ACUTE EVACUATION

A conceptual strategy to increase ass-evacuation during floods

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ABSTRACT

Mass evacuation has gained interest as a research topic over the last years, both from a transportation perspective as well as from a sociological perspective. Where mass evacuation was ignored as a serious option for decades (in the Netherlands), events like the Tsunami in Asia and hurricane Katrina in New Orleans have shown that evacuation must be considered as a plan B if flood prevention fails. Existing research in the field of mass evacuation has a primary focus on preventive evacuation. A common finding of these studies was that the time available for (total) preventive evacuation was in most cases less than the time needed. This paper discusses the possibilities for acute evacuation. Unlike other evacuation strategies, acute evacuation allows for evacuation after occurrence of and during exposure to a threat. Because of this uncommon characteristic there are several conditions to be fulfilled and some situations should hold for this type of evacuation to be possible as described in the paper. This paper concludes that research into acute evacuation is quite valuable for the authorities concerned with evacuation planning. It will enhance their ability to plan preventive evacuation and improve the allocation of evacuation routes. Besides, it will provide insight into the possibility of extending the total available evacuation time. Finally, it will help the inhabitants of potentially endangered areas to increase their prospects and possibilities of evacuation during unexpectedly and suddenly disasters.

KEYWORDS

Acute evacuation, modelling, strategic planning

INTRODUCTION

Serious disasters can force communities to evacuate to safer areas as can be seen during the resent overflowing of the river Vistula in southern Poland in May 2010. More than 7000 people had to be evacuated while several bridges were closed for traffic making an evacuation even more difficult. This is just one of many recent examples of a large-scale evacuation

forced by a natural disaster, which stresses the need for contingence plans when flood preventive measures are not sufficient or have failed to work. The Dutch government, aware of this need for some years, has initiated and funded several (scientific) projects to investigate the feasibility for mass-evacuation of areas along the cost and the major rivers. This work gained momentum when the catastrophic effects of hurricane Katrina were broadcast all over the world.

One major conclusion is that in most of the cases the time needed for a complete preventive evacuation is more than the time available (Editorial, 2010, Ministry of Internal Affairs, 2008). This conclusion is based mostly on computational evacuation simulations and qualitative research into evacuation management and organisation because the experience in the Netherlands with large-scale evacuation is very limited. By contrast, the United States has a wealth of experience and data about preparing and executing evacuations. Yet, despite this experience and good evacuation plans, even then the available time is mostly less than the time needed, as is illustrated by the number of non-evacuated people of New Orleans numbering between 100,000 and 300,000 (Wolshon, 2006).

The most frequently found reasons for this problem are the short notice time of a hazard, little time for decision making and warning, a short response time, insufficient road network capacity, or insufficient transportation means. Of course, it is mostly not an isolated problem but a mix of circumstances. To solve these problems two main schools of thought can be found in literature. The first is to optimise the (current) evacuation strategies by means of new dynamic modelling techniques to improve destination-route-flow schedules, minimizing evacuation time, or improve route assignment (Chiu et al., 2007, Gao et al., 2007, Mens et al., 2009). By far, the scope of these researches is focused on *preventive evacuation*. The second is to find other evacuation strategies than the 'standard' strategy to 'get as many people as fast as possible out of the threatened area'. Examples are the evacuation of people within the exposed region like *vertical evacuation or shelter* them in safe haven within the effected region (FEMA, 2009, Fijter de, 2007, Wolshon et al., 2005). The consequence of this kind of evacuations, is that it requires a *rescue* operation afterwards in a ravaged area that is likely difficult to reach. Both approaches lack the possibility to make use of the time between the start of a disaster and the moment the effects of a disaster manifest themselves to the evacuees. Even though in most cases this will be impossible, there are situations conceivable in which an evacuation during a disaster is feasible making mass evacuation possible.

The main contribution of this paper is that it proposes a theoretical basis for a new evacuation strategy named *acute evacuation.* This evacuation strategy is in addition to or operating together with other evacuation strategies, in order to increase the total number of evacuated people, making mass-evacuation more feasible. The theory is applicable to different kinds of disasters but in this research it is applied to flooding. Furthermore, the paper introduces a dynamic acute evacuation simulation model. This mathematical model and strategic support tool can be used to examine the feasibility of acute evacuation plans in relation to the degradation of road infrastructure that is under direct threat of a disaster.

This paper is structured as follows. In the first section the background behind acute evacuation is explained followed by a description of the different forms of acute evacuation. A brief discussion of the benefits and usefulness of research into acute evacuation is given in the third section. The explanation of the model framework and a brief application of it will follow to end with some conclusions and remarks.

ACUTE EVACUATION

As mentioned in the introduction, up until now, most of the research into evacuation focused on preventive evacuation although resent research of Pel is taking acute evacuation into account as well (Pel et al., 2009). The objective was mostly to estimate the time required for a preventive evacuation (Doef and Cappendijk, 2006, Gao et al., 2007, Han et al., 2006, Maarseveen et al., 2005) or to optimize and improve the management of evacuation (Chakraborty et al., 2005, Frieser, 2004, Kolen et al., 2007, Wolshon et al., 2001), all in order to improve evacuation plans and to give the authorities more and better information to consider and support their evacuation decision. Authorities are not keen on ordering or initiating an evacuation because of the economical (and political) consequences it will have if, in hindsight, it appears to have been in vain (Nolan, 2005). Therefore, an evacuation is mostly seen as an action of last resort, at the risk of being too late. Given a planning horizon of maximum 1 to 3 days for respectively a coastal or a river scenario at a 60% probability of disaster occurrence the chances to complete a preventive mass-evacuation decreases even more (Ministry of Internal Affairs, 2008). As a consequence, the authorities are left no other choice than to make a priority list in who to evacuate and who not.

Nevertheless, in case of a river flooding there is a possibility to gain some extra time for an area at risk will not flood immediately. According to flood simulation programs it can take three days before an dike ring area in the Netherlands is completely flooded (Alkema, 2003). This means that the effects of such a disaster quite likely do not emerge everywhere in the threatened area at the same time, so most people will have the prospect of evacuation (Meijdam et al., 2008). This suggests that, in a case of a preventive evacuation, the available time can be extended beyond the point of a disaster's occurrence. This kind of evacuation, executed during a disaster or calamity, is called acute evacuation because of the immediacy of its execution. Most reports and discussions found in literature reject this type of evacuation because it is stated that it is impossible to move under disaster conditions. This is true in the case of hurricanes, super storms, and earthquakes, but there are certainly other cases conceivable in which a more or less controlled evacuation is possible during the course of a calamity when the progress of the calamity is relatively slow, e.g. in a river flooding or a lava flow. Weather conditions during this kind of disasters are not necessarily bad as is in case in coastal floods, making it more conceivable that acute evacuation should be considered as a serious option.

A consequence of evacuating during the course of a calamity is that one has to cope with a steady disruption of the road network in the threatened area which will be the effect of a relatively slowly proceeding disaster. Roads will become impassable in time and the number of routes out of the exposed area and hence the possibilities to evacuate will be reduced. This is in contrast with fast occurring disasters, such as earthquakes or hurricanes, during which the road network will get damaged severely in a short period of time. Therefore a planning tool or simulation model for acute evacuation should incorporate road network disruption in the route assignment to prevent traffic flows to or over flooded roads.

Before outlining the benefits and usefulness of acute evacuation a brief description of different forms of acute evacuation is presented.

TYPES OF ACUTE EVACUATION

Acute evacuation can be subdivided into three different types, each with a different timeline (sequence of phases) as presented in figure 1. The first can be described as a *partial acute evacuation*. It is the transition from a preventive evacuation to an acute evacuation because the available time is less than the time needed for a complete preventive evacuation. In this

case, a preventive evacuation is ordered and during this evacuation a disaster strikes. The evacuation is already in progress and a certain number of people will already be out of the area at risk. People that are already on the move in the endangered area, hardly have any other choice but to continue their evacuation. This transition from preventive to acute may happen unexpectedly, due to, for example, miscalculation of the required evacuation time or circumstances that delayed the evacuation, yet it can also be an expected and calculated transition, in case acute evacuation is planned in order to increase the total available
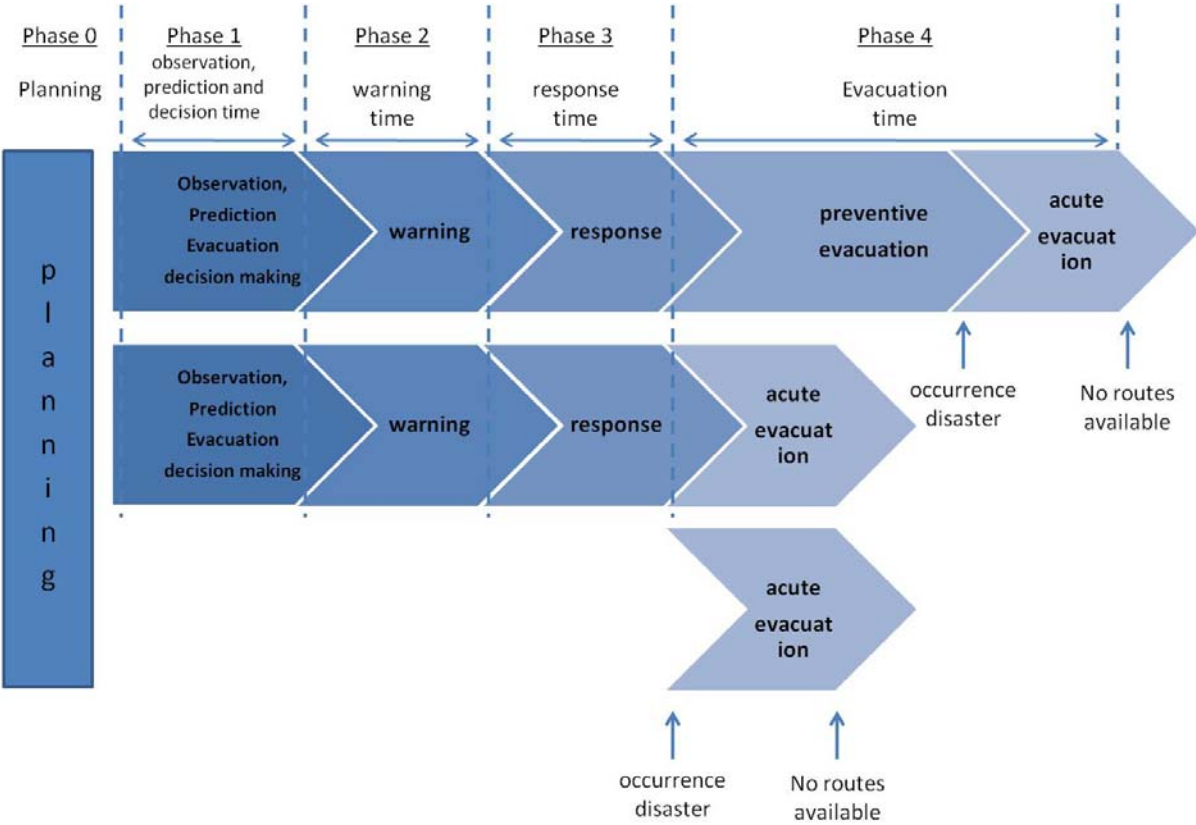

Figure 1: Three forms of acute evacuation. Top: partial acute evacuation, middle: prepared acute evacuation, and bottom: unprepared acute evacuation

evacuation time as will be explained in the next paragraph.

The second situation can be described as a *prepared acute evacuation*. People are aware of the risky situation and of the possibility of a calamity. Preparations for a preventive evacuation are being taken on voluntary or governmental initiative, but the official order for the evacuation is not yet effective at the moment a calamity occurs.

The third situation is different from the previous two by the absence of any form of warning or preparation. The disaster strikes suddenly and unexpectedly due to, for example, a terrorist attack or an accident on a dike. This situation can be denoted as an *unprepared acute evacuation*, and is the worst possible situation for an acute evacuation. In (Chiu et al., 2007) this is known as *no-notice evacuation*.

All three described types of acute evacuation will terminate if one of the following situations is true. Firstly, if everyone who should be evacuated is evacuated. Secondly, if no evacuation routes are available. The latter will occur when all evacuation routes are exposed to the physical effects of a disaster, making any form of evacuation impossible.

BENEFITS OF RESEARCH INTO ACUTE EVACUATION

The benefits and usefulness of acute evacuation can be linked to the three distinguished acute evacuation types.

In case of a partial acute evacuation, the total available evacuation time can possibly be extended when the options for acute evacuation are known; in other words, when it is known which routes will be available and for how long. Furthermore, the connection between a preventive evacuation plan and the possibilities for acute evacuation can be examined. Are designated routes for preventive evacuation linked, do they coincide with routes that are available during a disaster, or will they become impassable shortly after the occurrence? In the latter case, the routes for preventive evacuation are vulnerable. Evacuees will run a higher risk the closer their moment of departure is to the expected start time of the disaster. Having gained this insight, it becomes possible to determine the order of departure for urbanized regions by priority within an area at risk. The total evacuation time can be minimized and evacuation delay can be reduced by phasing an evacuation. Besides, more flexibility in time can be achieved (Chien and Korikanthimath, 2007).

For the other two acute evacuation types, the available time for evacuation is very limited and depends on the duration of accessibility and availability of routes to safer regions. Because of the limited available time, all means should be employed for the movement of people to safer areas. Therefore, it is the authors'-opinion that an acute evacuation, as pointed in the second and third scenario, only has a chance of success if the evacuation process is executed according to a predefined and well-considered plan known by the population, for the time available restricts the possibilities for decision-making, planning and communicating in detail to an absolute minimum. Valuable time will get lost if one has to go through this entire process. The most ideal situation would be if everybody knows, in advance, which route to take to their destinations. This can be achieved, for example, by distributing evacuation leaflets, indicating the route and destination for a set of most conceivable scenarios, as is suggested in the project 'From flood threat to evacuation' (Braak van den and Kolen, 2007). Despite the difficulties in applying such a strategy, it is expected to be the only strategy that maximizes the use of available time for evacuation and takes best advantage of the evacuees' last ability to (re)act. The idea that people in such emergency situations would panic and become irrational, and hence make any plan inoperable, is a frequently-heard fallacy according to a literature survey regarding evacuee behaviour (Helsloot and Scholtens, 2008).

Despite the lack of data and the need for simulations on real networks, the expectation is that for mass-evacuation of heavily urbanized regions, a *partial acute evacuation* is useful and feasible as long as the mentioned conditions are met. The duration of a complete flooding (up to 3 days) and the relative small difference between time available and time needed contribute to this expectation. A *prepared acute evacuation* is only thought to be effective in less urbanized regions in which a complete preventive evacuation is possible. *Unprepared acute evacuation* has the slightest chance to succeed in mass-evacuation situations although it can be effective for small scale evacuations as it is used for pedestrian- and building evacuations.

From the above discussion it can be concluded that research into acute evacuation has added value, mostly for the authorities concerned with evacuation planning. It will enhance their ability in planning preventive evacuation and improve the allocation of evacuation routes. Besides, it will provide insight into the possibility of extending the total available evacuation time. Finally, it will help the inhabitants of potentially endangered areas to increase their prospects and possibilities to evacuate during unexpected and sudden disasters.

MODEL FRAMEWORK

In this section a brief introduction of the core elements of the evacuation model are discussed. For more details and elaboration I would like to refer to (Mevissen and Kant, 2009).

To meet the described benefits as mentioned previously, a model for acute evacuation is considered most effective when used as a strategic planning tool for an evacuation process rather than a forecasting tool. Where a forecasting tool would require implementing realistic traveller behaviour, a planning tool can be limited to finding an optimal flow pattern subject to some basic demand parameters. The aim of the model is to optimize the usage of space and time from the start of the disaster. Following this line of reasoning, the trade-off between simulating 'realistic' behaviour and finding a (more theoretical and therefore less realistic) optimal flow pattern, is made in favour of the latter. The question of how feasible the derived evacuation strategies actually are, is one to be answered in future research. The objective of the modelling framework is to optimize the usage of the available evacuation time, by using the road network as long as possible, in order to maximize the number of evacuated people.

To meet the objective the core element of the framework is to incorporate the disrupting network in the route assignment as stated before. Each failing link (road) will disable a route if the link was part of it. The challenge is to find the Last Moment of Departure (LMD) from each origin using that route. Figure 2 shows the concept using an example for a combination of a failing link (D) on a specific route (A-B-C-D). The Last Trip is determined to establish until what departure time the route is available (the 'offset'). Results from previous runs
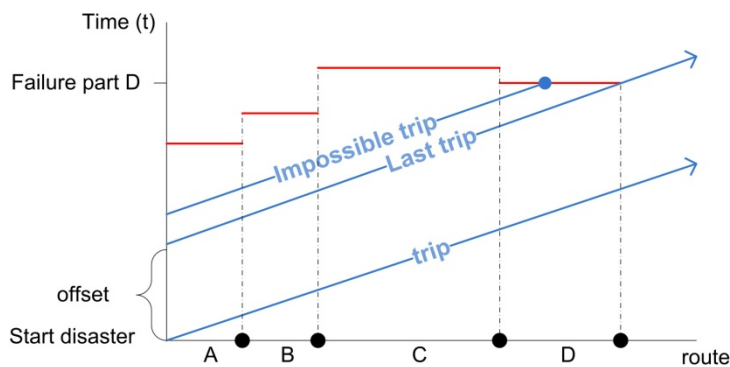

 Figure 2: Determining the last moment of departure for a failing link in a specific route

(although aggregated in blocks of several minutes) are used for this purpose, by developing a backward trajectory for a vehicle entering the failing link at the time of failure.

Once the LMD has been determined for all routes, the framework assigns the travel demand on the network, thereby only using available routes. Since a flooding means that links will fail over time, this leads to a series of network states. A simulation (run) is performed for each network state to calculate the LMD, taking into account the LMD of previous runs.

The model framework determines the optimal routing scheme for all states in a disrupting network. The optimal states are found using dynamic network and dynamic route choice mechanisms in an iterative fashion. The global process includes some preprocessing and a series of simulations for each network state. The entire process is undertaken in the OmniTRANS transport planning software package, using the StreamLine dynamic assignment framework.

Since the model aims for the use as a strategic planning tool to investigate the use of routes as long as possible for an evacuation plan, two principles are applied. The first is to consider the evacuees as a homogenous group, making rational decisions to optimize the individual situation. Secondly, the evacuees possess real time, en-route, and future information on the

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traffic conditions and state of the networks. This principle prevents people from getting confronted with network changes while being en route, hence their number of route alternatives decreasing. Evacuees are expected to make a pre-trip route and destination choice anticipating on upcoming events (link failures, expected congestions), based on a network that will change in time during the evacuation. Although this behaviour of evacuees is unrealistic in real life, it is acceptable for planning purposes to determine the optimal use of evacuation routes.

The first run performed by the simulation framework is a static assignment for each interval. In this way, a first indication is obtained for the travel times on the network, which are needed to apply the route choice model. The static assignment is followed by a dynamic assignment for the reference situation, see Figure 3. In the macroscopic dynamic assignment model, the assignment takes place as a flow of vehicles; therefore, route choice does not take place at the level of the individual traveller, but for a group of travellers. This model framework uses stochastic route choice to assign a group of travellers between the same origin and destination over multiple routes at once. These groups are combined from route choice intervals.

In this situation the optimal routing strategy takes place in an undamaged network. After the reference run a new run will start for every network state in time following the sequence of failing links until no link failure is detected. (loop 1 in figure 3). Appearing congestion is taken into account by executing several iterations within a single run to reach a stable state (loop 2 in figure 3). The first iteration routing scheme for a new run is based on the dynamic network conditions of the last iteration of the previous network state (previous run). This can be done because the disruption of the network is cumulative: once a link has failed, it is unlikely that it becomes available again at a later time during the evacuation. With this routing scheme the LMD is estimated before the start of a new run. During the iterations the LMD is being recalculated based on the newly obtained route travel times. At the end of the simulation the final routing schema is obtained indicating the LMD for all routes, the traffic flows (route choice) over the network and the travel times of all routes over the aggregated simulation time.
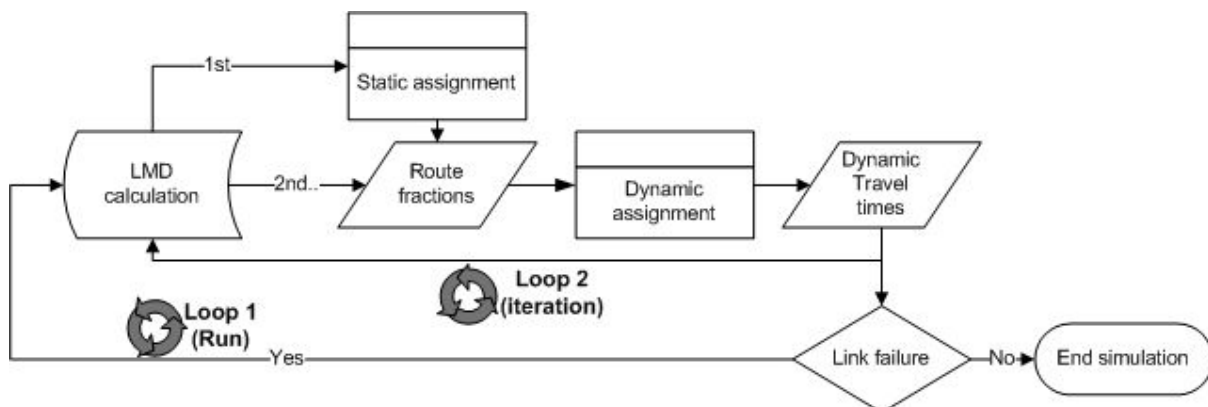

Figure 3: Model framework

NUMERICAL EXAMPLE

This section provides a simple but illustrative example of how the framework could be applied. Figure 4 presents a test network, consisting of three zones and fourteen roads (links). The zones 1 and 2 are the origins (zones of departure) with 3000 inhabitants each. The safe area (destination) is zone 3. The inhabitants of zone 1 have four routes at their disposal: 1:C-D-E-H-I(5), 2: C-D-G-H-I(8), 3: C-F-G-H-I(10), and 4: C-A-B-E-H-I(12). The number

between parentheses represent the free-flow travel time in minutes. Zone number 2 has two routes: 5: J-F-G-H-I(5), and 6: J-K-H-I(8). All link characteristics except the length are equal for all links even though figure 4 supposes otherwise. In the graphical part of the supporting tool, the link length can be changed numerical without having any geometrical influence on
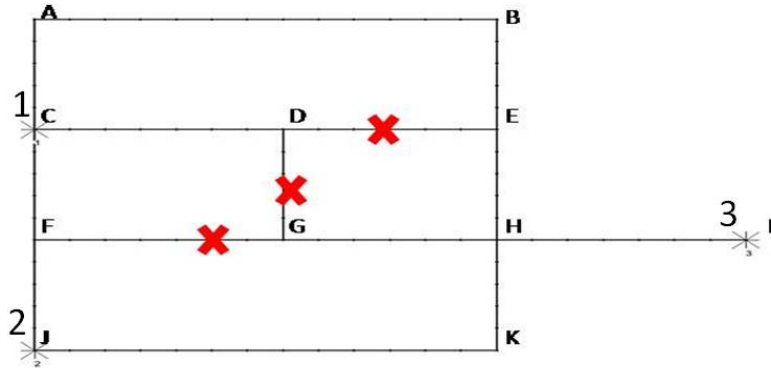

Figure 4: Test network

the graphical presentation. For example: link CF is 6 km while DG is 4 km.

For the simulation, evacuees will depart according to a logistic departure curve with a 100% leave in one and a half hour. For a complete preventive evacuation of this network the *required time* is three hours. In this example, only the *partial acute evacuation,* is demonstrated. Thereto, the *available time* (for preventive evacuation) is set at 30 minutes before a flood starts. After that the links DE, DG and FG will be disabled at 0, 20, and 40 minutes respectively from the start of the flooding. For the simulation timescale this implies a link failure at 30, 50, and 70 minutes from the start. This implies 4 runs (loop); a reference run (undamaged network) and one for each new network state.
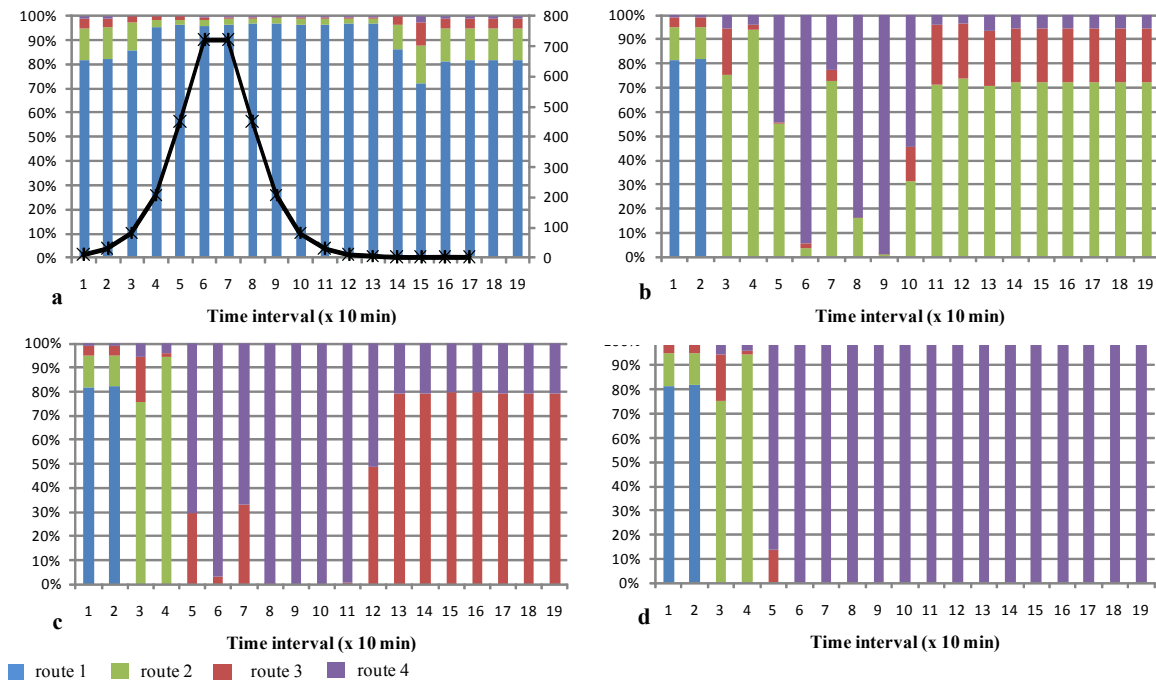

Figure 5: Route assignment for zone 1 with a) reference situation; b) network without link DE; c) network without DE and DG; d) network without link DE, DG, and FG.

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Figure 5 shows the route assignment of each network state for zone 1. Each assignment is visualized in a stacked column. The horizontal axis presents the timeline which is divided into time intervals of 10 minutes. The vertical axis presents the percentage of evacuees (departing in corresponding time interval) choosing a specific route. For example: in the reference situation at time interval 15, 70% of the people leaving from zone 1 at that moment, will take route 1, 15% will take route 2, etc (see figure 5a). In the same figure 5a, the line presents the actual volume of evacuees departing in a time interval which is presented on the right vertical axis. As can concluded from figure 5, there is a clear shift in route choice from the reference situation to the final end state. In the total preventive evacuation scenario (figure 5a) an evident choice for route 1 can be observed. Apparently, the capacity of route 1 is sufficient to satisfy most of the demand. For zone 2 this is route 5 (not shown). A preventive evacuation plan for this network can be based on the results of this simulation. The final situation (figure 5d), however, is completely different. To evacuate everyone without having people confronting with blocked routes en-route, route 1 is only preferred in the first two intervals followed by route 2 in interval 3 and 4, and ending with route 4 (longest route) for the rest of the evacuation. For zone 2 this is route 5 in the first 5 intervals and route 6 afterwards. To understand this final route choice behaviour the intermediate network states must be examined.

Figure 5b is the network state in case link DE fails at 30 minutes after the start of the evacuation. For route 1, which includes this link, the LMD is set to interval 2 (disabling the route from interval 3 and on). Departing in interval 2, the travel time to the end of link DE is less than 5 minutes making it unnecessary to set the LMD earlier. Because route 2 has an overlap with the preferable route 5 for zone 2, the travel times will increase during the peak in the travel demand (i.e. interval 5-8) which results in a switching route choice between route 2 and 4. The same behaviour is seen for zone 2 between route 5 and 6 (not presented in paper). The end of the evacuation flow is steady with a main choice for route 2 (70%).

Figure 5c shows the network state in which both links DE and DG fail, affecting mostly zone 1. The LMD for route 2 is determined to interval 4, leaving only two options for zone 1 to reach zone 3, namely route 3 and 4. Although route 3 is shorter than route 4, most evacuees choose route 4 because route 3 has, like route 2, an overlap with route 5 (F-G-H-I). This creates a similar situation as in the previous run. Again, the tail of the evacuation is on the route with the least cost being route 3.

Now, we return to the last network situation (figure 5d). The last failing link FG disables route 3 and 5, which is the first failing route for zone 2. Here we can see a difference in the LMD between two routes. Link FG gets disabled after 70 minutes from the start (interval 7). The LMD for route 5 is interval 6. Although the total route travel time at that moment is two times the free flow travel time, approximately 10 minutes, the end of link FG can be reached in time. However, the LMD of route 3 is calculated one interval earlier, (interval 5). Because link CF is six times the length of FJ the travel time over that link is longer, being 15,5 minutes in interval 5. This implies that leaving in interval 5 over route 3 it will take two time intervals to pass the end of link FG instead of one interval as is the case for evacuees over route 5. After interval 6 both zones have no other option than to take the only routes left, which are routes 4 and 6.

From the example above we can derive a number of conclusions. One of the main conclusions is that acute evacuation is an option even if there is a very short available preventive evacuation time. Despite the successive failure of three links in the network which disables 4 out of 6 routes, the evacuation can proceed as long as the LMD of each route is taken into account. Of course the environmental circumstances in this example are such that real congestion and complete disconnection did not occur but these first results are still encouraging to test the model on a real network together with accurate flood scenarios.

CONCLUDING REMARKS

In this paper we presented a new evacuation strategy named *acute evacuation.* An evacuation whose main characteristic is that it is executed during 'slow' proceeding disasters such as floodings. This evacuation strategy should contribute to and operates in connection with other evacuation strategies like preventive evacuation in order to increase the total number of evacuated people, making mass-evacuation more feasible and hopefully successful. The main contributions of this paper is that it presented the theoretical background of acute evacuation together with a dynamic simulation model to be used as a strategic planning tool for investigating the feasibility of acute evacuation.

Despite its simplicity, the numerical example presented at the end of this paper offers a good impression of the working of the model and the theory of acute evacuation. From the example we can learn that preventive evacuation plans can fail if the disaster effects on the road infrastructure are not taken into account. Secondly it shows that acute evacuation is an option even if there is a very short available preventive evacuation time. With this proposed framework evacuation planners can calculate the LMD for evacuation routes in advance. By implementing the derived routing scheme into an evacuation strategy the emergency services can direct the traffic to the right routes at the right time and most importantly close routes in time even when the flood has not occurred. Yet, directing and coordinating an evacuation properly is a problem and a research in itself. For real application the model must be tested on real networks together with accurate flood scenarios, but its first results are encouraging.

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