First International Conference on Evacuation Modeling and Management

Analysis of Near-Optimal Evacuation Instructions

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Abstract

In this paper, approximations of optimal evacuation instructions are analyzed. The instructions, consisting of a departure time, a destination, and a route, are for the evacuation by car of a population of a region threatened by a hazard. An optimization method presented in earlier research is applied on three different hazard scenarios resulting in an instruction set for each scenario. These instruction sets are different because of network degeneration caused by the different hazard scenarios. Analysis of the network occupancy during the evacuations as consequence of the instruction sets shows that the capacity is used in the scenarios for minimal 87%, 90%, and 87% for the period wherein the effect of the network degeneration is relatively small. Although the results are logical, no clear patterns are perceptible in the instructions leading to this network occupancy. This endorses to the viewpoint from the earlier paper, namely, that it is useful to apply an optimization method to create evacuation instructions instead of applying instructions set up by straightforward rules (like evacuating to the nearest destination). Furthermore, it shows the efficiency of this specific optimization method.

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Evacuation; Instructions; Optimization.

1. Introduction

Natural disasters, like bush fires and floods, cause many casualties. To avoid this as much as possible, authorities have to be prepared for such disasters. This preparation includes creating a plan to evacuate people from a threatened region. During an evacuation, all people involved have to leave the region over the roads still accessible. They make decisions about their departure times (including the decision to evacuate or not), routes and destinations. Without any interventions, the decisions people make are most probably not system-optimal, partly caused by a disposal of information. Giving optimal evacuation instructions to the people can rectify this and can thus lead to a more efficient evacuation.

In [4] a method is presented to optimize evacuation instructions for an arbitrary region threatened by a hazard. The method is a heuristic, thus application of the method results in an approximation of the optimal evacuation instructions, called near-optimal instruction set. In the method, departure time, destination, and route instructions are
simultaneously optimized for a dynamic evacuation problem. This is not the only method to optimize evacuation instructions, others heuristic methods are for example [6] and [10] (optimization of routes), [8] (optimization of destinations), and [9] and [1] (optimization of departure times, destinations and routes). A heuristic leads most probably not to the optimal solution, but to a solution which performance approaches the optimal performance. If a method to optimize evacuation instructions indeed leads to a performance close to the optimal performance, this is an indication of the appropriateness of the specific method to generate evacuation instructions. However, information about this near-optimality is lacking in all papers mentioned in this paragraph. In this paper, the near-optimality of the instructions created by applying the method presented in [4] is investigated.

A first indication of the high efficiency of the near-optimal instruction set is found in the case study in [4]. The study shows a high efficiency of these instructions compared to an instruction set created by straightforward rules (evacuating to the nearest destination, following the shortest free flow route, and departing in such a way that no congestion occurs, where evacuees nearest by their destination are evacuated first). When applying the near-optimal instruction set, 68% of the evacuees reach a destination, compared to 27% when the instructions set up by simple rules are applied. Thus, using an optimization method seems to be useful to create a set of evacuation instructions.

So far, it is unknown how far an instruction set determined by the optimization method approaches the optimal instruction set. However, because of the NP-hardness of the problem (see [3]), optimal solutions are not known. Therefore, a comparison between the near-optimal instruction set and the optimal instruction set is impossible. In this paper, the efficiency of the near-optimal instruction set is researched in a different way. The optimization method is applied for different scenarios and the use of the network capacity by applying the near-optimal instruction sets is analyzed. In the optimal case, the network capacity would be used as far as possible. This possibility depends on the network degeneration caused by the hazard and the demand pattern. The second point which is researched in this paper is the structure of the near-optimal instruction sets. In other papers, this is not discussed or the optimization methods are restricted and the results are thus not comparable. Obviously, the near-optimal instruction set is more efficient than the instruction set created by straightforward rules as mentioned in the previous paragraph. Maybe the near-optimal instruction sets show other patterns. When such patterns exist, efficient evacuation instructions could be easily created based on these patterns instead of using the optimization method. Before the analysis of the efficiency and the structure of the near-optimal instruction sets, a summary of the optimization method is given.

2. Summary optimization method

In this section, a summary of the optimization method is given, see [4] for the details of the method. The optimization method leads to a set of departure time, destination, and route instructions for people in a region threatened by a hazard. The method consists of two steps: 1) the generation of elements and 2) the algorithm. The elements generated in the first step are combinations of departure times and routes (indirectly implying origins and destinations). In each iteration of the second step, evacuation instructions are constructed by assigning each group of evacuees to an element. The evacuees are assumed to be divided into groups, where all evacuees in a group get the same evacuation instruction. This division automatically restricts the optimality of the solutions. Namely, in the optimal case it could be that each evacuee receives another instruction, for example to promote the spread of the evacuees over the network. However, this is not achievable for practical reasons. Firstly, the evacuation instructions have to be practically applicable for the authority, which is probably not the case for individually instructions. Secondly, the optimization method has to be applicable. When individual instructions are to be optimized, this would cost too much computation time and memory.

2.1. Generation of elements

The generation of elements is the creation of a selection of all possible combinations of routes and departure times, to contribute to the applicability of the optimization method (related to the computation time) and the practical applicability of the evacuation instructions following on the application (related to the number of different instructions). This generation of elements is performed once: the elements generated in this step are used for all iterations of the algorithm. The selection includes the following steps: 1) a fixed period between the departure times is determined resulting in a set of departure times 2) a restricted number of routes from all origins to one or more
destinations is selected with relatively low free flow travel times and with restricted overlap 3) possible combinations of departure times and routes are determined depending on the degeneration of the infrastructure caused by the hazard: combinations are labeled as possible if a destination can be reached when departing on the instructed departure time and following the instructed route under the condition of free flow travel time.

2.2. Algorithm

The structure of the algorithm is equal to the structure of a so-called ant colony optimization method (see [2]), an algorithm to solve numerical problems which is based on the behavior of ants. Each iteration contains a construction phase and an update of so-called pheromone trails, see Fig. 1.

In the construction phase all ‘ants’ in a colony create an instruction set. Each set contains a departure time, route and destination instruction for each group of evacuees. For each group, an element is selected by using a selection probability based on so-called problem-dependent information and pheromone trails. Problem-dependent information is constant for all iterations and gives elements which are expected to have a positive influence on the evacuation a relative high selection probability. These are elements with relative low free flow travel times and elements with relative early departure times. Pheromone trails are not constant: they give elements of good solutions of earlier iterations a relative high probability for selection in later iterations. The construction phase results in a number of instruction sets equal to the number of ants in the colony.

During the update of the pheromone trails the fitness of each instruction set follows on application of an evacuation simulation model and an optimization objective function. Based on the global-best instruction set (the best of all iteration-best sets) the values of the pheromone trails are updated, whereby the trails of elements included in the global-best instruction set are raised.

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Fig. 1 Algorithm of the optimization method
3. Case study

The optimization method (implemented in Matlab) is applied to hypothetical floods of Walcheren, a peninsula in the southwest of the Netherlands. Over 120,000 people on an area of 216 squared kilometers have to be evacuated by car, where the number of evacuees per vehicle is assumed to be equal to 2.5. Different flood scenarios are tested; called Scenario Northwest, Scenario West, and Scenario South, referring to the starting points of the floods (see Fig. 2). Walcheren is flooded in each scenario in four hours. Each evacuation is assumed to start two hours before the flood, by which the time available to evacuate is equal to six hours. First the approach of the application of the optimization method is explained and then the results are analyzed.

Fig. 2 Flood scenarios for Walcheren: Scenario Northwest, Scenario West and Scenario South. The network consists of 23 origins (A-W), 4 destinations (1-4), other nodes and 158 links. The capacity of the links varies between 1800 and 12000 veh/hour. The larger the visualization of the origin is, the higher the population of the origin (varying between 502 and 17,482 residents).

3.1. Approach of the application of the optimization method

To apply the optimization method, an evacuation simulation model and an optimization objective are needed, as explained in Section 2.2.

The traffic flows are simulated using the evacuation simulation model EVAQ, presented in [9]. This model contains the dynamic travel demand (evacuation and departure time choice), the en-route travel choice behaviour (destination and route choice) and dynamic network loading with queuing and spill-back (propagation of the traffic flows through the network). The network degeneration caused by a hazard is included in the model.
The applied optimization objective is the objective presented in [4], wherein a function of the number of arrived evacuees for each time period is maximized, where early arrived evacuees are higher appreciated than later arrived evacuees. The performance of a set of instructions, \( f_E \), is determined by the following objective function:

\[
f_E = \sum_{t=1}^{T} \exp(-\beta t) \cdot q_E(t)
\]

(1)

where \( q_E(t) \) is the number of evacuees reaching a safe destination in time period \( t \), depending on assignment \( E \), \( T \) is the time period with the latest arrivals and \( \beta \) is a weighting parameter with \( \beta \geq 0 \). This parameter makes the function generic; when \( \beta = 0 \), the optimization objective is equal to maximizing the number of arrived evacuees. When the value of \( \beta \) is higher, the importance of early arrivals is increased. For the applications presented in this paper, the value of \( \beta \) is set to 0.1. It should be noticed that while the instructions are optimized based on the objective presented in this section, the near-optimality is analyzed based on the use of the network capacity (as described in Section 1).

For both the optimization method and the optimization objective, values are set for the parameters. The values are for completeness given in Table 1. The network dealt with in the case study contains 5 origins with a population bigger than the group size (10,000), and 18 origins with a population smaller than the group size. Thus, the residents of the latest mention group do all get the same route and destination instruction, while there can be two different instructions for the residents of the other origins. This paper focuses on the analysis of the results; therefore the influence of the values of the parameters on the functioning of the method and objective are not analyzed here. Information about the parameters can be found in [4].

**Table 1.** Values for the parameters in the optimization method and the optimization objective

<table>
<thead>
<tr>
<th>Parameter in the optimization method</th>
<th>Symbol</th>
<th>Explanation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation of elements</td>
<td>( \Delta k )</td>
<td>Fixed period between the departure times</td>
<td>0.5 hours</td>
</tr>
<tr>
<td></td>
<td>( N_{\text{routes}} )</td>
<td>Maximum number of routes combined with a departure time</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>( G )</td>
<td>Factor to prevent the selection of routes with too high travel times</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>( G )</td>
<td>Group size</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>( \zeta )</td>
<td>Factor to prevent the selection of routes with too high overlap</td>
<td>0.8</td>
</tr>
<tr>
<td>Algorithm</td>
<td>( \zeta )</td>
<td>Weighting parameter to influence the dependency of the problem-dependent information on travel times of the routes</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>( \zeta )</td>
<td>Weighting parameter to influence the dependency of the problem-dependent information on departure times</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>( \chi )</td>
<td>Size ant colony</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>( \chi )</td>
<td>Parameter to influence exploration and concentration of the search process</td>
<td>0.98</td>
</tr>
<tr>
<td>Parameter in the objective function</td>
<td>( \beta )</td>
<td>Parameter to set the importance of early arrivals</td>
<td>0.1</td>
</tr>
</tbody>
</table>

### 3.2 Analysis use of network capacity

For each scenario a near-optimal instruction set is determined. The use of the network capacity for the application of these instructions is researched. During the evacuation, this capacity can not be entirely used because of the
already mentioned network degeneration and the demand pattern. For the optimal evacuation, the resulting capacity is totally used. Deviations are possible because of the also already mentioned group instructions instead of individual instructions and because of the use of a heuristic.

The network capacity is not known exactly, but an upper bound on the capacity is known, based on the capacities of the bottlenecks to each destination. The links directly upstream of the destinations 1, 2, 3, and 4 (see Figure 2) have capacities of respectively 2,000, 4,400, 2,000, and 2,000 vehicles per hour. However, the links directly upstream of the destinations 2 and 3 have the same upstream link with capacity 4,400, limiting the combined capacity of link 2 and 3 to 4,400 vehicles per hour. Furthermore, 4,790 evacuees from origin B (see Figure 2) can travel to destination 2 and 3 without making use of the mentioned upstream link. Combining this information, the network capacity is bounded from above by 8,400 vehicles or 21,000 evacuees per hour and 1,916 vehicles or 4,790 evacuees over the whole evacuation. Since the use of the network capacity is evaluated based on the capacities of the links directly upstream of the destinations, there is another cause for the deviation from the entire use of the capacity: during the start of the evacuation there is no possibility of arrivals because of the travel time over the network.

The near-optimal instruction sets are different and so are the arrival patterns of the corresponding evacuations. Table 2 shows that 23%, 14%, and 29% of the evacuees do not reach a destination (given the total number of evacuees of 121,838) for respectively the scenarios Northwest, West and South. For each scenario, only part of the residents in each origin I, J, K, and S reaches a destination. A possible explanation is the large population in these origins (at least 15,000 people for each origin).

Table 2. The numbers of not in time evacuated people during the evacuations for the scenarios, specified per origin.

<table>
<thead>
<tr>
<th>Origin</th>
<th># People belonging to the origin</th>
<th>Scenario Northwest</th>
<th>Scenario West</th>
<th>Scenario South</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>904</td>
<td>-</td>
<td>-</td>
<td>654</td>
</tr>
<tr>
<td>G</td>
<td>3,508</td>
<td>1,738</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>17,310</td>
<td>9,238</td>
<td>8,001</td>
<td>12,632</td>
</tr>
<tr>
<td>J</td>
<td>15,000</td>
<td>6,372</td>
<td>102</td>
<td>865</td>
</tr>
<tr>
<td>K</td>
<td>15,000</td>
<td>160</td>
<td>2,808</td>
<td>148</td>
</tr>
<tr>
<td>M</td>
<td>2,540</td>
<td>-</td>
<td>-</td>
<td>892</td>
</tr>
<tr>
<td>S</td>
<td>17,482</td>
<td>8,114</td>
<td>6,495</td>
<td>13,131</td>
</tr>
<tr>
<td>T</td>
<td>17,482</td>
<td>-</td>
<td>-</td>
<td>7,230</td>
</tr>
<tr>
<td>V</td>
<td>2,638</td>
<td>451</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W</td>
<td>1,523</td>
<td>1,499</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Total # not in time evacuated people | 27,573 | 17,406 | 35,552 |

Based on a maximum capacity over the first four hours of the evacuation equal to 88,790 evacuees, the difference between the outflow and the outflow under network capacity is maximum 13%, 10%, and 13% for respectively the scenarios Northwest, West, and South over this period. The arrival rates given in Fig. 3 are quite similar for the first four hours of the simulation, indicating a fixed arrival rate which can be reached under the evacuation scenarios, which is a part of the network capacity because of the reasons mentioned before.

During the last two hours, the arrival patterns for all scenarios differ and the arrival rates are not constant. The reason for the difference in arrival rate during the last two hours is the degeneration of the network caused by the hazard scenarios from the beginning of the third hour until the end of the evacuation. Since the hazard scenarios are different, the arrival patterns during the last two hours are also different.
Fig. 3. Arrival rates of the evacuations as consequence of the application of the near-optimal instruction sets for the scenarios Northwest, West, and South.

The use of the network capacity is further studied by analyzing the arrival rates for all destinations separately, see Fig. 4, 5, and 6. In the figures, the arrival rate are shown, which can be compared with the capacity of the links directly upstream of the destinations, equal to 2,000, 4,400, 2,000, and 2,000 veh/hour for respectively destination 1, 2, 3, and 4. If the arrival rate is equal to the capacity of the upstream link, the capacity of the link is completely used (the density on the link is then equal to the critical density). The figures show: 1) the arrival rate equals the capacity of the link directly upstream of the destination, for all destinations and for all scenarios during a large part of the evacuation, 2) the logical absence of arrivals during the start of the evacuation, 3) gaps in the arrival rates, 4) “shared” use of the links directly upstream of the destinations 2 and 3, 5) both concentrated and spread arrivals by evacuees of one origin, and 6) different moments on which the arrivals end for the different links and scenarios.

The absence of arrivals during the start of the evacuation is caused by the travel time over the network as already explained. Besides this gap, the arrival rate equals the capacity on the link directly upstream of destination 1 during the whole period that evacuees are present on the network for each scenario (see Fig. 4a., 5a., and 6a.). Of course, in the end the arrival rate decreases to zero. For the destinations 2 and 3 more gaps in the arrival rates are perceptible (see Fig. 4bc., 5bc., and 6bc.). For Scenario Northwest, all gaps are explained by the shared use of the link capacities (the actual capacity of the links leading to destination 2 and 3 is lower than the sum of both link capacities as explained earlier in this section, therefore the capacity of these links is “shared”). For the scenarios West and South, this holds for part of the gaps. Some (parts of the) gaps are caused by other reasons. It could indicate a non-optimality (caused by applying an approximation optimization method), but also it could be that these gaps are inevitable because reasons mentioned before (related to the network degeneration and the demand pattern). The gaps in the arrival rate for destination 4 (see Fig. 4d., 5d., and 6d.) are caused by the same reasons. Sometimes, the evacuees of an origin use a link concentrated (i.e. evacuees originated in R for Scenario West, see Fig. 5b.), but also spreading is perceptible (i.e. evacuees originated in J for Scenario West, see Fig. 5b.). Based on these patterns, both spreading and concentrating seems to lead to optimality. The variability in the latest moment of arrival is caused by the hazard pattern, which causes network degeneration. The hazard strikes both the links directly upstream of the destinations and the other links, origins, and intermediate nodes. Caused by this network degeneration, the links directly upstream of the destinations can not be used during the whole 6 hour evacuation period.

To conclude, the network capacity is used in the scenarios Northwest, West, and South during the first four hours of the evacuation for respectively minimal 87%, 90%, and 87%. Part of the deviation from the full use of the capacity is caused by the inability for evacuees to reach the destination during the start of the evacuation. Also, during the last hours of the evacuation, full use of the network capacity is impossible because of network degeneration caused by the hazard. Further, it is probable that part of the deviation is caused by the structure of the optimization method, wherein departure times are instructed to groups of evacuees rather than giving individual instructions. However, this structure is needed to design an applicable optimization method. Of course, it is likely that part of the deviation could be a non-optimality, caused by the application of an approximation optimization method. However, the utilization of the capacity together with the mentioned reasons for deviation from the full use of capacity indicates a good approximation of the optimal use of capacity.
Fig. 4. Arrival rates Scenario Northwest, for destination a. 1, b. 2, c. 3, and d. 4. The letters are the origins of the evacuees.
Fig. 5. Arrival rates Scenario West, for destination a. 1, b. 2, c. 3, and d. 4. The letters are the origins of the evacuees.
Fig. 6. Arrival rates Scenario South, for destination a. 1, b. 2, c. 3, and d. 4. The letters are the origins of the evacuees.
3.2. Analysis evacuation instructions

After analyzing the network occupancy, in this section the instruction sets themselves are analyzed. The approximations of the optimal instruction sets are visualized in Fig. 7. This figure indicates the early and late departure times, the links which are used by instructing the routes and the number of people assigned to the destinations. The departure times, routes and destinations are analyzed.

Starting with the departure times, Fig. 8 shows the departure times against the latest moment to depart whereby the evacuees can reach one of the destinations (given the network degeneration). A relation is visible for Scenario South: almost all the people belonging to an origin which evacuation possibilities are limited to the first three hours are assigned to an instruction containing departure times 0 and 0.5, while almost all the people whose origin can be reached also after the first three hours are assigned to a departure time higher than or equal to 1. Since this relation does not hold for the other scenarios, this seems not to be a general pattern.

The percentages of people assigned to the shortest free flow routes are equal to 36%, 35% and 33% for respectively Scenario North West, Scenario West, and Scenario South. The shortest free flow route is an attractive route because this route results in the shortest travel time under free flow conditions. However, it seems to be more efficient to spread the evacuees over the network than to assign all the evacuees to the shortest free flow route. Fig. 7 shows that some links are not used for each scenario. One of these links would lead to relative long routes compared to the links around the unused link, which can be a reason that using this link is not optimal.

The percentages of people assigned to the nearest destination (based on the shortest free flow route) are equal to 55%, 56%, and 60% for respectively Scenario North West, Scenario West, and Scenario South. This corresponds to the assignment of people to the shortest route: it is attractive to assign people to the nearest destination but it seems to be optimal to spread the people over this and other destinations. Table 3 shows that for each scenario most people are assigned to destination 2, following by destination 4, 1, and 3. This can be explained by the fact that the links directly upstream of the destinations 2, 3, and 4 are struck by the hazard on approximately the same moment for all scenarios. The link directly upstream of destination 1 in Scenario Northwest is flooded after 3.5 hours, and in the other scenarios after almost 6 hours. This difference is visible in the assignment of evacuees: the table shows that circa 17,000 people are assigned to destination 1 for Scenario Northwest compared to circa 30,000 to the other destinations. Thus, less people are assigned to a destination when the hazard strikes the link directly upstream of the destination earlier. This property is obvious: when a link directly upstream of a destination is flooded earlier, the outflow capacity of the link is lower.

To conclude, the instruction sets have some expected properties like the assignment of part of the evacuees to the nearest destination and the shortest free flow route. However, no patterns are visible over all instructions explaining the optimality of the instructions. It is clearly not optimal to assign all evacuees with the instruction to take the shortest route to the closest destination. In sum, optimal evacuation instructions appear to have a complex structure, which cannot be captured in simple decision rules.
a. Scenario Northwest

b. Scenario West
Fig. 7. Visualization of the near-optimal instruction set for Scenario Northwest (a.), West (b.), and South (c.). The hazard pattern is given (the areas which are flooded after 2, 3, 4, 5, and 6 hours of evacuation). The links do not indicate their direction. The letters on the links are the origins of the evacuees using the link.
Fig. 8. Instructed departure time for each evacuee for the moment that the hazard strikes the origin of the evacuee.

Table 3. The numbers of people instructed to follow destination 1, 2, 3, or 4 and the arrived percentage.

<table>
<thead>
<tr>
<th>Destination</th>
<th>Scenario Northwest</th>
<th>Scenario West</th>
<th>Scenario South</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17,237 (90%)</td>
<td>31,351 (81%)</td>
<td>29,280 (85%)</td>
</tr>
<tr>
<td>2</td>
<td>58,696 (88%)</td>
<td>51,092 (96%)</td>
<td>54,686 (67%)</td>
</tr>
<tr>
<td>3</td>
<td>11,300 (18%)</td>
<td>4,790 (100%)</td>
<td>4,790 (100%)</td>
</tr>
<tr>
<td>4</td>
<td>34,605 (72%)</td>
<td>34,605 (73%)</td>
<td>33,082 (60%)</td>
</tr>
</tbody>
</table>

4 Conclusion

In this paper the effectiveness of near-optimal instructions is investigated. Instruction sets optimized for three different cases lead to an evacuation wherein minimal 87% to 90% of the capacity is used (for the period wherein the effect of the network degeneration is relatively small). Besides this small network degeneration effect, part of the deviation from the full use of the capacity is caused by the inability for evacuees to reach the destination during the
start of the evacuation. Further, it is probable that part of the deviation is caused by the structure of the optimization method, wherein departure times are instructed to groups of evacuees rather than giving individual instructions. Finally, it is likely that part of the deviation could be a non-optimality, caused by the application of an approximation optimization method. However, the utilization of the capacity together with the mentioned reasons for deviation from the full use of capacity indicates a good approximation of the optimal use of capacity.

The optimized instructions themselves are also analyzed. Some expected properties are found like the assignment of part of the evacuees to the nearest destination and the shortest free flow route. However, no patterns are visible over all instructions explaining the optimality of the instructions. It is clearly not optimal to assign all evacuees with the instruction to take the shortest route to the closest destination. In sum, optimal evacuation instructions appear to have a complex structure, which cannot be captured in simple decision rules.

The complex structure of the instruction sets shows the need of applying an optimization method to create evacuation instructions instead of setting up instructions by straightforward rules (like evacuating to the nearest destination) as assumed in earlier work. Further, the utilization of the capacity also shows the efficiency of the specific optimization method applied in this paper and presented in [4].

**Acknowledgments:** This work was supported by ITS Edulab, a cooperation between Rijkswaterstaat Centre for Transport and Navigation and Delft University of Technology.

**References**