12th IFAC Symposium on Transportation Systems
Redondo Beach, CA, USA, September 2-4, 2009

A Generic Method to Optimize Instructions for the Control of Evacuations

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Abstract: A method is described to develop a set of optimal instructions to evacuate by car the population of a region threatened by a hazard. By giving these instructions to the evacuees, traffic conditions and therefore the evacuation efficiency can be optimized. The instructions, containing a departure time, a destination, and a route, are created using an optimization method based on ant colony optimization. Iteratively is searched for an approximation of the optimal evacuation instructions. The usefulness of the optimization method compared to other optimization methods is the simultaneous optimization of the departure time, destination, and route instructions instead of the optimization of only one or two of these variables for a dynamic instead of static evacuation problem. In a case study, the functioning of the method is illustrated. The relative high fitness in the case study of the set of instructions following from the optimization method compared with the fitness of a set of instructions set up by straightforward rules (like evacuating to the nearest destination) shows also the usefulness of applying an optimization method to create a set of evacuation instructions.

Keywords: Evacuation, Instructions, Control, Optimization, Ant Colony Optimization

1. INTRODUCTION

Natural disasters, like bush fires and floods, cause many casualties. In the last decade there have been between 17,000 and 240,000 casualties each year (Knight, 2008). In some cases, it is possible to avoid these disasters by taking preventive measures. However, this is not always the most cost efficient way of dealing with the threat (Lave et al., 1990). It can be more efficient to accept the risk of a hazard. Then, if a region is really threatened by a hazard, the population has to be evacuated.

During the 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 giving instructions to people, the decisions people make are most probably not system optimal for the following reasons: 1) people are not fully informed and 2) people act out of a user, instead of a system optimal thinking. Giving evacuation instructions can rectify the disposal of information. In this paper, a method is described to develop a set of optimal evacuation instructions, named an evacuation scheme, to control an evacuation by car. Only when people exactly follow these instructions, they will act out of a system instead of a user optimal thinking. Theoretically, giving mandatory instructions can do this. However, in practice it is very likely that some people will deviate from these instructions. To obtain a realistic view on how the evacuation evolves, also the effect of recommended evacuation instructions (allowing for deviation from the instructions) is analysed in this paper.

In the method described in this paper, the instructed departure times, routes, and destinations are simultaneously optimized. The method is generic, which means that the method can be applied for an arbitrary region and hazard. It is also possible to combine the optimization method with an arbitrary optimization objective and simulation model. Many optimization methods for evacuation instructions have been developed before, most of them only optimizing the departure time, or route, or destination, or just two of these parameters (e.g., see Liu et al., 2006; Miller-Hooks and Sorrel, 2008). Optimizing all parameters is done before e.g. by Chiu et al. (2007) for a simplified problem wherein travel times and capacities are assumed as static values, contrary to the method described in this paper.

2. PROBLEM DESCRIPTION

Let B denote the total number of people to be evacuated in a threatened region. This region contains origins $r \in R$, with corresponding residents, B_r. These residents have to be evacuated via a network which is assumed to be totally accessible before the hazard strikes the network and to become partly accessible when the hazard has struck parts of the network. The problem is to create an optimal evacuation scheme, E, containing evacuation instructions $e \in E$. Each instruction contains a departure time, route and destination, which are simultaneously optimized. The destination instruction is included in the route instruction. Hereby each instruction only contains a departure time, k_e, and a route p_e. Therefore, all destinations are connected with an artificial super destination, with links having a length equal to zero and infinite capacity, as applied e.g. by Chiu et al. (2007).

The evacuees are assumed to be divided into groups $g \in G$, where all evacuees in a group get the same evacuation instruction. Each group belongs to a specific origin, and the number of evacuees in group g is denoted by B_r^g. The number of evacuees in each group is equal to a constant group size, B^{constant}, except a possible rest group for each origin when B_r is no multiple of B^{constant}. By varying the group size, the applicability of the optimization method (related to the computation time) and the feasibility of the evacuation scheme following on the application (related to the number of different instructions) are influenced.

3. APPROACH

To solve the evacuation problem, a heuristic is applied to find an approximation of the optimal evacuation scheme. Developing a method that finds the optimal solution in an efficient way is impossible because of the NP-hardness of the problem (see Huibregtse, 2008). The proposed optimization method is based on ant colony optimization (ACO), a construction algorithm developed by Dorigo et al (1996). The structure of ACO is used and in this paper adapted for the evacuation problem. The optimization method is described in Section 4. In this section the applied optimization objective and simulation model are discussed. Other optimization objectives and simulation models can also be used in the optimization method, but the chosen objective and model have some advantages above others which are also discussed in this section.

3.1 Optimization objective

To compare the performance of different evacuation schemes an optimization objective is needed. An objective is applied dealing with uncertainties in a hazard that may strike a region, i.e., uncertainties in the time period the hazard strikes the region and the location of the hazard, see Franklin (2008). This is contrary to optimization objectives proposed in other studies that do not deal with these uncertainties (assuming that all people can be evacuated in time or that the available evacuation time is exactly known prior to an evacuation).

The optimization objective is to maximize a function of the number of arrived evacuees for each time period, where early arrived evacuees can be higher appreciated than later arrived evacuees. As there is a risk of not being able to evacuate everyone, it is preferred to evacuate people earlier than later. This is represented in the fitness of an evacuation scheme:

$$f_E = \sum_{t>0} \exp(-\beta t) q_E(t) \tag{1}$$

where $q_E(t)$ is the number of evacuees reaching their destination in time period t, depending on evacuation scheme E, and β 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 arrived evacuees. When the value of β is higher, the importance of early arrivals is increased. Because β is multiplied with t, the appropriateness of the value for β is influenced by the total evacuation time. Therefore, by determining β, a global estimation of this time can be helpful. An appropriate estimation is the duration of an evacuation without instructions (a voluntary evacuation). The objective of the optimization is to maximize (1):

$$\{k_e, p_e : e \in E\} = \underset{k_e \in K^{\text{pos}}, p_e \in P^{\text{pos}}}{\arg\max} f_E \tag{2}$$

where K^{pos} and P^{pos} respectively are the set of all possible departure times and the set of all possible routes.

3.2 Evacuation simulation model

The traffic flows resulting from an evacuation scheme are simulated using the evacuation simulation model EVAQ developed by Pel et al. (2008). 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 (propagation of the traffic flows through the network). The use of EVAQ makes it possible to analyse both mandatory and recommended evacuations. Advantages of using EVAQ compared to other evacuation simulation models are the inclusion of more detailed behavioural aspects of the evacuees and the effects of a hazard on the infrastructure. EVAQ can also be used to determine the duration of a voluntary evacuation needed for the objective function.

4. OPTIMIZATION METHOD

The optimization method consists of 1) the generation of elements and 2) the algorithm. The elements $u \in U$ 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 (and thereby evacuation schemes) are constructed by assigning each group of evacuees to an element. The second step is based on ACO, while the first step is developed for this specific problem.

4.1 Generation of elements

The elements are a selection of all possible combinations of routes and departure times. A selection is made to again contribute to the applicability of the optimization method and the feasibility of the resulting evacuation scheme. Another reason to select some of the possible routes is to avoid assigning of groups to unlikely routes (e.g., routes with relatively high free flow travel times).

Appropriate routes for early departure times may not be appropriate for later departure times (due to degeneration of the infrastructure caused by the hazard). Therefore, elements are created in two phases, see Fig. 1. First, elements are generated by constructing a route set for a totally accessible network and combining this with departure times for which it is possible to reach a destination following each route in the route set. Then, the route set is adapted and combined with next departure time(s) which result in new elements. This adaptation is continued until it is no longer possible to reach any of the destinations for the next departure time.

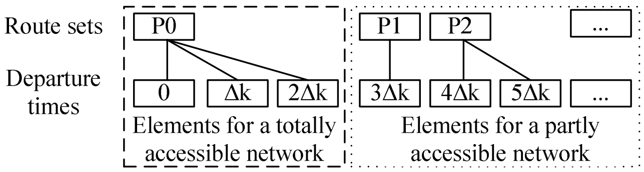

Fig. 1. Generation of elements.

4.1.1 Elements for a totally accessible network

The generation of elements for a totally accessible network consists of the steps visible in Table 1.

In step 1 candidate routes are generated for each origin, these are routes having relatively short free flow travel times. These routes are determined by repeatedly applying Dijkstra's algorithm (Dijkstra, 1959), where the travel times on the links are iteratively changed using Monte Carlo simulations, see Bliemer and Taale (2006). Each generated route is compared with the shortest free flow route for the origin: if the travel time of the generated route is less than a factor ξ_1 as high as the travel time of the shortest free flow route, the generated route is added to the candidate route set.

Table 1. Elements for a totally accessible network

1. Creation of candidate route sets based on network
2. Creation of selection route sets based on overlap in routes
3. Division of selection route sets in route set *P* and back-up routes
4. Selection of departure times

In step 2 selection route sets are created, which are subsets of the candidate route sets, based on the overlap between the routes in the candidate route sets. One by one the fastest free flow route is removed from the candidate set and the overlap between this route p^* and each route p in the (in the beginning empty) selection route set is computed:

$$\theta^{\text{route}}_{pp^*} = \frac{\sum_{a\in A_{pp^*}} \tau_a^{\text{free}}}{\tau_{p^*}^{\text{free}}} \qquad (3)$$

where A_{pp^*} is the set of links included both in p^* and p and $\tau_{p^*}^{\text{free}}$ is the free flow travel time of p^*. If none of the overlaps for p^* is higher than the maximum allowed overlap $\theta_{p^*}^{\text{route,max}}$, p^* is added to the selection route set.

In step 3 a number of routes equal to the maximal number of routes per origin $\psi_{\text{routes}}^{\max}$ (or all the routes, when there are less then $\psi_{\text{routes}}^{\max}$ routes in the selection set) out of each selection set is added to the route set *P*. These are the routes having the shortest free flow travel times. All the routes in the selection sets that are not added to *P* are collected as back-up routes. These back-up routes are possibly used in the adaptation of *P* in the generation of elements for a partly accessible network.

The departure times $k \in K$ appropriate in combination with *P*, selected in step 4, are all multiples of Δk (a fixed period between the departure times) from 0 up to and including the last departure time for which *P* is appropriate, k^{P}. This last term is equal to $\min\{k^r, k^p\}\forall r \in R^P, p \in P$, where R^P is the set of origins for which routes are included in *P*. The last departure time belonging to an origin, k^r, and the last departure time belonging to a route, k^p, are also multiples of Δk. They are equal to the last departure time at which it is possible to respectively leave the origin and follow the route without being impeded by the hazard under free flow conditions. The time needed to load a group of evacuees on the network (depending on the capacity and the number of evacuees per vehicle) is taken into account. The elements, all combinations of departure times $k \in K$ and routes $p \in P$, are collected in *U*.

4.1.2 Elements for a partly accessible network

The elements for a partly accessible network are generated by repeating the steps visible in Table 2. Several adapted route sets are generated, each corresponding to a set of consecutive departure times, as also shown in Fig. 1. When it is no longer possible to leave an origin and reach a destination for the next departure time, the creation of elements stops immediately.

Table 2. Elements for a partly accessible network

5. Collection of routes causing the inappropriateness of *P*
6. Removal of routes out of *P* belonging to inaccessible origins
7. Replacement of routes in *P* with back-up routes
8. Removal of routes out of *P* belonging to unreachable origins
9. Replacement of routes in *P* with newly generated routes
10. Selection of departure times

In step 5 the routes and origins causing the inappropriateness of *P* for the next departure time, $\overline{P}$ and $\overline{R}$, are collected. These are the routes and origins for which respectively holds that k^p and k^r are equal to k^P. Steps 6 up to and including 9 are followed until the sets $\overline{P}$ and $\overline{R}$ are empty. When they become empty, the departure times are selected in step 10.

If there are origins causing the inappropriateness $(\overline{R} \neq \varnothing)$, routes belonging to the origins $\overline{R}$ are removed from *P* in step 6 and when these routes are part of $\overline{P}$, also from $\overline{P}$.

If the set of back-up routes is not empty, unavailable back-up routes are removed from the back-up routes in step 7, where the availability is based on the last departure time belonging to a route k^p. When there are back-up routes belonging to the same origin as routes in $\overline{P}$, the last mentioned routes in $\overline{P}$ are removed and the corresponding routes in *P* are replaced by as many as possible appropriate back-up routes (the shortest back-up route first). The used back–up routes are eliminated from the set of back-up routes.

In step 8, the possibility to reach any of the destinations from all origins where routes in $\overline{P}$ belong to, is checked by registering all the accessible upstream links reachable from the aforementioned origins. If this is impossible for an origin, routes in P and $\overline{P}$ corresponding to the origin are removed.

In step 9 new routes are generated to replace routes $\overline{P}$ in P in the same way as routes are generated in step 1 and 2, using a reduced network: only accessible links at departure time $\max\{K\}+\Delta k$ are included. For the overlap of the routes both routes found in this step and routes in P are compared.

In step 10 departure times K are selected belonging to P. They are equal to all multiples of Δk from k^{earliest} up to and including k^{P}, where k^{earliest} is equal to $\max\{K\}+\Delta k$. All combinations of departure times $k \in K$ and routes $p \in P$ are new elements added to U.

4.2 Algorithm

The structure of the algorithm is equal to the ACO structure, namely, each iteration of the algorithm contains a construction phase and an update of so-called pheromone trails.

4.2.1 Construction phase

In the construction phase all ants in a colony $m \in M$ create a solution, in this case, an evacuation scheme. Each group of evacuees is assigned to an element belonging to the same origin as the group, whereby groups can be assigned to the same element (in contrast to the original ACO structure). All elements have a selection probability based on 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 value of f_E a relative high selection probability. Pheromone trails are not constant: they give elements of good solutions of earlier iterations a relative high probability.

The problem-dependent information κ_u for each element u is for this specific problem based on information about the departure times and routes belonging to the elements:

$$\kappa_u = \vartheta_{p_u} \zeta_{k_u} \in \langle 0,1] \tag{4}$$

where ϑ_{p_u} is information about the free flow travel time of route p belonging to element u, and ζ_{k_u} is information about departure time k belonging to element u. The higher the value for κ_u is, the higher the probability on selection of element u is based on problem-dependent information. The boundaries for κ_u follow on the boundaries of both information parts described hereafter.

The information about the free flow travel time of route p belonging to element u gives an element with a relative low free flow travel time a relative high value for the problem-dependent information. Therefore holds:

$$\vartheta_{p_u} = \left(\frac{\min\limits_{u \in U_r} \left\{ \tau_{p_u}^{\text{free}} \right\}}{\tau_{p_u}^{\text{free}}} \right)^{\xi_2} \in \left[\frac{1}{\xi_1}, 1 \right] \tag{5}$$

where U_r is the set of elements belonging to origin r, and ξ_2 is a weighting parameter with $0 \le \xi_2 \le 1$. When $\xi_2 = 0$, the problem-dependent information does not depend on the travel times of the routes. The higher the value for ξ_2 is, the larger the distinction in the problem-dependent information based on the differences in travel times is. The maximum value of ξ_2 avoid the situation wherein the selection probability of an element becomes negligible. As consequence of the boundaries for ξ_2 and the factor ξ_1, holds $1/\xi_1 \le \vartheta_{p_u} \le 1$.

The information about the departure time k belonging to element u gives an element with a relative early departure time a relative high value for the problem-dependent information. Therefore, ζ_{k_u} is determined as follows:

$$\zeta_{k_u} = 1 - \xi_3 \frac{k_u}{\max K_{r_u}} \in (0,1] \tag{6}$$

where K_{r_u} is the set of departure times for which there are elements belonging to r_u, the origin r belonging to element u. For weighting parameter ξ_3 holds $0 \le \xi_3 < 1$ and the properties of this parameter are comparable to those of ξ_2.

The selection probability of an element is proportional to the product of the problem-dependent information and the value of the pheromone trail:

$$h_u(i) = \frac{\gamma_u(i)\kappa_u}{\sum\limits_{u \in U_r} \gamma_u(i)\kappa_u} \in (0,1] \tag{7}$$

where $\gamma_u(i)$ is the value of the pheromone trail belonging to element u in iteration i for which holds $\gamma_u(1) = 1 \forall u \in U$. The construction phase results in evacuation schemes each containing the selected elements (routes and departure times) and the groups of evacuees assigned to these elements. An example of a created evacuation scheme is given in Fig. 2.

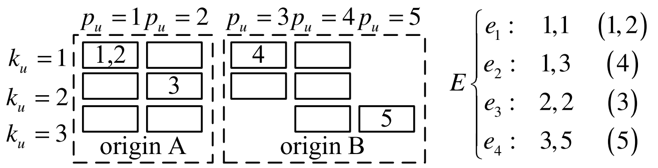

Fig. 2. Example of a created evacuation scheme. Groups 1,2 and 3 belonging to origin A and groups 4 and 5 belonging to origin B are assigned to elements (combinations of departure times 1, 2 and 3 and routes 1, 2, 3, 4 and 5). Evacuation scheme E contains four instructions (i.e. e_1 containing $k_e = 1$ and $p_e = 1$ where groups 1 and 2 are assigned to).

4.2.2 Update of pheromone-trails

During the update of the pheromone trails the fitness of each evacuation scheme follows on application of EVAQ. The evacuation scheme having the highest fitness in the iteration is the iteration-best evacuation scheme, E_{ib}, the one having the highest fitness over all iterations is the global-best evacuation scheme, E_{gb}. The value of the pheromone trail for element $u \in U$ in iteration i is determined as follows:

$$\gamma_u(i+1)=\begin{cases}\rho\gamma_u(i)+\xi_4\Delta\gamma_u(i) & \text{if } u\in U_{gb}\\ \rho\gamma_u(i) & \text{otherwise}\end{cases}\in\langle 0,\infty\rangle \tag{8}$$

where $\Delta\gamma_u(i)$ is the amount of pheromone added to the elements U_{gb}, the set of elements where groups are assigned to in the global-best evacuation scheme. The amount of pheromone $\Delta\gamma_u(i)$ is determined for the evacuation problem as follows:

$$\Delta\gamma_u(i)=\frac{f_{E_{\mathrm{gb}}}}{B}\frac{\sum_{g\in G_u} B^g_{r_u}}{B_{r_u}}\in[0,1) \tag{9}$$

where G_u is the set of groups assigned to u. The first part of (9) makes $\Delta\gamma_u(i)$ depending on the performance of the global best evacuation scheme scaled between 0 and 1. The second part of (9) is added to let $\Delta\gamma_u(i)$ depend on the number of evacuees assigned to an element instead. The parameters ρ, with $0<\rho<1$, and ξ_4, with $\xi_4>0$, in (8) influence the exploration and concentration of the search process. Appropriate values of ρ and ξ_4 depend on the scale of the problem. When the number of possible evacuations schemes is higher (there are more departure times, routes and/or groups), a higher exploration and thus a relatively high value for ρ and a relatively low value for ξ_4 are useful. An appropriate value of ξ_4 also depends on the time available to find an evacuation scheme: when the danger is critical, the value has to be relatively high to quickly find a solution.

5. CASE STUDY

The optimization method is applied to a hypothetical flooding of Walcheren (see Fig. 3), a peninsula in the southwest of the Netherlands. Over 120,000 residents on an area of 216 squared kilometers have to be evacuated, whereby the number of evacuees per vehicle is assumed to be equal to 2. The flooding strikes the area from the west to the east in an estimated 6 hours, whereby the importance of early arrivals is assumed to be of such a level that a suitable value for the parameter for the objective function, β, is 0.1.

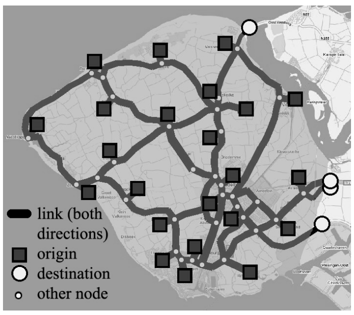

Fig. 3. Case study: flooding of Walcheren.

It is possible to apply the optimization method both for a mandatory and a recommended evacuation. In this case study the method is applied for a mandatory evacuation and the effect of applying the resulting evacuation scheme as recommended instructions is shown. Also a comparison with a voluntary evacuation is made. Finally, a comparison is made between the resulting evacuation scheme and an evacuation scheme set up by simple evacuation rules, to show the necessity of the use of an optimization method as the one described in this paper. As mentioned in the introduction, most other optimization methods solve reduced problems disabling a fair comparison.

5.1 Approximation of the optimal evacuation scheme

To apply the optimization method using the program Matlab, assumptions for the parameters have been made, based on the results of some test cases (see Huibregtse, 2008). The parameters for the generation of the elements Δk, $\psi^{\max}_{\text{routes}}$, ξ_1, B^{constant} and $\theta^{\text{route,max}}_{p*}$ are set respectively to 0.5 hours, 5, 2, 10,000 and 0.8. The parameters for the algorithm, ξ_2, ξ_3, $|\{m\}|$, ρ and ξ_4 are set to respectively 1, 0.5, 10, 0.995 and 0.1. Besides the mentioned test cases, a more extensive sensitivity analysis of the values for the parameters of the algorithm is subject of future research.

The result of the application of the optimization method, which took 105 hours computation time using a desktop computer with Core 2 Duo @ 3.0 Ghz and 2GB RAM, is presented by the fitness of all iteration-best evacuation schemes in Fig. 4. The upward trend indicates a search for an optimum. Exploration is visible in the first iterations (the differences between the evacuation schemes and therefore between their fitness values are relatively large) and concentration in the last iterations (the differences are relatively small). The approximation of the optimal evacuation scheme following on the application is the global-best evacuation scheme.

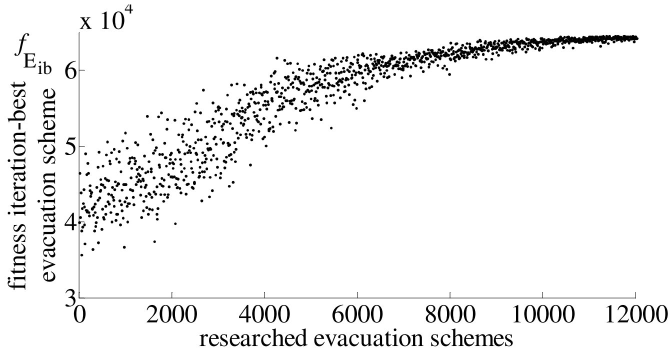

Fig. 4. Fitness of the iteration-best evacuation scheme after a number of researched evacuation schemes.

5.2 Comparison between the mandatory, recommended and voluntary evacuation

In this section a mandatory and recommended evacuation (both following on the approximation of the optimal evacuation scheme) and also a voluntary evacuation are compared. The values chosen for parameters in EVAQ are for completeness given in Appendix A. For the recommended evacuation, different degrees of control of the evacuation are tested. Because of these different degrees and a stochastic process included in EVAQ for a voluntary and recommended evacuation, the results for the recommended and voluntary evacuations are not one arrival pattern each, but several arrival patterns of which the band widths are given in Fig. 5. The cumulative arrivals are highest in a mandatory evacuation, followed by the recommended and voluntary evacuation for about the whole evacuation. The values of f_E for the recommended evacuation are between 55,000 and 62,000, compared to around 65,000 for the mandatory evacuation and 42,000 for the voluntary evacuation. The differences can be the mentioned lack of information and the lack of system optimal thinking by the individual evacuees.

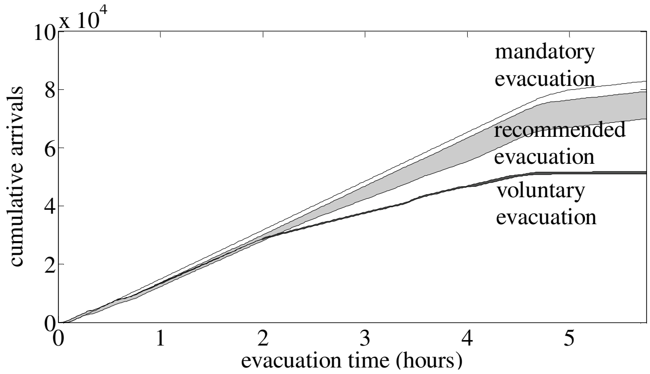

Fig. 5 Arrival patterns of voluntary, recommended and mandatory evacuations, applying the approximation of the optimal evacuation scheme.

5.3 Comparison approximation of optimal evacuation scheme and evacuation scheme set up by simple rules

In this section the approximation of the optimal evacuation scheme is compared to an evacuation scheme set up by some simple (but possibly naïve) evacuation rules. These rules are 1) the nearest destination is instructed, 2) the fastest free-flow route is instructed, and 3) the departure times are instructed in such a way that no congestion occurs, where evacuees nearest by their destination are evacuated first (see Genugten, 2005).

The arrival patterns following on the application of both evacuation schemes as mandatory instructions are shown in Fig. 6. The cumulative number of arrivals is highest when applying the approximation of the optimal evacuation scheme for the whole evacuation. The value of f_E for the evacuation scheme set up by the simple rules is equal to about 27,000. Comparing this value to the values for the mandatory, recommended and voluntary evacuations in Section 5.2, application of an optimization method seems to be necessary to get an appropriate evacuation scheme.

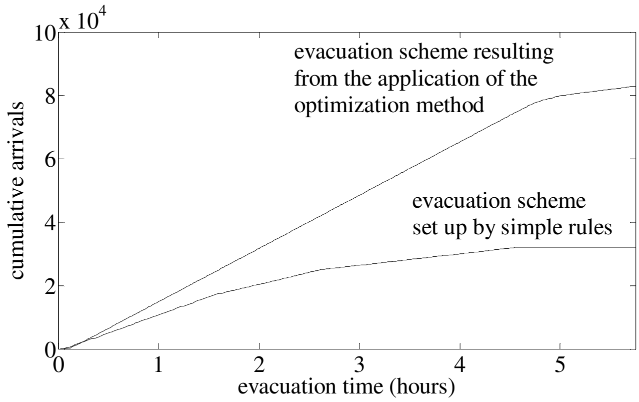

Fig. 6. Arrival pattern of the evacuation by applying the approximation of the optimal evacuation scheme and the evacuation scheme set up by simple rules.

6. CONCLUSIONS

The developed optimization method searches for an approximation of the optimal evacuation instructions, where the departure times, routes and destinations are simultaneously optimized. Application of the method on a fictive flooding of Walcheren shows an upward trend, exploration and concentration in the fitness of iteration-best evacuation schemes. This illustrates the functioning of the optimization method. This case study further confirmed that applying the instructions is helpful to control an evacuation: the arrival pattern for a recommended evacuation (wherein evacuees partly follow the instructions) is much better than when no instructions are given. The case study finally showed the usefulness of the optimization method: the resulting evacuation scheme of the optimization method scheme leads to a much better arrival pattern then an evacuation scheme set up by a set of simple instructions.

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

REFERENCES

Bliemer, M.C.J., and Taale H. (2006). Route Generation and Dynamic Traffic Assignment for Large Networks, *Conference Proceedings 1st DTA Conference*, Leeds, U.K.

Chiu, Y., Zheng, H. ,Villalobos, J., and Gautam, B., (2007). Modeling no-notice mass evacuation using a dynamic traffic flow optimization model, *IIE Transactions*, 39(1), 83-94.

Dijkstra, E.W. (1959). A Note on Two Problems in Connexion with Graphs, *Numerische Mathematik*, 1, 269-271.

Dorigo, M., Maniezzo, V., and Colorni, A., (1996): The ant system: optimization by a colony of cooperating agents, IEEE Transactions on Systems, *Man and Cybernetics*, 26(1), 29-41.

Franklin, J.L. (2008). 2007 National Hurricane Center Forecast Verification Report, National Hurricane Center, NOAA/NWS/NCEP/Tropical Prediction Center.

Genugten, W.L.M. (2005). De effecten van evacuatiestrategieën op het verloop van grootschalige evacuaties, MSc Thesis, Delft University of Technology, Delft, The Netherlands.

Huibregtse, O.L. (2008). Een generieke en efficiënte optimalisatiemethode voor evacuatieschema's, MSc Thesis, Delft University of Technology, Delft, The Netherlands.

Knight, L. (editor) (2008). *World Disasters Report 2008*, International Federation of Red Cross and Red Crescent Societies, Satigny/Vernier, Switzerland.

Lave, L.B., Resendiz-Carrillo, D., and McMichael, F.C. (1990). Safety Goals for High-Hazard Dams: Are Dams Too Safe? *Water Resources Research*, 26(7), 1383-1391.

Liu, Y., Lai, X., and Chang, G. (2006). Two-Level Integrated Optimization System for Planning of Emergency Evacuation. *Journal of Transportation Engineering*, 32(10), 800-807.

Miller-Hooks, E., and Sorrel, G. (2008). The maximal dynamic expected flows problem for emergency evacuation planning. *Proceedings of the 87th Annual Meeting of the Transportation Research Board*, Washington DC, U.S.

Pel, A.J., Bliemer, M.C.J., and Hoogendoorn, S.P. (2008). EVAQ: A New Analytical Model for Voluntary and Mandatory Evacuation Strategies on Time-varying Networks. *Proceedings of the 11th IEEE Intelligent Transportation Systems Conference*, Beijing, PR China.

Appendix A. PARAMETERS IN EVAQ

Information about all parameters in EVAQ can be found in Pel et al. (2008). The parameters for both a recommended and a voluntary evacuation λ, φ, α_0, α_1, β_1 and β_2 are set to respectively 0.5, 0.1, 5, 0.01, 1 and 0. The parameters in EVAQ only included for a recommended evacuation are ω, α_2, β_3 and β_4 and for these parameters several values are tested to simulate different degrees of control of the evacuation. Parameter ω is set to 0.5, 0.6, 0.7, 0.8 and 0.9 and the parameters α_2, β_3 and β_4 are all set to 1, 7/3 and 9.