu/finalreports/EVAC-RU4474.pdf`

Jha, M., Moore, K. and Pashaie, B. (2004), "Emergency evacuation planning with microscopic traffic simulation", Paper 04-2414, Transportation Research Board Annual Meeting, Washington, D.C.

Klüpfel, H. (2006), "The simulation of crowd dynamics at very large events – Calibration, empirical data, and validation", *in* Gattermann et al. (2006), pp. 285-296.

Klüpfel, H., Meyer-König, T., Keßel, A. and Schreckenberg, M. (2003), "Comparison of an Evacuation Exercise in a Primary School to Simulation Results", *in* Fukui, M., Sugiyama, Y., Schreckenberg, M. and Wolf, D. (Eds.), Traffic and granular flow '01, Springer, Berlin Heidelberg New York, pp. 449–454.

Kuligowski, E. (2004), Review of 28 egress models, Technical report, National Institute of Standards and Technology (NIST), Gaithersburg, MD.

Kwon, E. and Pitt, S. (2005), "Evaluation of emergency evacuation strategies for downtown event traffic using a dynamic network model", Paper 05-2164, Transportation Research Board Annual Meeting, Washington, D.C.

Lämmel, G., Rieser, M., Nagel, K., Taubenböck, H., Strunz, G., Goseberg, N., Schlurmann, T., Klüpfel, H., Setiadi, N. and Birkmann, J. (in press), "Emergency preparedness in the case of a tsunami – evacuation analysis and traffic optimization for the Indonesian city of Padang", in *Pedestrian and Evacuation Dynamics,* Proceedings of the 4th international conference.

Lim, E. and Wolshon, B. (2005), "Modeling and performance assessment of contraflow evacuation termination points", *Transportation Research Record,* Vol. 1922, pp. 118–128.

Lu, Q., George, B. and Shekhar, S. (2005), "Capacity constrained routing algorithms for evacuation planning: A summary of results", in Medeiros, C., Egenhofer, M. and Bertino, E. (Eds.), Lecture Notes in Computer Science, Vol. 3633, pp. 291–307.

MATSIM www page (accessed 2008), MultiAgent Transport SIMulation. `http://ww.matsim.org`

McCloskey, J., Antonioli, A., Piatanesi, A., Sieh, K., Steacy, S., Nalbant, S., Cocco, M., Giunchi, C., Huang, J. and Dunlop, P. (2008), "Tsunami threat in the Indian Ocean from a future megathrust earthquake west of Sumatra", *Earth and Planetary Science Letters,* Vol. 265, pp. 61–81.

Nishinari, K., Kirchner, A., Nazami, A. and Schadschneider, A. (2004), "Extended floor field CA model for evacuation dynamics", *IEICE Transactions on Information and Systems,* Vol. 3 No. E87-D, pp. 726–732.

Ortúzar, J. de D. and Willumsen, L. (1995), *Modelling transport*, Wiley, Chichester.

Predtetschenski, W. and Milinski, A. (1978), *Planning for Foot Traffic in Buildings*, Amerind Publishing Co. Pvt. Ltd., New Delhi.

Rogsch, C. (2005), Vergleichende Untersuchungen zur Simulation von Personentrömen, Diploma thesis, Universität Wuppertal.

Sattayhatewa, P. and Ran, B. (2000), "Developing a dynamic traffic management model for nuclear power plant evacuation", Paper, Transportation Research Board Annual Meeting, Washington, D.C.

Sbayti, H., Lu, C.-C. and Mahmassani, H. (2007), "Efficient implementation of method of successive averages in simulation-based dynamic traffic assignment models for large-scale network applications", *Transportation Research Record,* Vol. 2029, pp. 22–30.

Schadschneider, A., Klingsch, W., Klüpfel, H., Kretz, T., Rogsch, C. and Seyfried, A. (to appear), "Evacuation dynamics: Empirical results, modelling and applications", *in* Meyers, B. (Ed.), Encyclopedia of Complexity and System Science, Springer, Berlin.

Schneider, V. and Könnecke, R. (2002), "Simulating evacuation processes with ASERI", *in* Schreckenberg and Sharma (2002), pp. 303–314.

Schreckenberg, M. and Sharma, S. D., (Eds.) (2002), *Pedestrian and Evacation Dynamics*, Proceedings of the 1st international conference, Duisburg, 2001, Springer.

Sheffi, Y. (1985), *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods*, Prentice-Hall, Englewood Cliffs, NJ, USA.

Simon, P., Esser, J. and Nagel, K. (1999), "Simple queueing model applied to the city of Portland", *International Journal of Modern Physics C,* Vol. 5 No. 10, pp. 941–960.

Simon, P. and Nagel, K. (1999), "Simple queueing model applied to the city of Portland", Paper 99-0861, Transportation Research Board Annual Meeting, Washington, D.C.

Theodoulou, G. and Wolshon, B. (2004), "Alternative methods to increase the effectiveness of freeway contraflow evacation", *Transportation Research Record,* Vol. 1865, pp. 48–56.

Weidmann, U. (1993), *Transporttechnik der Fussgänger*, Vol. 90 of *Schriftenreihe des IVT*, 2 edn, Institute for Transport Planning and Systems ETH Zürich. In German.

Wen, Y., Balakrishna, R., Ben-Akiva, M. and Smith, S. (2006), "Online deployment of dynamic traffic assignment: architecture and run-time management", *Intelligent Transport Systems*, IEE Proceedings, Vol. 153, pp. 76–84.

Figures
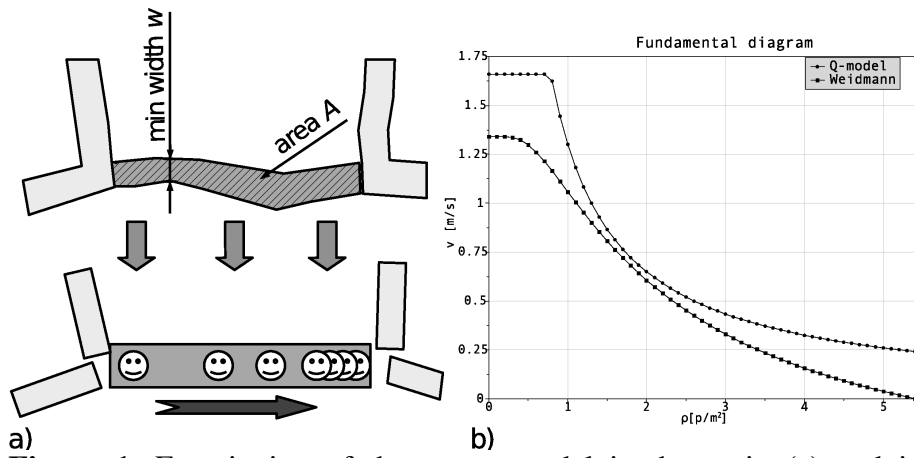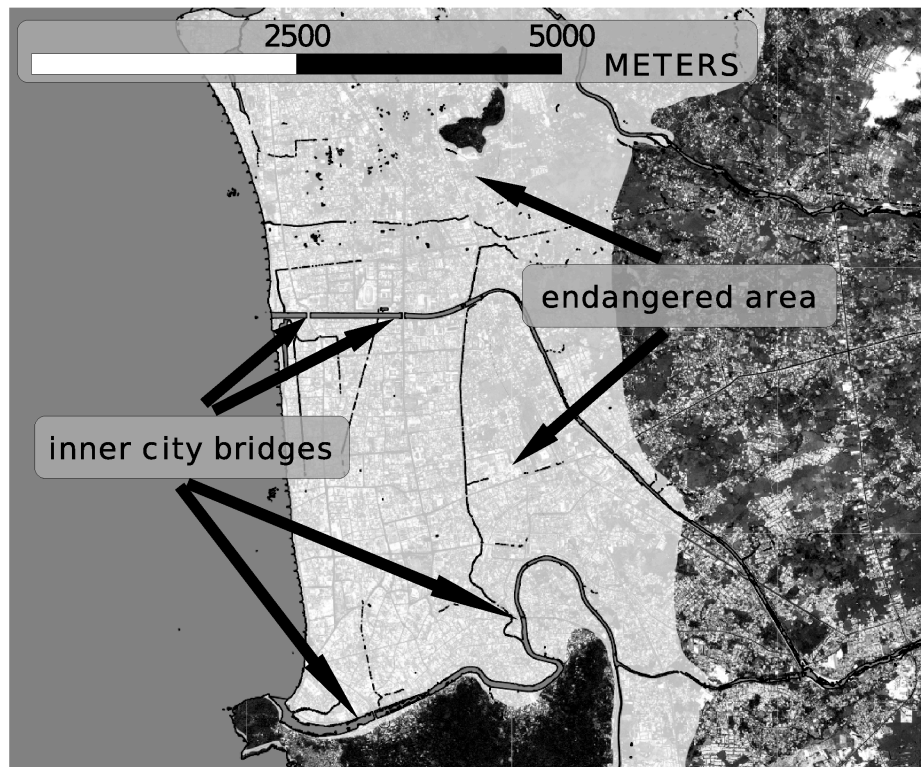
Figure 2: Satellite imagery of the city shows the evacuation area (light gray) and some main bridges where bottlenecks are expected during an evacuation. Satellite imagery by the German Aerospace Center, Oberpaffenhofen (2007)
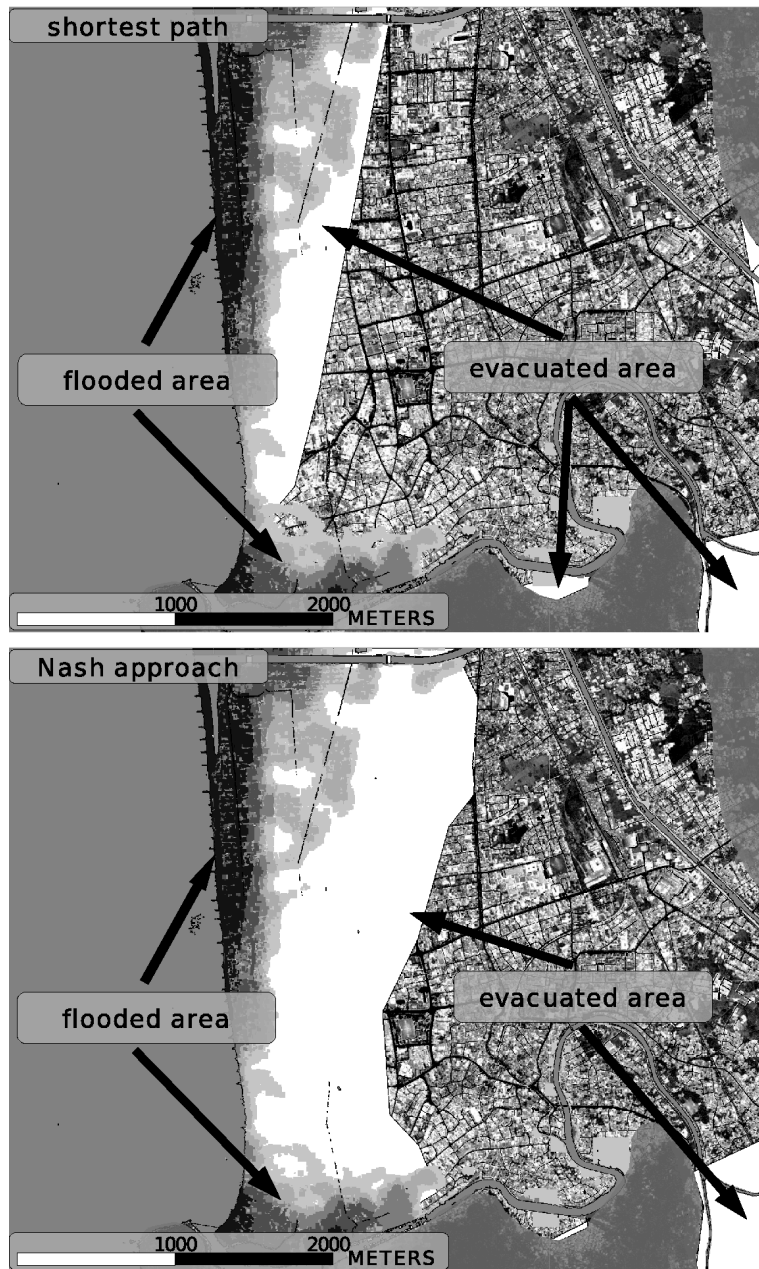
Figure 3: The area that could be evacuated within 30 *min* and the maximum expansion of the inundation. Top: A solution where every agent is on the shortest path. Bottom: Result of run 2 after 100 itations of learning (Nash equilibrium approach). The evacuated area in the Nash equilibrium approach is considerably larger than in the shortest path solution. Satellite imagery by the German Aerospace Center, Oberpaffenhofen (2007)
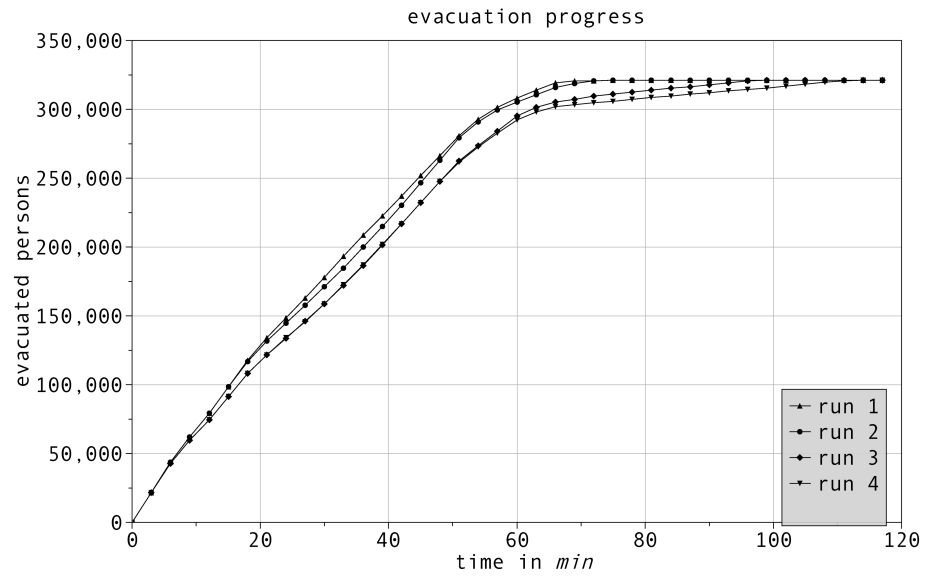
Figure 4: Evacuation curves for run 1 to run 4. These curves look similar, but if the bridges are blocked (run 3 and run 4) the overall evacuation time increases by about 40 min compared to run 1 and run 2, where all bridges are open.
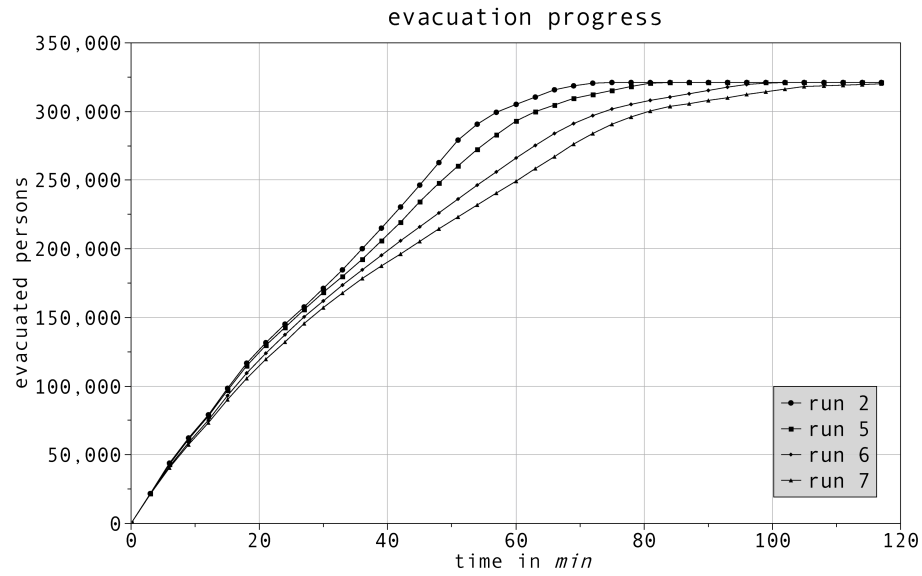
Figure 5: Evacuation curves of run 5 to run 7 compared with run 2. It is shown that increasing the distance costs does not increase the overall evacuation time. But the comparison of run 2 with run 7 shows that without distance costs (run 2) about 300 000 agents managed to evacuate within 60 *min*, where in run 7 (distance costs of 10 units per kilometer) in the same time only 250 000 agents managed to escape.
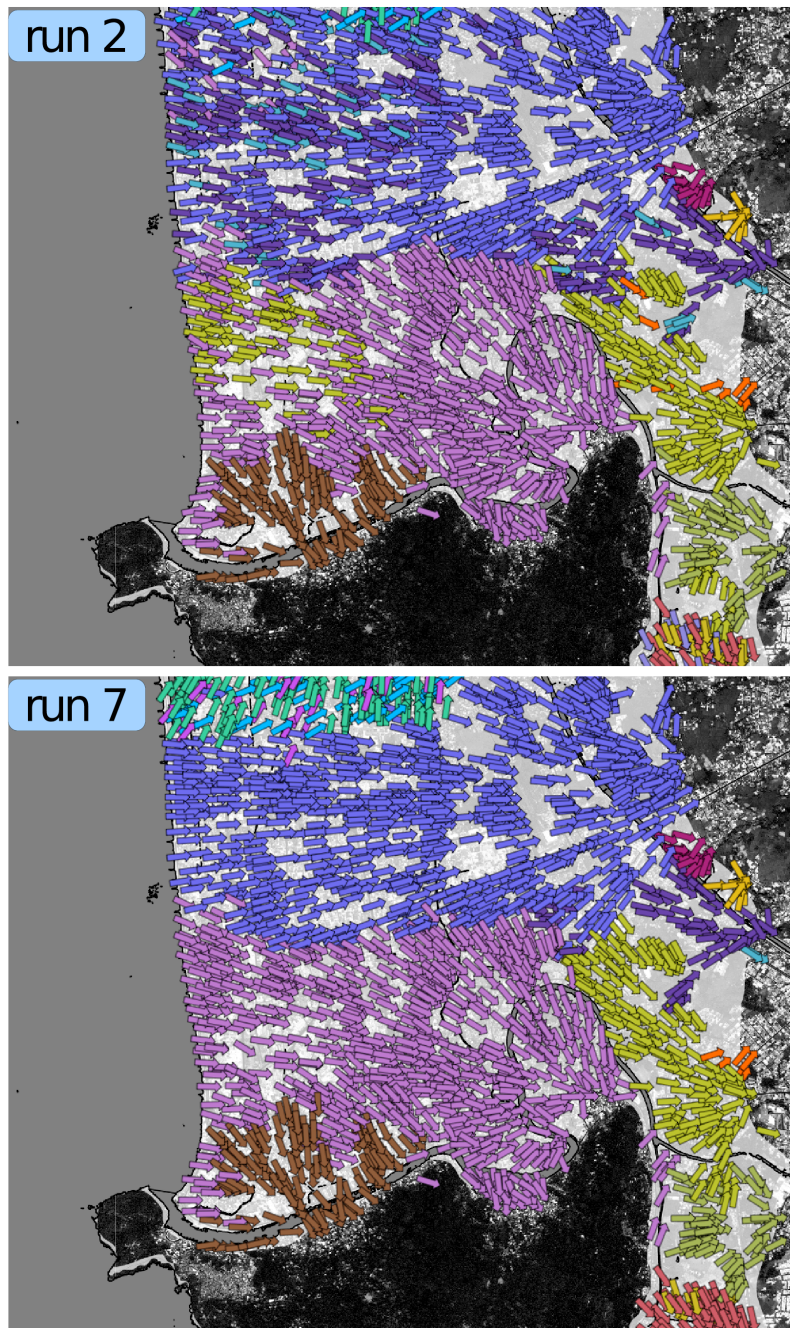
Figure 6: Comparison of the evacuation destinations for run 2 und run 7: The arrows point towards the evacuation destinations, with same color indicates the same destination. Satellite imagery by the German