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A framework for large-scale multi-modal microscopic evacuation simulations

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Abstract

In recent years, the interest in multi-modal simulation models has increased significantly. In such models, various transport modes are simulated simultaneously, including the interactions between agents using different modes. Typical fields of application are, for example, studies on car sharing and public transport. However, they are in general not able to handle scenarios with exceptional events. Evacuation models often support multiple transport modes and unexpected events but are designed for small-scale scenarios only.

Obviously, there is a gap between these two areas that has to be closed by a multi-modal evacuation simulation. This paper presents the combination of two simulation approaches and another one for large-scale multi-modal simulations, one to simulate evacuations. Both approaches are integrated in a single simulation framework. Its capabilities are demonstrated on a real world large-scale evacuation scenario which includes also microscopic elements.

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1. Multi-modal evacuation simulation

1.1. Requirements

After events like the terrorist attacks on September 11th, the disastrous tsunami that hit coastal regions around the Indian Ocean in December 2004, or the devastating earthquake and subsequent tsunami in Japan in March 2011, the interest in large-scale evacuation simulations has grown enormously. In transport planning and traffic management, this creates the necessity of simulating scenarios where unforeseeable exceptional events occur. In this context, such an event can be described as an incident that cannot (e.g. an earthquake) or only partially (e.g. a major sports events where the number of sold tickets is known, but impact on the transport system can only be estimated) be foreseen. A second important requirement is a model's ability to simulate multi-modal traffic flows since large non-vehicular traffic can occur during an evacuation.

1.2. Evacuation simulation

An approach to fulfill the first requirement is called *within-day replanning* and presented by Dobler *et al.* (forthcoming). They describe why traditional simulation approaches, which are based on an iterative optimization of traffic demand, will fail when applied to scenarios with exceptional events. The proposed within-day replanning approach is based on performing only a single iteration. Within this iteration, agents continuously collect information and adapt their plans to react to changing environmental conditions. Doing so requires a more complex behavioral model than the ones traditionally used in the field of transport planning. Traditional approaches assume that a person tries to improve its daily schedule and the joint optimization of all people leads to a user equilibrium.

However, depending on what kind of exceptional event occurs, such a behavioral model is not appropriate anymore. An example would be a major flooding, resulting in evacuation of the affected region. Here, a person will evaluate different reaction alternatives. A first option would be trying to reach a safe area immediately. Another would be to first try to meet some family members and then leave the affected area together. To allow a person to choose between such alternatives, a detailed and flexible behavioral model is required. A common implementation of such a model is the so-called BDI (beliefs, desires, intentions) approach (see e.g. Wooldridge, 2000, Eymann, 2003).

1.3. Multi-modal simulation

In recent years, the interest in multi-modal simulation models has increased significantly. In such models, various transport modes are simulated simultaneously, including the interactions between agents using different modes. Today, there are two major areas of agent-based transport simulations. On one hand, models for large-scale scenarios with hundreds of thousands or even several million entities have been developed (see e.g. Balmer *et al.*,2004).. To keep their computational effort feasible, they are based on simplified physical representations of traffic flows as they are known from the field of dynamic traffic assignment. On the other hand, there are models with a high level of detail and a microscopic modeling of the underlying physics for small scenarios with some hundred or a few thousand agents. While the first class only deals with vehicular traffic, the second one usually also deals with pedestrians and cyclists.

Dobler and Lämmel (2012) describe an approach that closes the gap between these two areas using a flexible multi-modal simulation that is able to handle scenarios where the level of detail varies. Doing so combines the best of both worlds and gives the opportunity to simulate large-scale scenarios, while staying highly resolved where needed and being more aggregated where possible.

1.4. Modeling approach

This paper presents the combination of the within-day replanning approach and a multi-modal traffic flow simulation in a single framework. After introducing the underlying agent-based transport systems micro-simulation, the implementations of the within-day replanning module and the multi-modal simulation as well as their combination are discussed. Subsequently, a scenario is described which is used to demonstrate the framework's capabilities. Afterwards, results of the scenario's simulation are presented. Finally, the paper closes with conclusions and an outlook on further work.

2. MATSim

2.1. Modeling approach

MATSim is a framework for iterative, agent-based transport systems micro-simulations written in Java. It is currently being developed by teams at ETH Zurich and TU Berlin as well as senozon AG, a spin-off company founded by former members of both institutes. MATSim consists of several modules that can be used independently or as part of the framework. Moreover, it is possible to extend the modules or replace them with new implementations. Balmer (2007) and Balmer *et al.* (2008) give a detailed description of the framework, its capabilities and its structure.

Due to its agent-based approach, every person in the system is modeled as an individual agent in the simulated scenario. Each agent has personalized parameters such as age, sex, available transport modes and scheduled activities. MATSim's application to a large-scale Switzerland scenario (over 6 million agents simulated on a high resolution network with 1 million links) is presented by Meister *et al.* (2010).

Figure 1 shows the structure of a typical, iterative MATSim simulation run. After creation of initial demand, agents' plans are modified and optimized in an iterative process until a relaxed system state (typically a user equilibrium) is found. The results can be analyzed later.



Fig. 1. Structure of the iterative MATSim loop

The loop shown in the figure contains *execution (simulation)*, *scoring* and *replanning* elements. Within the simulation module, agents' plans are executed. Afterward, the scoring module uses a utility function to calculate the executed plans' quality. Charypar and Nagel (2005) describe the basic utility function for MATSim. Based on scoring module results, the replanning module creates new plans by varying start times and durations of activities, as well as routes and modes used to travel from one activity to another.

Simulation of traffic behavior is also part of the iterative loop. The simulation module's task is to execute agents' plans within the simulated scenario. The so-called *QSim* is a deterministic implementation of a queue model using a time step based approach with a one-second step size. Within each time step, the state of the queues is considered.

2.2. Within-day replanning

When adding within-day replanning to MATSim, its structure is adapted as shown in Figure 2 On one hand, the additional *within-day replanning* module is added, which interacts with the mobility simulation. On the other hand, multiple iterations are only necessary if a combined simulation approach is used.



Fig. 2. (Iterative) within-day replanning MATSim loop

The implementation allows arbitrary changes in an agent's scheduled plan, including a trip's route and mode as well as an activities location, duration and type. Also complex operations like adding, removing or swapping of activities are possible. A more detailed description of the implementation of within-day replanning im MATSim is given by Dobler *et al.* (forthcoming).

2.3. Multi-modal extension

MATSim's multi-modal simulation extension consists of two separate modules (see Dobler and Lämmel (2012) for a detailed discussion). The first one is based on a simple and fast model that adds a multi-modal extension to each link object in the mobility simulation (see Figure 3). While traffic flow dynamics are simulated by MATSim's mobility simulation using a queue model, they are not taken into account in the multi-modal extension. Having a look at typical pedestrian and cyclist traffic flows shows that congestion is very rare compared to vehicular traffic and therefore justifies the application of this simplistic approach in large parts of a scenario.



Fig. 3. Multi-modal link extension

Agents traveling on a link are stored in a priority queue which orders the agents based on their scheduled link leave time (see Figure 4). This time is calculated when an agent enters a link based on parameters like the agent's age and gender as well as the links steepness (see Weidmann, 1992, Parkin and Rotheram, 2010). In each time step it is checked, whether the queue contains agents who have reached their link leave time and therefore have to be moved to their route's next link. An agent's position on a link is not determined by the model. However, under the assumption that agents move with constant speed, their position can be interpolated. On one hand, this approach is computationally very efficient because computation effort is only created when an agent enters or leaves a link but not while the agent is traveling along a link. On the other hand, agents can travel with different speeds and therefore overtake each other.

↓ 11416		12084	12312
agent Id, link leave time		agent Id, link leave time	agent ld, link leave time
ld: 123, t: 15742		ld: 123, t: 15742	ld: 123, t: 15742
ld: 261, t: 14698		ld: 261, t: 14698	ld: 261, t: 14698
ld: 491, t: 14574	add	ld: 512, t: 14618	ld: 512, t: 14618
ld: 398, t: 13921	,	ld: 491, t: 14574	ld: 491, t: 14574
ld: 946, t: 13885		ld: 398, t: 13921	ld: 398, t: 13921
ld: 780, t: 12312		ld: 946, t: 13885	ld: 946, t: 13885
		ld: 780, t: 12312	ld: 780, t: 12312

Fig. 4. Link representation in the simple model

At time 12084, agent 512 enters the link and is—based on its calculated link leave time 14618—inserted into the queue. At time 12312, agent 780 has reached its leave time and therefore is removed from the queue.

For regions with higher traffic flows, the second multi-modal module is used which is based on a force-based 2D approach. This module provides a very high level of detail including consideration of traffic flows at cost of additional computational effort. Moreover, additional information about a road's geometry is required.

The module distinguishes between two stages in the movement model. The first stage deals with the low level movement of the agents, meaning collision avoidance, velocity adaptation and so on. The second stage deals with the more high level movement of the agents, meaning moving along a given route. Both stages are modeled based on additive attracting and repelling forces, which are "pushing" the agents through the environment. The general force model is defined according to Newton's law ($F = m \cdot a$). For a detailed discussion of the force-based 2D approach see Lämmel and Plaue (2012).

3. Scenario

The capabilities of the developed framework for multi-modal evacuation simulations are demonstrated on a model of the city of Zurich. The dam of the Sihlsee is located approximately 35 km south-east of the city. A dam-break would lead to a major flooding of the city center with a height up to 8 m (Zivilschutz der Stadt Zürich, 2012). Figure 5(a) shows the city, the dam and the flood wave's path. The area in the city center that would be affected is shown in Figure 5(b). Moreover, we assume that this incident happens while the Zurich city marathon takes place. As shown in Figure 6(a), parts of the marathon's track (yellow) are also affected. The markers in Figure 6(b) show the marathon's route in detail.



Fig. 5. Scenario

The marathon starts a few meters outside the affected area. However, the runners enter the area shortly after the start (links marked with 01 and 02). After approximately 10 minutes, they leave the area again (links 03 to 05). The following parts of the track, links 06 to 16, are again located in the affected area. Link 17 and parts of link 01 are not affected, but subsequent link 02 is again inside the flooded area. The next parts of the track leave the city center (links 03 and 18). When returning to the city again, the track goes along links 19, 03, 07 to 15 and finally link 01. Again, most of them are located in the flooded area.



Fig. 6. Marathon track

For the simulation, a model containing 450,000 agents—a 25% sample of the entire population—that are simulated on a planning network with 24,000 nodes and 60,000 links, is used. Approximately 1,000 of those agents are attending the Zurich city marathon. Figure 7(a) shows a map of Switzerland containing

the road network and the study area (colored light grey). The population consists of all people that touch the study area during one of their activities or trips. Therefore—as shown in Figure 7(b)—not only the canton's residents but also people who cross the canton, are included.



(a) Switzerland without traffic flows

(b) Switzerland with traffic flows at 08:15 a.m.



If the Sihl-dam breaks, the flood wave will reach the outer city boarder after 85 minutes. Another 25 minutes later the city center is reached (Zivilschutz der Stadt Zürich, 2012). When the dam breaks, sirens and radio announcements are used to alert the population immediately. For the simulations conducted, we assume that the dam breaks at 09:30 a.m., which is 30 minutes after the Zurich marathon was started. At this point in time, most of the marathon's participants are on parts of the track which are located in the affected area. Furthermore, we assume that all affected people evacuate to a place outside the affected area as fast as possible, although most buildings would withstand the flooding and several of them have floors above the expected flooding height.

Lämmel *et al.* (2010) also simulate the flooding of Zurich's city center. However, the authors focus on a much simpler approach where only pedestrians are considered. Moreover, all pedestrians share the same physical parameters, like walking speed and no extraordinary events like a marathon are considered. For the simulation they used an iterative, queue-based model without within-day replanning capability.

4. Implementation

For multi-modal evacuation simulations, both modules described above are combined. To do so, the within-day replanning module is adapted in a way that it supports all transport modes available in the multi-modal simulation. As a result, new *replanners* (code that adapts certain aspects of an agent's plan) are implemented which change a trip's transport mode. Moreover, an agent can stop its current trip, perform a mode-switch activity and continue the trip with a new transport mode.

For the experiments conducted with the scenario described in the previous section, a scenario specific behavioral model is implemented. A Rayleigh distribution is used to model the time span between the

dam-break and the point in time where an agent gets informed and starts to evacuate. Its probability density and cumulative distribution function are defined like:



Fig. 8. Rayleigh probability density and cumulative distribution function for $\sigma = 600$

A value of 600 is used for σ . After 12 minutes 51,3% of all agents are informed; 98,9% are informed after 30 minutes. An agent's behavior depends on its position as well as its current state (performing an activity or a trip):

- Inside the affected area
 - o Activity: End activity immediately and leave the area as fast as possible.
 - Trip: If the trip's destination is outside the affected area, optimize evacuation route. Otherwise change the trip's destination to the nearest location outside the affected area.
- Outside the affected area
 - Activity: stay at current location.
 - Trip: If the trip's destination is outside the affected area ensure that its route does not cross the affected area. Otherwise change the trip's location to a place outside the affected area.

Additionally, the agents try to continuously optimize their routes during the evacuation. To do so, they use real time traffic flow information from their environment. For the routing decisions, only travel times but no other factors like travel distance are taken into account. All participants of the Zurich city marathon are simulated using the force-based approach. After the evacuation has started, all other pedestrians inside or crossing the affected area are switched to this simulation mode too.

5. Results

Figure 9 shows the evacuation progress. The peak at 09:00 a.m. results from participants of the Zurich city marathon. As shown in Figure 6(b), the runners enter and leave the affected area multiple times during their run. Most of them are on affected parts of the track when they are informed that they have to

evacuate. After approximately 30 minutes all agents are informed. Therefore, as defined in the behavioral model, all agents who performed activities in the affected area have ended them and started to evacuate. One hour after the dam-break 99,5% of all affected people have left the evacuation area, which is 25 minutes before the flood wave reaches the city boarder.

Lämmel *et al.* (2010) report an evacuation duration of approximately 45 minutes for the pedestrian population. This is comparable to our findings since their model optimizes evacuation routes iteratively and also starts the evacuation immediately.



Fig. 9. Evacuation progress

Figures 10 and 11 show pedestrian and vehicular traffic flows between 09:30 and 10:30 a.m. in the evacuation area. A pedestrian agent is represented as a circle, a vehicle as rectangle. The color of a vehicle/person represents its speed relative to the reference speed (red: min, green: max). For vehicles the reference speed is defined by a links allowed speed, for pedestrians a value of 2.0 m/s is taken.

Analyzing pedestrian traffic flows shows that they can leave the affected area without being significantly slowed down by congestion. However, having a look at the traffic flows between 10:00 and 10:30 a.m. shows that the later, the more pedestrians are moving with slow speed (agents colored red). This is caused by the influence of agent's age and gender as well as the steepness of their evacuation routes.

Having a look at the vehicular traffic flows shows that several links outside the affected area that are used as evacuation routes become quite congested. This results in spill-back to the affected area and leads to even more congestion in the city center. Comparing pedestrian and vehicular traffic flows in Figure 9(a) approves this finding: the number of pedestrians in the affected area decreases much faster than those of people traveling by car.



Fig. 10. Pedestrian traffic flows

The experiments employed were run on a computer with two quad core CPUs (each an AMD Opteron 2380) using 16 GB of shared memory. Using all 8 cores, simulation's overall runtime was 3 hours and 15 minutes. Simulation of traffic flows conducted 3~hours, reading input and writing output data took another 15 minutes. Analyzing the simulations computational effort shows that the behavioral model as well as the force-based 2D and the within-day replanning module consume the majority of the computing power (each approximately 30%). The remaining 10% are consumed by the simple multi-modal implementation as well as simulation module for vehicular traffic.



(e) 10:30 a.m. Fig. 11. Vehicular traffic flows

6. Conclusions and Outlook

We explained why there is a growing interest in microscopic large-scale multi-modal evacuation simulations. On one hand, existing models for multi-modal simulations are limited by factors like available computation power and therefore are either large-scaled or microscopic. Moreover, they are in general not able to handle scenarios with exceptional events. On the other hand, evacuation models support multiple transport modes and unexpected events but are designed for small-scale scenarios only.

The proposed framework gives the opportunity to simulate large-scale evacuation scenarios in feasible time by staying highly resolved where needed and being more aggregated where possible. Moreover, the

flexible structure of the underlying within-day replanning module allows to implement modular behavior models which are designed for specific scenarios.

Future steps will include the design and implementation of a flexible behavioral model which models agent's decisions on household level. This will allow us to model the decision making process during an evacuation much more accurately. In combination with the multi-modal simulation, the behavioral model can calculate values like a households speed when evacuating joined by foot, which is limited by the slowest family member.

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