Modelling the evacuation process in case of flooding
AN APPLICATION OF A DYNAMIC TRAFFIC MODEL, A COMPARISON TO EXISTING MODELS AND AN OPTIMIZATION OF THE EVACUATION PROCESS

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SUMMARY

As part of the European FLOODsite project and my Master thesis in Econometrics in Logistics and Operations Research, this thesis contains a research on the application of a number of evacuation models.

Firstly a new application was done with the Dynamic Traffic Assignment model Indy, developed by TNO and the TU Delft. The target was to see how it performed compared to other existing specialised evacuation models. For this they were all applied to a research area consisting of Walcheren and Zuid Beveland in the Netherlands. The result showed that especially the results of the Evacuation Calculator and the application of Indy were almost equivalent to each other. However for a good analysis of the bottleneck during the evacuation process it is recommended to use the more advanced model of Indy.

Furthermore a broad number of alternative scenarios were investigated with the new Indy-based model. The use of a tunnel as an exit point, an advanced method for assigning the various zones to exits and coupling the most probable flood scenarios are just a few of these extended scenarios.

The final part of the thesis describes another new application in evacuation modelling. By iteratively applying a maximum flow problem from the area of Operations Research, the evacuation process was optimized. Where most of the other models used input generated priori, the max flow application optimizes the same properties during the evacuation process. The newly optimized input was then used as input for the Indy-based model. It showed an improvement of nearly 7 percent in the total evacuation time.
CONTENTS

Document Information ................................................................. ii
Document History ................................................................. ii
Acknowledgement ................................................................. ii
Disclaimer ................................................................. ii
Summary ....................................................................... iii
Contents .................................................................... v

1. Introduction ............................................................................... 8
1.1 Background ....................................................................... 8
1.2 Problem description .......................................................... 9
1.3 Research structure .............................................................. 9

2. Comparing evacuation models .................................................. 11
2.1 Evacuations ....................................................................... 11
2.2 The evacuation models .......................................................... 13
  2.2.1 DSS ESCAPE ................................................................. 13
  2.2.2 Evacuation Calculator ..................................................... 15
  2.2.3 A dynamic traffic assignment model: Indy ....................... 18
2.3 Applying Indy to evacuation modelling .................................. 24
  2.3.1 Description of the area ..................................................... 24
  2.3.2 Approach ....................................................................... 27
  2.3.3 Results of the application of INDY on the Schelde pilot ....... 31
2.4 Comparing Indy to DSS ESCAPE en the EC ......................... 35
  2.4.1 Comparing the models theoretically .................................. 35
  2.4.2 Comparison of the results of the models ......................... 36
2.5 Some alternative scenarios using Indy .................................... 1

3. Optimizing evacuations .............................................................. 9
3.1 Introduction ....................................................................... 9
3.2 The maximum flow problem .................................................. 9
  3.2.1 Problem definition .......................................................... 9
  3.2.2 The push/relabel algorithm ............................................. 11
3.3 Applying the max flow algorithm to evacuation modelling .......... 16
3.4 Results and discussion .......................................................... 17
3.5 Conclusions and recommendations ....................................... 1

4. Overall conclusions and recommendations .................................. 3

5. References ........................................................................ 4

Tables
Table 1: Overview of the exits links and their capacity ........................................ 27
Table 2: The outcomes of INDY of all the basic scenarios ...................................... 32
Table 3: Comparison of the Departure Profiles ..................................................... 32
Table 4: Scenarios compared by the assignment used. ........................................... 32
Table 5: Scenarios compared on the exits used. ...................................................... 33
Table 6: Comparison of the outcomes of the three models .................................... 36
Table 7: Comparison of evacuation times using linear and S-curve departure profiles .................................................. 2
Table 8: Outcomes of INDY with the addition of the tunnel .................................... 4
Table 9: Outcomes of INDY with the shortest path 4
Table 10: Outcomes of INDY using automatic assignment 6
Table 11: Overview of the available shelters 7
Table 12: Results the simulations with/without the shelters 7
Table 13: Results of the partial evacuation 8
Table 14: Results of max flow application 17
Table 16: Number of people assigned to the available exits 19

Figures
Figure 1: The modules of DSS ESCAPE 14
Figure 2: The dynamic traffic assignment model framework 19
Figure 3: Blocking back effects at the first time instant 22
Figure 4: Bottleneck effects at a later time step 22
Figure 5: Location of the research area (marked green) 24
Figure 6: The reference assignment using all the exit points. 29
Figure 7: The nearest assignment using all the exit points 29
Figure 8: Optimized assignment using all the exit points 30
Figure 9: S-curve departure profile over eight hours 31
Figure 10: (shown in red) when only using the eastern exits 34
Figure 11: Linear (red) and S-curve (blue) 16-hour departure profile 2
Figure 12: Entrance Westerschelde tunnel at Terneuzen 3
Figure 13: OmniTrans network with the Westerschelde tunnel (optimized assignment) 3
Figure 14: Traffic flows after 15 hours of evacuation (multiple routes) 5
Figure 15: Traffic flows after 15 hours of evacuation (shortest route only) 5
Figure 16: All zones assigned to new virtual point 6
Figure 17: Possible flood scenario 7
Figure 18: The example network with the link capacities 12
Figure 19: Initial preflow is send through the network 13
Figure 20: An active node is selected 13
Figure 21: Relabelling of the active node 13
Figure 22: Excess pushed further onto the network 14
Figure 23: Active node selection and relabelling 14
Figure 24: Excess flow of an active node pushed further onto the network 14
Figure 25: Flow pushed back to the source after relabelling of new active node 15
Figure 26: The maximum flow is found 15
Figure 27: Departure profile from max flow application 18
Figure 28: Zones to exits assignment from max flow application 18
1. Introduction

In this Master thesis in Econometrics in Logistics and Operations Research an investigation is done on the application of both a Dynamic Traffic Assignment model as well as an application from the Operation Research on the evacuation process in case of flooding. It has been carried out as part of the European project called FLOODsite. FLOODsite covers the physical, environmental and socio-economic aspects of floods from rivers and the sea. It is done for Task 17 of this EC research project that focuses on evacuation modelling related to flood events.

In this introduction there is first described why these evacuation models must be developed. Thereafter the objectives of my thesis are discussed. The final part of this chapter is on the structure of the thesis.

1.1 Background

During the whole human history the news has spread out stories about flooding all over the world. Coming both from the sea and the rivers, these floodings have caused a lot of casualties and damage. Although the number of flooding appearances has not increased significantly over the years, the number of casualties has [GENUGTEN 2005]. This is caused by the increasing density of people living close to the sea and rivers (close to half of the world’s population). It emphasizes the vulnerability of those people in case of emergency. Since the danger of flooding will never disappear, we must take measures to at one hand try to prevent floodings as well as possible and at the other hand try to limit the consequences. Building new dikes and developing (intelligent) warning systems contribute in achieving these goals. Good planning of evacuation strategies helps to get as much people out of the emergency area as possible and reduces the potential number of casualties.

In the Netherlands, with more than half of the country lying beneath sea level, we are also exposed to the dangers of flooding. The main threat is from the North Sea and the rivers. In 1953 the Netherlands had the worst flooding in the Dutch recent history. The spring tide together with a storm surge caused the water level to increase to such a height that the dikes in Zuid Holland and in Zeeland broke through. The number of casualties (both people as well as cattle), as well as the damage done to households and the landscape was enormous. Following this disaster the government took measures and created the Delta plan to help defending against new threats from the sea. Although there is still a probability of flooding, the likelihood of national disaster is a lot lower now than in 1953.

The research area of the thesis will be a specific part of Zeeland. This area consists of the northern part of the Westerschelde. This region is divided into three dike rings: Walcheren, Zuid-Beveland West and Zuid-Beveland East. The Western part by the North Sea, the southern part by the Westerschelde, the northern part by the Oosterschelde and the eastern part by the Kreekrak and the Schelde-Rijn Canal. The main threats for flooding to occur come from the North Sea and the Westerschelde.
1.2 Problem description

But the potential damage of flooding has increased over the years. This is mainly the result of an increasing population living in the area at risk. It is therefore important to have an efficient evacuation plan. Evacuations put a lot of pressure on the existing infrastructure. By planning the evacuation process beforehand, the evacuation time can be minimized, which may reduce the number of casualties.

The simulation and planning of an evacuation can be done by applying various models on it. Two of them are the DSS (Decision Support System) ESCAPE [WINDHOUWER 2004] which the province of Zeeland currently uses to estimate evacuation times and the Evacuation Calculator (EC) [ZUILEKOM 2004], a specialized Evacuation model developed by the University of Twente. The latter uses a static traffic assignment model to simulate the traffic flows on the network. These static models have a number of shortcomings of which most are not apparent in their dynamic counterparts. Dynamic traffic assignment (DTA) models differ from static models in that traffic flows can differ over time in contrast to constant flows in static models. Opposed to static models, traffic jams and their spill back can be simulated correctly with dynamic models, as well as structural changes in the network during the simulation. So in case of simulating large-scale evacuations, the use of the dynamic model may provide the most insight. For a new evacuation model the dynamic traffic assignment model of Indy will be used. This model has been developed by TNO and the Delft University of Technology. The model allows the analysis of traffic scenarios on transportation networks. Via its flexible modelling of the interactions between travel demand and infrastructure capacity, INDY can predict the traffic conditions of a road network over time, identify the locations where congestion occurs and estimate the corresponding delays.

The thesis will mainly focus on comparing the use of the DTA-model of Indy with the other mentioned existing evacuation models. Furthermore a maximum flow algorithm will be applied to optimise the evacuation process with respect to the destination (exit point) choice and departure time components.

Summarizing, the following objectives are to be answered throughout my thesis:

- How does a Dynamic Traffic Assignment model (Indy) applied to evacuation modelling perform in comparison to existing specialized evacuation calculators (DSS ESCAPE/Evacuation Calculator)?
- How can we optimize process of evacuation with respect to departure times and evacuation routes using a maximum flow algorithm?

1.3 Research structure

After an introduction on evacuations in general (section 2.1), the research will first focus on the performance of Indy in simulating evacuations compared to other evacuation calculators in chapter 2.4. A comparison will be made with the DSS ESCAPE and with the EC. The Delft Hydraulics (DH) already simulated different evacuation scenarios of the case-study in Zeeland with both of them [LUMBROSO 2007]. To be able to make a good comparison between the three, the same settings and assumptions are to be made. A number of basic scenarios are looked at.
In the final part of chapter 2 (section 2.5) a number of alternative scenarios will be investigated. One of them concerns the incorporation of possible flooding scenarios into the evacuation planning. The DH has models that can simulate flooding patterns in case of a dike breakthrough or overflow. Coupling the most probable scenarios makes it possible to indicate which parts are most critical and should be evacuated first. Another scenario is that of using shelters. What is the effect of this usage on the evacuation process? Other scenarios include the use of a tunnel as an exit and a different departure profile.

In the final step of my thesis an optimization will be done on evacuations (chapter 3). The main goal here is to minimize the total evacuation time by altering the departure times and the zone to exit assignment. A maximum flow algorithm will be applied to evacuations trying to assign evacuees to the different exit points and let them leave at certain time periods, such that the road network is used in the most efficient way possible. Congestion can then be minimized: congestion changes the capacity of the road in a negative way and therefore slows down the evacuation.

First a short description of the maximum flow problem is made. After that the maximum flow algorithm of Goldberg and Tarjan [GOLDBERG 1988] is discussed. Finally this algorithm is applied to the evacuation process. The resulting origin/destination-matrices can also serve as input to Indy for evaluation.

Conclusions on the thesis as well as recommendations on further research are made in the final chapter.
2. Comparing evacuation models

This chapter presents a comparison of the different evacuation models applied to a study area in Zeeland for a number of different scenarios. Firstly some things are described about evacuations in general. After that the different models are explained, with more attention given to Dynamic Traffic Assignment models in general and Indy. Next the research area in Zeeland is introduced as well as the application of Indy to evacuation modelling. Thereafter the results of the application of the three models are presented and discussed. Finally some more scenarios are looked at using the Indy application.

2.1 Evacuations

Planning of evacuations is part of disaster management. Though a lot is known about disasters, the planning of evacuations is something that needs more attention. In the Netherlands a large-scale evacuation isn’t a common process. Only during the big flooding in 1953 and the threatening flooding of the rivers in 1995, a large-scale evacuation was used. In 1953 the flood, which caused a great number of casualties, came fully by surprise. There were no emergency systems available, and so people were not warned and therefore prepared at all. Complete chaos was the result. The dikes at that time were very badly maintained. As a reaction to this tragedy the Dutch government began building the Deltaplan to prevent future disaster like this. Both 1953 as well as 1995 are cases of the largest threat of a disaster in the Netherlands: Flooding. These threats come from both the sea as well as the rivers. Because of climate changes the probability of flooding will increase over the years. Combined with the increasing population along the coast and the increasing density of people living in cities, potential flooding will cause bigger damage and produce more casualties than ever before. In response to these disasters, evacuation planning is an important issue. The capacity of the infrastructure cannot handle the demand by traffic in times of evacuations. This is why large-scale evacuations have become more difficult which leads to increasing evacuation times. Good planning of evacuation has become very important, while it helps to partly solve these problems.

Once the evacuation signal is given, the inhabitants of the evacuation area will massively try to flee out of the area. In the Netherlands people are obliged to respond to an evacuation call. This will lead to an enormous amount of traffic making use of the infrastructure at the same time. Also the evacuating traffic is located on just a small part of the network. There are only a small number of exit points: safe locations where people are directed to. And the number of routes leading to these exit points is also limited. Thus only a small part of the existing infrastructure is actually used. This is especially true towards the exit points, where the different evacuation routes come together. The probability of congestions and traffic jams will thus increase towards the exit points.

A number of factors influence the total evacuation time:

- The number of people that need to be evacuated (demand).
- The capacity of the infrastructure (supply).
- The difference in demand and capacity during the evacuation.
- The human behaviour.
- Disturbances in the network (for instance road blocks).
Using evacuation models to simulate evacuation beforehand gives a good impression of how the actual evacuation will evolve over time due to these factors.

**Traffic demand**
The traffic demand has a large impact on the process of the evacuation. How many people will use the available infrastructure? Its size is determined by the number of people living in the area and by the number of people per vehicle. It also depends on the type of vehicle people will use. A motor for example can carry a maximum of two persons, but doesn’t take much road space. A bus on the other hand uses much more space than a car, but its capacity is much larger. Also cattle can be present in the area and, if decided so, must be evacuated too. And these must be transported by large capacity vehicles as well.

Traffic demand is also dependent on the location of people at the time of an evacuation call. It will most probably not be the case that everyone is at home with their family at that moment. For example children can be at school and parents may be working. It takes some time (using some form of transportation) for them to gather, and that increases the traffic demand.

Departure time is another important factor. If everyone leaves their home at the same time, this will lead to an overload of the network. But if the departures are more spread over time the traffic demand per hour will be relatively low. All departure times taken together form a departure profile. Departure profiles depend on the type of evacuation (reactive or preventive) and on the way people react on evacuation calls. Also preparation (including gathering your family) affects the departure profile.

**Network capacity**
The available network capacity determines whether the evacuation process proceeds safely. It mainly depends on the size of the available infrastructure. Part of the network may not be accessible due to several reasons. For instance some parts must be kept free for emergency vehicles. And road parts could be made inaccessible due to the extreme weather conditions coinciding with the flooding.

A large part of the available road network will not be occupied during the evacuation process. Only the roads that are part of the evacuation routes are used. The number of evacuation routes depends on the number of exit points and the size of the network. More exit points and/or a larger network means more evacuation routes and leads to a more spread traffic. This will probably decrease congestion.

The evacuation capacity of a network depends on the capacity of the last links leading up to the exit points. At the very beginning the amount of traffic is extremely low on most of the evacuation routes, and can easily be handled by the capacity of the roads. At the end of the routes, towards the exit points, the roads used are often the highways and have the largest capacity. But this is also the point where the most traffic is formed due to joining evacuation routes. That is why these last roads are crucial when it comes to the evacuation capacity of a network. The evacuation time to a large extent depends on the capacity of the exit links.

Different things may cause trouble and therefore slow down the traffic on parts of the network. A decrease in the number of lanes and crossing traffic flows (on intersections) lead to decreasing capacity and can cause congestion during the evacuation. The latter must therefore be prevented as much as possible. An intelligent way of assigning traffic to exit points can help to accomplish this.
2.2 The evacuation models

The three applied evacuation models are discussed in the following part. In the province of Zeeland two static models have been used: the Decision Support System (DSS) ESCAPE, which will be described first, and second the Evacuation Calculator (EC). An application of a Dynamic Traffic Assignment model will be added to these two existing models. The Dynamic Traffic Assignment models are first described in general after which a particular model (Indy) is introduced.

2.2.1 DSS ESCAPE

ESCAPE (European Solutions by Cooperation And Planning in Emergencies) was a joint venture involving the Province of Zeeland (the Netherlands), the Provinces of Oost-Vlaanderen and West-Vlaanderen (Belgium) and the county of Essex (England). As a part of the ESCAPE project a Decision Support System (DSS) has been developed. The DSS answers the question whether an evacuation can be carried out safely within the available time. It gives those who must take this decision objective support by providing an overview of the information relevant to the decision and the implementation of the evacuation. Vital to the system’s advice is whether sufficient time is available to get all the residents to safety. Based on data regarding the demographics and infrastructure, DSS calculates the time required using a specially designed evacuation model. This model selects a strategy that will minimise the duration of the evacuation while avoiding congestion on the evacuation routes. When certain routes cease to be available during the evacuation, DSS suggests alternatives and indicates their impact on the duration of the evacuation. Should it appear that the available time is too short for all the residents to leave the affected area, DSS gives advice as to which residents must be given shelter and which residents can still leave the area. An important assumption is that the evacuation must be complete by the time the dike is breached. Main reason is that a situation, in which people are caught unaware by high water while on the road in the area at risk, must be avoided. A second important assumption is that the evacuation must be organised. This is primarily because congestion will result if the road capacity is insufficient to handle the traffic leaving the area, and congestion will significantly increase the total evacuation time. Simulation has shown that an evacuation under these circumstances will take up to 2 or 3 times more time. If the choice of route is left open, gridlocks may result, obstructing the road network. This can be prevented with planned departure times and allocated routes.

In the following the focus will remain on the evacuation module of ESCAPE. First the framework evacuation model is discussed shortly. Thereafter the evacuation module used in ESCAPE is discussed in more detail.

DSS Emergency Planning system
The DSS Emergency Planning system is a modular system (see Figure 1).
Figure 1: The modules of DSS ESCAPE

At the heart of the system lies the decision module. This module stores the information required to take a responsible decision. The system’s recommendation is based on this information and the decision rules. Before a recommendation can be issued, the DSS Emergency Planning system must be fed with relevant data, such as GIS (Geographical Information System), weather and water-level data. These data are then used by the evacuation module to estimate the duration of the evacuation and by the scheduling module to draw up an implementation plan.

**Evacuation module**

The evacuation model of ESCAPE estimates the time needed for all the inhabitants to leave the area: from the moment the first people enter their cars until the last person reaches safety. This estimate depends amongst others on the number of exit points available through which the people can escape the area at risk. It is assumed that the evacuation will proceed in an organised manner, where everyone responds to the evacuation call and to advices. The residents get advices on their evacuation route as well as on their departure time.

**The evacuation network**

The road network that is used during the evacuation has been simplified to keep evacuation relatively simple. Logical sub areas, called the zones, make up the area at risk and all residents of one zone are assigned the same route advice to the same exit. This way the communication needed before and during the evacuation is kept simple.

The evacuation model offers two route options. The first is the assignment to each zone of the quickest route to an exit based on the free flow of traffic. For this, the algorithm of Dijkstra is used to solve the static shortest path problem. From each zone the shortest paths to all exits, based on the travel time with free flow speeds, is found by the algorithm. The exit with the shortest travel time is then chosen. In this way, to each exit point a shortest path tree in terms of free-flow travel time is found. This approach has the advantage of avoiding crossing traffic flows. In addition, people will probably accept the advice given because it seems a logical choice for them.
However this arrangement will not lead to an even distribution of vehicles to the exits because of the uneven distribution of people living in an area. It could happen that at some exits people are still waiting while others are unoccupied.

The second assignment of zones to exits is build to avoid this. In this assignment the evacuation model generates routes that reduce the total evacuation time by leading a few zones to other exits. The evacuation time per exit is now kept as similar as possible. As in the first option, all residents in the same zone just use one route to their assigned exit. First, the optimum number of cars per exit are estimated, such that the estimated evacuation time per exit will be equal if the capacity of the exit road is used completely the whole time during the evacuation. For the assignment from zones to exits, heuristic methods are applied that try to minimise the total travel time, under the constraint of the estimated optimum number of cars per exit. A greedy heuristic is then used that first assigns the zones with the highest amount of cars by giving them the best available exit in terms of free flow travel times. Afterwards, a simple local optimisation algorithm searches if a permutation of the assigned exits gives a better result.

**Departure times**
To guarantee free flow on the network, it is necessary that no single route be allocated a greater load than the capacity of its bottleneck, the most limiting link in the route. This capacity is used to work out the maximum flow that may exit the zones over time for all routes in the evacuation. The departure times are also calculated by taking the travel time to the bottleneck and the fact that extra capacity becomes available as soon as all residents have left a zone into account.

The developed algorithm performs the following steps:
1. For each link, it is first counted of how many times this link is part of the evacuation routes. This number divides the capacity of this link within the evacuation routes and thus equally assigns it to each zone that uses it.
2. Now for each zone, the minimum available capacity on its route is determined. This defines a feasible flow for each zone such that the sum of the flows will not exceed capacities on any link.
3. The capacities are then subtracted with these flows and the procedure of assigning flows to zones is repeated iteratively with the remaining capacities, such that finally all available capacity of the evacuation routes is used.
4. Since all vehicles are assumed to drive with the same free flow speed, it is easily calculated backwards what the departure time interval is for each zone to arrive within a given time-interval at the exit. Also, all vehicles departed within these (different) departure intervals from all zones will arrive in the same time interval at common links, since their route from this link to the exit is equal and they arrive within the same time interval. This procedure is repeated for ascending arrival times with a given interval time.

**Busses and shelters**
The possibilities of using busses for those requiring help and the use of shelters is also incorporated into the model though these options are not used in the simulations mentioned in this thesis.

### 2.2.2 Evacuation Calculator

The Evacuation Calculator (EC) was developed by Kasper van Zuilekom (University of Twente) and funded by the DVS (Dienst Verkeer en Scheepvaart, Rijkswaterstaat). Their aim was to
develop a model that could calculate how much time is required for evacuation and could determine the effect of traffic management during the evacuating process on the required evacuation time. The EC is build on trip production en distribution, and can take into account both people and cattle. The application is not bound to a specific traffic model or zonal system. It has been included in the Dutch Flood Management System (Flood Information System, HIS). These are the three objectives of the EC:

- Give a conservative estimate of the evacuation time for the Dutch Flood Management System.
- Give insight on bottle necks in the evacuation process by supporting a number of traffic management methods and sensitivity analyses.

OmniTRANS is the supporting Traffic Model for the EC as part of the RWS-DWW Flood Management System. The available road network covers the whole of the Netherlands. The area is split into zones using the four digit postal code as spatial scale. The socio-economic data for these zones are collected by RWS from the Nieuw Regionaal Model (NRM) to be used for regional model studies. OmniTRANS (also used with Indy) is suited for both static and dynamic traffic assignment models. However the EC only uses the static variant. For specific dike ring studies the social economic data are updated and the network is adjusted to the situation during high water levels. It is possible that certain road parts are flooded already before the evacuation starts or have a high probability of being flooded during the evacuation time. Those roads must not be part of any evacuation route.

### The evacuation modelled in the Evacuation Calculator

First the EC calculates the number of trips needed to evacuate each zone (source zone) in the area at risk. This number of trips per zone depends on the number of people present in that particular area. The NRM provides these numbers. Combined with a departure profile, which indicates the departures of people over time, the number of trips per zone per interval can be calculated. The EC uses a departure profile that is based upon earlier experiences with evacuations during hurricanes in the United Stated of America [VAN DER DOEF 2006]. This is the logistic curve; also know as the S-curve.

When all the needed trips are identified, the EC distributes these numbers for all source zones over the different exits available. For this distribution EC offers four standard options:

- **Reference**: The evacuees from each zone are distributed over each exit available relative to the shortest travel distance between them. The closer a zone is to an exit, the more people from the zone are send to that exit.
- **Nearest exit**: People will leave for the nearest exit point.
- **Traffic management**: The travel distance will be minimised given a use of the exits proportional to the capacity of the exit links (last links leading up to the exit points).
- **Outflow areas**: The user may select any part of the area which needs to be evacuated. Exits are to be selected as well. The third option (Traffic management) now distributes the inhabitants of this partial evacuation over the selected exit points.

Two of them are comparable to the ones used in ESCAPE. Nearest exit and traffic management correspond respectively to the first and second option of ESCAPE. Crossing flows of traffic on the network will lead to avoidable waiting times and bring along a high risk of disturbances such as accidents. The last three distribution options avoid crossing traffic flows whereas the first option will most certainly trigger them.
In the final step of the evacuation process in the EC, it is calculated how much time is needed for all people to organise themselves for departure and to drive from the source zone to the exit zone. The EC then determines the required time for outflow of all the traffic at the various exit points. The calculated traffic flows from sources to exits are assigned to the road network by using a static traffic assignment model. Here the so call All-Or-Nothing assignment is utilized. All the trips between a zone and an exit will be using the same route, specifically the shortest route available. This happens no matter what the conditions on the roads are due to other traffic.

The EC focuses on the general evacuation process. The evacuation of vulnerable people from for instance hospitals is not incorporated explicitly in the model. The organisation of evacuation assistance, traffic management and other rescue and help services is not incorporated either.

**Needed data**
The time needed for the actual evacuation of an area in the EC depends on:
- Number of person who need to be evacuated.
- Departure profile over a certain number of hours.
- Distances from the zones to the various exits.
- Average velocity at which the inhabitants drive to the exits.
- The outflow capacity of various exits.

Taking the previously named factors into account, the EC requires the following input data:
- The source zones, defined areas based on the four digit postal codes.
- The exits point: safe locations just outside the area at risk.
- A distance table between the source zones and exits.
- The number of people present in each source zone.
- The capacities of the exits links: these are the final links in the routes leading up to the exit points.

**Assumptions**
To make a calculation with the EC a number of assumptions must be made. The most important ones are listed here:
- **People present:** All inhabitants are assumed to be present at their homes when the evacuation call is there.
- **Evacuation call response:** It is assumed that everyone responds on the evacuation order and everyone follows advices given on evacuation routes.
- **Departure times:** The model requires a departure profile, which indicates how quick people leave their homes after an evacuation call is given. For this departure profile mostly an S-shaped curve is used. This S-curve is also used in the application with Indy.
- **Average velocity:** The model requires an assumption on the average travel velocities. This velocity depends amongst others on the type of roads, the conditions of the roads and the occurrence of traffic jams. Mostly an average velocity of 20 or 30 km/h is used. Since cars usually drive faster, the use of this low figure means that some delay is incorporated.
- **Outflow at the exits:** The capacity of the exits depends on the road type and on expected traffic jams at or near the exit. If traffic jams outside the evacuated area are expected which reduce the capacity of the exit, the capacity of the exit in the model must be reduced by a reduction factor. In previous applications of the EC a reduction factor of 0.2 was used on the exit capacities. This factor of 0.2 was based on in-depth analysis of several dike ring areas using a macroscopic dynamic assignment.
2.2.3 A dynamic traffic assignment model: Indy

In this section the Dynamic Traffic Assignment (DTA) model of Indy is presented. DTA models are first discussed in general. Though not specifically designed for evacuation modelling, a DTA model can be well applied to this field. Thereafter Indy will be introduced as well as information on how this model can be used in evacuation modelling.

The Dynamic Traffic Assignment Model

In this section the macroscopic Dynamic Traffic Assignment (DTA) model is discussed. Macroscopic models treat traffic in terms of flows, whereas microscopic models consider each vehicle individually. These models can serve as a good tool to make forecasts about future traffic conditions on transport networks. They can also estimate effects of traffic management, and therefore the models are often used by policy analysts. Although static traffic assignment models already provide insight, the dynamic version is able to capture the true dynamic nature of traffic. Thus it will give more accurate forecasts. In this section the input and the output are first discussed. Also some words are said on the differences between the static and dynamic versions. Then the dynamic assignment framework is discussed, including the route choice and dynamic network loading.

General description of the model

The transport network and the travel demand serve as the input for an assignment model. The transport network consists of nodes, links and the corresponding link characteristics (e.g. length, maximum speed, number of lanes etc.). The network essentially describes the infrastructure supply. The travel demand is given by an origin-destination (OD) matrix with the number of trips from origin nodes to destination nodes. The traffic assignment model is to determine the optimal trade-off between supply and demand such that the travellers choose their optimal route. Typical outputs are link and route flows and travel times and/or costs.

The static assignment problem is essentially a special case of the dynamic assignment problem where only 1 time period is considered. Within this time period, typically the length of a morning peak, the travel demand is assumed to be evenly distributed over the period. The link parameters are assumed to be constant as well. A person travelling from origin to destination in the static assignment model will contribute to all links along the route at the same time, since only one time period is considered. Obviously this may lead to very unrealistic outcomes. Examples are the incorrect assumption that all traffic can complete their trips within a certain period of time, and under- and overestimation of the true congestion due to peak demand.

Dynamic Traffic Assignment framework

The general framework for dynamic traffic assignment is discussed now (pictured in Figure 2). As input we need the transportation network embodying the infrastructure supply and the dynamic OD matrix representing the travel demand. The dynamic OD matrix consists of elements denoting the number of trips from an origin to a certain destination departing at a specific time. In the case of evacuation the OD matrix is created by using both the static OD matrix (containing the total number of trips) and a departure profile. This profile shows the departures of the people over time. More will follow on this later. The dynamic traffic assignment (DTA) model uses these inputs to compute link and route travel times and link and route flows.
A DTA model typically has two main parts: a route choice model and a dynamic network loading model. The route choice model distributes for each departure time and for each OD pair the trips in the dynamic OD matrix over the available routes. The resulting route flows are then transferred to the dynamic network loading (DNL) model. This part of the DTA model simulates the flows over the network and computes the dynamic link travel times and the dynamic link flows. A travel time function will now determine for each link the travel time given the number of vehicles on or flowing into the link. The more traffic there is on a link in terms of density, the higher the travel time of it. After the DNL model has simulated the initial traffic flows, the route travel times are transferred back to the route choice model. Users may adapt their chosen route according to the new traffic conditions. This procedure works iteratively. Route choice is not the only choice that travellers can make. They must also decide on their departure times. To avoid the congestion in peak periods travellers can for instance plan to leave earlier. Given the OD travel times for each departure time, the departure time choice model determines the optimal departure time for all travellers. Essentially the model produces departure time rates. When multiplied by the static OD matrix a new dynamic OD matrix is obtained and a new DTA is performed. The departure choice model is an optional component in the framework and many DTA models do not have this component. The DNL model and the route choice model are explained in some more detail now.

The route choice model
The route choice model basically considers the utilities of all route alternatives for each traveller and determines for all travellers the route that provides the highest utility. In other words determine, given the dynamic OD demand, route flow rates such that no traveller can be better off by choosing another route. This will lead to a so-called dynamic user-equilibrium. The utility is usually expressed in costs. Costs include route travel times and may include fuel costs and others costs as well. The objective of the route choice function is to find route flow rates such that all demand is assigned to a route and such that the route costs for each OD-pair for each departure
time are minimized. What it boils down to is that iteratively route flows rates are determined, based on the current route costs. If there is flow on more expensive routes, then flow is reallocated to cheaper routes until the costs of all routes converge. The question remains how to determine the route costs. The route costs are usually computed by a summation of the corresponding link costs along a route. This summation can basically be performed in two ways, depending on the kind of route choice one would like to model:

- Instantaneous route choice.
- Actual route choice.

In the first case travellers consider the link travel costs (or travel times) on the network at the time of their departure and assume that these costs (or travel times) do not change when travelling along their chosen route. Thus the route costs are simply a summation of the initial constant link costs on the chosen route. The route that yields the lowest cost is chosen. Though this may not be the best option since link costs and travel times may vary over time.

In the second case, that of actual route choice, the travellers consider the link travel costs (or travel times) on the network that they will actually experience when making the trip along a certain route. When making their decision taking the actual route costs into account, the travellers have always made the best decision. There is no alternative route that may have provided them with lower costs when they have reached their destination. One may argue that it is not possible to know beforehand what the traffic conditions may be when travelling to ones destination. But since DTA route models with route choice are usually for the long term, we assume that travellers know from experience over time what the best route alternative is. Thus actual route choice behaviour will generate more realistic results than modelling instantaneous route choice behaviour. But it is also more difficult to calculate since we now have to follow the travellers along their route in order to know what the actual traffic conditions are that they are facing. Thus we need to know the dynamic link travel times. These travel times are unknown and need to be determined by the dynamic network loading.

The dynamic network loading model

Now that the route flows are determined by the route choice model, we have to load these flows onto the network using the dynamic network loading model (DNL). Essentially it propagates flow over the network along the routes from origin to destination taking the interactions with other travellers into account. The DNL model can be written as a system of equations. These represent the constraints such as the flow conservation constraints, the flow propagation constraints, the first-in-first-out constraints and finally the capacity constraints. Given the route flow rates the objective is to find a consistent dynamic traffic pattern in which all these constraints are satisfied. The output consists of dynamic link flows, densities and travel times. These constraints are now briefly discussed.

Flow conservation essentially means that flow is not generated nor lost on the network (not taking the origin and destination nodes into account). For each node and for every time instant the flow into the node at a time instant minus the flow that has this node as it’s destination at this time instant must be equal to the flow out of the node at this time instant minus the flow that originates from this node at this time instant.

That actual movement of vehicles along the route over time is mainly determined by the flow propagation constraints. The constraints make sure that flow entering a certain link exits the link again after the link travel time elapses. The constraints may be different for different assignment models. One way of formulating them is the following. When a vehicle (flow) enters a link at a time instant, they face the traffic on that link at that time. The link density determines the link
travel time $t$ at that moment. The flow propagation constraints will propagate this vehicle (flow) along its route such that it enters the next link at a later time instant. In other words, the flow propagation constraints determine the trajectories of the vehicles.

*First-in-first-out constraints* are usually not added explicitly in the model, but are checked afterwards if they are satisfied. These constraints aim to have no flows overtaking each other on a link. A vehicle (flow) that enters the link first should also exit the link first. At first sight this may seem to contradict the reality in which overtaking occurs naturally. However, in assignment models we generally assume a homogeneous flow in which all vehicles behave similarly. If flow enters later but exists earlier, then this is not consistent with the user-optimal idea. Some users may better be off by waiting some time before entering a link, which is not taken into account in the flow propagation constraints. Hence, FIFO is usually a desired property of the model. However, explicitly adding FIFO constraints make the problem very complex to solve. They can be checked afterwards by looking at the trajectories. If they intersect at some time, FIFO is clearly violated.

*Capacity constraints:* Each link has a physical maximum of inflow and outflow, depending on the number of lanes and the link type. The maximum outflow is usually referred to as the capacity of the link. The capacities may vary over time due to prevailing traffic conditions or for example traffic management measures. So at a node the outflow capacity of the incoming link must not exceed the inflow capacity of the following link. In case were the capacity drops, for instance a decrease in the number of lanes, the flow through the links is limited such that congestion occurs. This will clearly affect the link travel time and therefore the propagation constraints. Besides a physical maximum on the flow there is a physical maximum on the number of vehicles on each link. Vehicles occupy a certain amount of space and this space is limited. This is most evident in case of complete congestion, where the vehicles occupy several kilometres of road space. Congestion occurs when flow cannot freely exit the link anymore due to over saturation of the capacity. Then a queue builds up. When the queue grows until it reaches the beginning of the link, it will also influence the capacity of the links upstream such that a queue starts building up on the previous links as well. This effect is called *spillback*. Spillback constraints can be expressed as an upper bound on the density, called the jam density.

**Indy**

The DTA algorithm INDY, which was jointly developed by TNO, TU Delft and the KU Leuven, allows the analysis of traffic scenarios on transportation networks. INDY is able to predict the traffic conditions of a road network over time via its flexible modelling of the interactions between travel demand and the infrastructure. It can also identify the locations where congestion occurs, determine the effects of bottlenecks and estimate the corresponding delays. It can also take into account different user classes (e.g. driver and vehicle types), making the framework completely “multi-class”. However, in the evacuation modelling only one user class (i.e. one driver and one vehicle type) is taken into account. This is because the dynamic version of congestion modelling is not yet able to handle more than one user class. This does not strongly influence the results since large vehicles are not typically used during a storm surge. INDY is also able to model dynamic traffic management measures.

INDY is able to model congestion. Figure 3 and Figure 4 show the effects of a traffic jam at two different time steps. Figure 3 shows initial building up of the traffic jam. Figure 4 shows the effect of the blockage on other road parts at a later time step.
Figure 3: Blocking back effects at the first time instant: a piece of road is pictured with traffic driving on it from the South to the North. The colored rectangular parts on each section of the road represent the density on that section. The higher (or red colored) these parts are, the more density there is.

Figure 4: Bottleneck effects at a later time step

The way of modelling the congestion is shown on this simple network in Figure 3 and Figure 4 where the people drive from south to north. The height and the colour of the rectangles projected on the road provides information on the current density of vehicles on that part of the network. The green rectangles indicate that there is no congestion and that there is free flow. The large red rectangular indicates areas where the congestion is very heavy.

The situation pictured on the left shows the way in which congestion is modelled in a static way. The vehicles build up in a ‘vertical’ waiting line. With this vertical waiting line only the delaying time of the traffic waiting just before the bottleneck is accounted for and not the other traffic flows on the network. This waiting line is created at the bottleneck location but not in front of it as would occur in real traffic jams. This static name should not be confused with the static...
assignment model. Static in this sense means a static way of modelling blocking back. The latter on the other hand concerns the time element in traffic modelling.

On the right side the dynamic version is shown. Here we see the appearance of so-called horizontal rows. Now the waiting line is located in front of the bottle neck. It is modelled in a more realistic way than the static version. Traffic flows on one road part can now feel the effect of congestion further down the road.

**Optimising the traffic flow**
INDY can search for an optimal spread of road-users over all possible routes. During this process the actual situation on the road is taken into account. Not all macroscopic dynamic models are capable of this. Furthermore is INDY route-based instead of link-based. This means that the travel times of all the different routes are kept track of, instead of just adding the different link travel times. This is important in evacuation modelling where the evacuation routes are often known beforehand and are given as input. Balancing the flow of traffic will give better results than when road-users are just routed over the shortest paths. The results of INDY can therefore be used to influence the route choice of the road-users in order to minimize the congestion during the evacuation process.

**Modelling junctions**
The current version of INDY is not able to model the effect of junctions yet. Delays because of traffic lights as well as crossing and merging traffic flows are not modelled explicitly. However, in evacuation modelling the numbers of crossings tend to be lower than in normal situations.
2.3 Applying Indy to evacuation modelling

This section first begins with an examination of the research area. Things like exit points and possible shelters are discussed. Next the procedure of applying Indy to evacuation modelling is outlined. Amongst other things we will discuss on setting up the origin/destination-matrix and how the parameters of Indy are set. A number of scenarios are looked at with Indy. These scenarios are based on the ones already simulated with the other models. The results of these scenarios are presented in the final part of this section.

2.3.1 Description of the area

The area that will serve as the research area is the region north of the Westerschelde (see Figure 5). This area consists of two regions: Walcheren and Zuid-Beveland. The latter is split into two parts by a canal. The same holds for Walcheren and the Western part of Zuid-Beveland, as well as the Eastern part of Zuid-Beveland and the main land (Noord-Brabant). Therefore Walcheren, Zuid-Beveland West and Zuid-Beveland East can be seen as three islands.

Furthermore the islands are surrounded by the following water bodies: in the west the North Sea, in the south the Westerschelde Estuary and in the north the Oosterschelde. Flood threats mainly occur from the North Sea and Westerschelde Estuary. Because of a barrier (part of the Deltaworks) between the North Sea and the Oosterschelde, the latter is free of extreme high water.
levels. The Westerschelde is an important navigation route towards the harbour of Antwerpen along the Schelde River in Belgium. Thus the Westerschelde Estuary was never closed by a comparable barrier at the Oosterschelde as part of the Deltaworks because the harbour of Antwerpen needed to remain accessible for large ships.

The area of research was reclaimed from the sea. Many ancient embankments in the area still remain as a memory of this stepwise land reclamation. These secondary embankments limit flood extents when floods occur. The area has approximately 200,000 inhabitants, of which most live in the cities Goes, Middelburg and Vlissingen.

The area was hit by a disastrous flooding in 1953 which caused large areas of the Netherlands become flooded. Many people died because of this and many others lost their homes and possessions. After 1953 new safety standards for flood risk management were developed. In the research area flood protection standards have been set to 1/4000 a year. This means that sea conditions with probabilities exceeding 1/4000 a year should not cause floods. Because 100% safety from flooding cannot be guaranteed, and since many inhabitants still remember or know about the 1953 floods, flood issues are very important here. In case flooding does occur in the area, the people in the area have three options:

In case a flooding does occur in the area, the people in the area have three options:
- They can move to local safe(r) areas. These areas are for instance tall buildings or the dunes.
- The people may evacuate out of the area at risk.
- If the flooding is only expected to be little, people may also be advised to stay at their homes. If necessary they should move to the upper floors of their houses.

These options are now explained in somewhat more detail.

Evacuation
If large scale flooding is expected evacuation may be wise. Although the research area consists of islands, people may leave the area at all sides. Possible exit routes are:
- The highway A 58, which leaves the area over a bridge at the east side;
- Two very small bridges at the east site.
- Two dams at the northwest side of the area. These dams connect the research area with the island Noord-Beveland. From that island, cars may go to the north across the Oosterschelde Barrier. This barrier is closed for traffic during storms.
- At the south there is a main road going to Terneuzen. This road connects the research area with the mainland at the south of the research area by a large tunnel underneath the Westerschelde Estuary.
- Furthermore, there are ferries for pedestrians and there is a railroad which goes to the east (across a bridge).

Whether all these routes will be available for evacuation depends on the moment of evacuation. If storms are already blowing, dams may be closed. The tunnel may also be closed well before flooding actually occurs. The bridges in the east may be used also during storms. If evacuation occurs when the storm is already blowing or after flooding has started, some roads may be blocked by fallen trees or other objects or by flood water.
The Province of Zeeland (in which the research area is located) will only advise or order evacuation if it is likely that evacuation may be finished before flooding occurs. Since cars are dangerous places to be during a flooding, traffic jams should not be caught by flood water!

The decision on evacuation or not, therefore, depends on the expected time of flooding and the expected flood patterns, the weather conditions and the expected duration of evacuation from a certain area. Evacuation should not be advised when combinations of heavy storms and precipitation or combinations of freezing temperatures and precipitations are expected. In those cases, accidents may block roads and evacuation may last too long.

**Evacuation procedure**

In the case study area the procedure in which decisions are taken on evacuation is currently triggered by the water level forecasts at Vlissingen. Forecasts are provided by the SWD (Stormvloed Waarschuwingdienst), the Hydro-meteo Dienst Zeeland, and RWS. Forecasts have a lead-time of 6 hours. Currently an effort is being made to extend lead-times to 48 hours.

If the forecasted water level at Vlissingen exceeds 3.10 metres above the Mean Sea Level (+msl) alarm state 3 is reached. This alarm state 3 is part of an alarm system with 5 states which describe the risk of a disaster. In each state certain actions are required. A warning is sent out when the expected level exceeds 3.70 metres + msl. Alarm state 4 is reached when the expected water level exceeds 4.10 metres + msl. In alarm state 3 the mayors of the municipalities are responsible for emergency response. In alarm state 4 the governor of the province takes overall responsibility.

The Province of Zeeland, in which our case study area is situated, has prepared a calamity plan for all municipalities with respect to flooding. In those plans transport means are arranged for schools, hospitals and nursing. Other people are expected to evacuate themselves. When the Governor of the Province decides that evacuation is necessary, this is communicated to the relevant authorities. The public is informed by radio and TV broadcasts. The police are responsible for traffic management during evacuation. No further procedures exit.

Recent studies of evacuation processes have estimated durations of different steps within the evacuation process [VAN DER DOE 2006]:

- Time needed for decision making: 1 hour.
- Response time of organisations and institutions: 4 hours.
- Preparation time of organisations and inhabitants: 8 hours.
- Evacuation time: unknown.

**Organisation of the evacuation**

Evacuation may be organised in different ways: people may just be advised to leave, without further information. They may also be advised to take a certain route to a certain exit point. If it would be possible to organise traffic flows, people may even be ordered to take a certain route to a certain exit point. If the level of organisation is very high, people may even be ordered to leave at a certain time and take a certain route. It is not sure whether people will obey those orders and leave at the time told and go in the direction told.

To inform and advise the public and to organise an evacuation, the government needs at least the following information:

- Information on most likely location and time of failure of the embankments.
- Likely flood patterns.
- Weather conditions.
- Duration of evacuation of the different sub areas within the region.
• Population characteristics and location of vulnerable people, objects and dangerous industries (chemical factories, large fuel deposits).
• Location of shelters and safe spots inside the area.

2.3.2 Approach

In this section the implementation of INDY is described as well as the setup of the basic scenarios.

OmniTrans and the network
OmniTrans is an integrated multi-modal transportation planning package. It basically serves as the platform which INDY runs on. OmniTrans makes it possible to view the used road network, and projects the simulation results from INDY onto the network. The network used is based on the National Regional Model (NRM) PoCo4 network. PoCo4 means that the zones and the road network are based on their four digit postal codes. This can be seen as a measure of detail in the area. For the current research area, this order of detail is sufficient. For smaller areas such as small cities it may not be detailed enough to produce reliable conclusions because of the limited number of roads available.

Use of INDY in evacuation modelling
Because INDY is a DTA model, it is able to simulate traffic over the network in a realistic way such that the results serve as a good indication of the expected traffic outcome resulting from an evacuation. In evacuation modelling INDY input is also input into the origin destination (OD) matrix. In this matrix the trips that INDY should assign to the network are the trips needed to bring people from their homes to a safe(r) location. Thus it specifies the trips from all the zones lying in the area at risk to the different exit points. Once a departure profile is set, INDY simulates all these trips over time according to this profile. After the simulation is completed, the results can be visualised by using the transport program OmniTrans. This allows the user to make conclusions about the input values. For instance one is able to locate bottlenecks and then give arguments on what the causes could be. Different scenarios can now be compared to each other.

Exit points
The five exit points (safe areas outside the at-risk area) are located at positions where roads leave the area. In this case study, these are roads heading up north and to the east (see Table 1). The network (roads and centroids/zones) that is used in INDY is part of the NRM (New Regional Model) as are the social-economic data such as the inhabitants of each zone.

Table 1: Overview of the exits links and their capacity

<table>
<thead>
<tr>
<th>Exit</th>
<th>Description of exit point</th>
<th>Number of Lanes</th>
<th>Exit type</th>
<th>Capacity (cars per hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highway A58 to the North of Brabant</td>
<td>2</td>
<td>Bridge</td>
<td>4,000</td>
</tr>
<tr>
<td>2</td>
<td>Secondary road to the North of Brabant</td>
<td>1</td>
<td>Bridge</td>
<td>1,600</td>
</tr>
<tr>
<td>3</td>
<td>N57 Middelburg to Noord-</td>
<td>1</td>
<td>Dam</td>
<td>1,600</td>
</tr>
</tbody>
</table>
In the basic scenarios there were two options related to the available exit points:

- All exit points were available for evacuating the area at risk, with the exception of the tunnel to Terneuzen.
- Only the eastern roads leading to Brabant were used. This option was considered because the exit points in the north are surrounded by water, and may therefore become inundated in the event of a flood.

### Assignment of exit points to the at-risk zones

The assignment of exit points to the at-risk zones was an important factor in the evacuation modelling, as it determines how the traffic is spread over the network. Improper exit-point assignment can result in increased traffic congestion, thereby lengthening the total evacuation time.

To create the basic scenario three assignment methods were applied:

- Reference assignment;
- Nearest assignment;
- Optimized assignment.

The *reference assignment* is based on the situation in which the inhabitants are free to choose their own route following an evacuation call. For this assignment the inhabitants are divided over the exit points according to an impedance ratio, which gives a measure of the travel difficulty from the zones to the exit points. The closer a zone is to an exit point, the lower the impedance ratio. These ratios are listed in the skim matrix, which contains a measure of zone-to-zone travel impedance. These impedances can be in terms of distance, time or generalized cost. In the skim matrix generated for this study, only distance was taken into account. Exit points are determined by optimizing the impedance ratio for the inhabitants within each zone. Figure 6 presents the *reference assignment*.  

<table>
<thead>
<tr>
<th>Beveland</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4 N62 Westerschelde tunnel</td>
<td>2</td>
<td>Tunnel</td>
<td>3,200</td>
</tr>
<tr>
<td>5 N256 Goes to Noord-Beveland</td>
<td>1</td>
<td>Dam</td>
<td>1,600</td>
</tr>
</tbody>
</table>
For the nearest assignment, the zones are assigned to their nearest exit point. Each zone was assigned the nearest exit point based on the shortest distance (captured in the skim matrix). The nearest assignment is presented below in Figure 7.

In the optimized assignment, the distribution is done such that exit capacity and travel distance are both optimized. The exit capacity is based on the road capacity of the last link before the exit point. The distance between the zones and exit points is given by the skim matrix (discussed above). The assignment method begins by selecting the exit point with the lowest ratio of assigned evacuees to exit capacity. This exit point is then assigned to the nearest zone, and the ratios are recalculated. This procedure continues until all the zones have been given an exit point. The optimized assignment is presented below in Figure 8.
A significant advantage of using the nearest assignment is that traffic cross flows, which are a delaying factor in the flow of traffic, are largely avoided. This delay because of the first ineffective assignment is however not implemented.

**Departure profiles**

The departure profile represents the percentage of departed evacuees as a function of time. During the first simulation, S-curve departure profiles were used (Figure 9). The 16-hour S-curve is based on previous research on evacuee departures resulting from hurricanes. The 8-hour S-curve is essentially the same as the 16-hour S-curve only the evacuee response time is twice as fast. The 8-hour S-curve was used to evaluate how a faster evacuee response time affects the total evacuation time. The 16-hour S-curve can be considered representative of response times in the event of a foreseen flood, while the 8-hour profile is more representative of the response time for a more sudden flood event. Figure 9 shows an 8-hour S-curve departure profile.

The departure profile is entered using departure fractions. For example, for an evenly divided 8-hour departure profile, each hour is assigned a fraction of 1/8 of the original OD matrix. The more realistic S-curve profile was created using Matlab, and the resulting fractions (per hour) were transferred to INDY.
The basic scenarios

The basic scenarios are based on the scenarios simulated earlier with DSS Escape and the Evacuation Calculator by Delft Hydraulics. A total of 12 basic scenarios were created using combinations of the following factors:

- **Departure profile:** An 8-hour or a 16-hour S-curve;
- **Exit points:** All of them (excluding the tunnel) or only those leading to Noord Brabant;
- **Assignment of exit points:** Zones were assigned exit points using one of the three methods discussed earlier – the *reference* assignment, the *nearest* assignment, or the *optimized* assignment.

### 2.3.3 Results of the application of INDY on the Schelde pilot

In this section the results of the INDY simulation are presented and discussed. Once a simulation was completed, Matlab was used to process the results and create diagrams. With OmniTrans it is possible to review the completed simulations both dynamically and statically. Table 2 gives the resulting evacuation times for the 12 basic scenarios. Table 3 compares the resulting evacuation times for the two different departure profiles, Table 4 compares the resulting evacuation times for the different exit points used, and Table 5 compares evacuation times for different assignment methods, and Table 5 compares evacuation times for different exits used.
Table 2: The outcomes of INDY of all the basic scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Departure profile</th>
<th>Assignment</th>
<th>Exits used</th>
<th>Evacuation time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S-curve over 8h</td>
<td>Reference</td>
<td>Only roads to Brabant</td>
<td>36h45</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>22h15</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Nearest</td>
<td>Only roads to Brabant</td>
<td>39h15</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>30h45</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Optimized</td>
<td>Only roads to Brabant</td>
<td>36h30</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>21h45</td>
</tr>
<tr>
<td>7</td>
<td>S-curve over 16h</td>
<td>Reference</td>
<td>Only roads to Brabant</td>
<td>37h00</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>22h15</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>Nearest</td>
<td>Only roads to Brabant</td>
<td>40h15</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>31h45</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Optimized</td>
<td>Only roads to Brabant</td>
<td>37h00</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>22h30</td>
</tr>
</tbody>
</table>

Table 3: Comparison of the Departure Profiles

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Exits used</th>
<th>S-curve over 8h</th>
<th>S-curve over 16h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Only roads to Brabant</td>
<td>36h45</td>
<td>37h00</td>
</tr>
<tr>
<td></td>
<td>All (except tunnel)</td>
<td>22h15</td>
<td>22h15</td>
</tr>
<tr>
<td>Nearest</td>
<td>Only roads to Brabant</td>
<td>39h15</td>
<td>40h15</td>
</tr>
<tr>
<td></td>
<td>All (except tunnel)</td>
<td>30h45</td>
<td>31h45</td>
</tr>
<tr>
<td>Optimized</td>
<td>Only roads to Brabant</td>
<td>36h30</td>
<td>37h00</td>
</tr>
<tr>
<td></td>
<td>All (except tunnel)</td>
<td>21h45</td>
<td>22h30</td>
</tr>
</tbody>
</table>

It was expected that the 16-hour S-curve departure profile would result in faster evacuation times, due to the load on the road network being spread over more hours. The results show that in fact the 8-hour S-curve resulted in faster evacuation times, although the difference was not significant. The maximum difference in resulting evacuation times was 3.5 percent. The 8-hour departure profile proved more effective because during the first hours of evacuation, when the road networks are not at capacity, twice as many evacuees had departed in the 8-hour scenario as in the 16-hour scenario.

Table 4: Scenarios compared by the assignment used.

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Exits used</th>
<th>Reference</th>
<th>Nearest</th>
<th>Optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-curve over 8h</td>
<td>Only roads to Brabant</td>
<td>36h45</td>
<td>39h15</td>
<td>36h30</td>
</tr>
<tr>
<td></td>
<td>All (except tunnel)</td>
<td>22h15</td>
<td>30h45</td>
<td>21h45</td>
</tr>
<tr>
<td>S-curve over 16h</td>
<td>Only roads to Brabant</td>
<td>37h00</td>
<td>40h15</td>
<td>37h00</td>
</tr>
<tr>
<td></td>
<td>All (except tunnel)</td>
<td>22h15</td>
<td>31h45</td>
<td>22h30</td>
</tr>
</tbody>
</table>

Comparing the results on basis of the exit-assignment method cannot be done easily. The difficulty is that crossing flows of traffic are not accounted for when applying INDY. These conflicting flows may appear at junctions (flows cross each other) or at merging roads (two flows become one). The first has the most notable delaying effect. The method of assigning exit points...
has great impact on the number of crossing flows that may appear. While in the optimized and nearest assignments these crossing flows are minimized, they are not minimized in the reference assignment. Because INDY does not account for these cross flow, the evacuation times for the case of reference assignment may be significantly underestimated. Therefore, only the nearest and optimized assignments are currently able to be compared, since they are comparable in their minimized number of crossing flows.

The evacuation times resulting from the optimized assignment were significantly shorter than those resulting from the nearest assignment. As shown in Figure 7, in the nearest assignment almost all of the evacuees are routed towards the two Northern exit points. This is because the area is relatively horizontally stretched, and north-south distances are notably shorter than East-West distances. As a result, two exit points were scarcely used, including the exit point with the largest capacity. This result enforces the reasoning for a tactical assignment done prior to the evacuation. This would require that inhabitants be informed of their exit point prior to the evacuation.

Table 5: Scenarios compared on the exits used.

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Assignment</th>
<th>Only exits in Brabant used</th>
<th>All (except tunnel) exits used</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-curve over 8h</td>
<td>Reference</td>
<td>36h45</td>
<td>22h15</td>
</tr>
<tr>
<td></td>
<td>Nearest</td>
<td>39h15</td>
<td>30h45</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>36h30</td>
<td>21h45</td>
</tr>
<tr>
<td>S-curve over 16h</td>
<td>Reference</td>
<td>37h00</td>
<td>23h30</td>
</tr>
<tr>
<td></td>
<td>Nearest</td>
<td>40h15</td>
<td>31h45</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>37h00</td>
<td>22h30</td>
</tr>
</tbody>
</table>

A decrease in the number of exits increases the evacuation time significantly. Differences in evacuation times for scenarios where only the number of exits was varied ranged from 21% to 39%. This is because the same number of evacuees is using a smaller part of the road network at the same time.

When only using the eastern exits, congestion occurs very early near the exit points where all the evacuation paths join each other. The congestion then spreads throughout large portions of the road network, as shown 12 hours after the evacuation began in Figure 10 below. Roads highlighted in red represent congestion in the network; roads highlighted in green represent traffic moving at (approximately) the speed limit.
Figure 10: (shown in red) when only using the eastern exits
2.4 Comparing Indy to DSS ESCAPE and the EC

In this section the application of Indy in evacuation modelling is compared to the other models specially designed for evacuations. First the differences are discussed from a theoretical perspective. Thereafter the different outcomes of the models are compared to each other.

2.4.1 Comparing the models theoretically

In this section some words are addressed to the differences between the application of Indy in evacuation modelling and the other two specialized evacuation models.

Indy <–> DSS ESCAPE
The application of Indy to evacuation modelling and the evacuation module of ESCAPE differ enormously. Where Indy is a macroscopic dynamic traffic assignment model, really simulating traffic over the network, ESCAPE only calculates statically how long an evacuation will take. ESCAPE determines the departure times and assignment of inhabitants to exits during the optimization of the evacuation process. Indy needs this information prior to the simulation. ESCAPE estimates a route travel time based individual link travel times which are estimated by the flows using them statically; Indy simulates the traffic flows in real time keeping track of the actual route travel times. ESCAPE only considers one route for each origin/destination combination, where Indy can consider multiple routes.

ESCAPE has the advantage of being able to estimate evacuation times within a minute for the area of research. Indy, depending on the number of generated routes, needs almost half an hour to finish the simulation.

Due to the total different operational work done by the two models, it might be interesting to see how the results compare to one and other.

Indy <–> Evacuation Calculator
Indy and the Evacuation Calculator (EC) both run with the help of OmniTRANS. They also commonly share the same preparations (e.g. a priori assignment of zones to exit points) and input (e.g. OD matrix, departure profile). Like Indy the EC is based on a traffic assignment model. The EC uses a static traffic assignment model in stead of the dynamic version (Indy). In contrast to a static model, Indy does really simulate the flows of traffic in a very realistic way. Blocking back at bottlenecks is simulated in a very realistic way. The EC does not even need a real network to provide insight in evacuation times. It only uses the capacity between certain points and a prior estimated average speed to know how long the traffic needs to leave the area at risk. Depending on the overload on certain parts of the roads, a delay on this part may be taken into account. The blocking back however because of this bottleneck will only affect those arriving at the exact location of the bottleneck; it will not affect traffic flows on other roads. Just like ESCAPE, the EC only looks at one possible route per zone/exit combination whereas Indy considers multiple paths.

Again Indy needs more time to evaluate an evacuation process than the other model, EC.
2.4.2 Comparison of the results of the models

The results of the simulations done by Indy were presented in section 2.3.3. It is interesting to compare these to the outcomes of the other discussed models: Evacuation Calculator (EC) and DSS ESCAPE. The three models differ in their approach and applied methods. All the results are listed in the table below. The outcomes of ESCAPE and the EC were obtained by the Delft Hydraulics. ESCAPE does not use input related to departure profiles and exit point assignment. In the last three columns the evacuation times are stated.

Table 6: Comparison of the outcomes of the three models

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Assignment</th>
<th>Exits used</th>
<th>EC*</th>
<th>ESCAPE**</th>
<th>Indy</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-curve over 8h</td>
<td>Reference</td>
<td>Only roads to Brabant</td>
<td>39h</td>
<td>-</td>
<td>37h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>22h</td>
<td>-</td>
<td>22h</td>
</tr>
<tr>
<td></td>
<td>Nearest</td>
<td>Only roads to Brabant</td>
<td>16h</td>
<td>-</td>
<td>40h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>32h</td>
<td>-</td>
<td>24h</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>Only roads to Brabant</td>
<td>13h</td>
<td>54h</td>
<td>37h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>12h</td>
<td>44h</td>
<td>22h</td>
</tr>
<tr>
<td>S-curve over 16h</td>
<td>Reference</td>
<td>Only roads to Brabant</td>
<td>40h</td>
<td>-</td>
<td>37h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>23h</td>
<td>-</td>
<td>24h</td>
</tr>
<tr>
<td></td>
<td>Nearest</td>
<td>Only roads to Brabant</td>
<td>25h</td>
<td>-</td>
<td>40h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>33h</td>
<td>-</td>
<td>32h</td>
</tr>
<tr>
<td></td>
<td>Optimized</td>
<td>Only roads to Brabant</td>
<td>22h</td>
<td>54h</td>
<td>37h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All (except tunnel)</td>
<td>21h</td>
<td>44h</td>
<td>23h</td>
</tr>
</tbody>
</table>

*When taking the results of the EC it is assumed that the average velocity is 30 km/h and there is no reduction factor on the capacities of the exit links.

**An explicit departure profile is not used in DSS ESCAPE: the departure times are set from within the model.

The results of ESCAPE are only comparable to those from Indy and the EC when choosing the optimized assignment. The results of ESCAPE are quite difficult to be compared with because of the different way of modelling. Overall it can be seen that the estimates given by ESCAPE are greatly larger than the other two estimates in all cases.

The EC and Indy do show some similar results. For instance when looking at the reference assignment and using all exits, which represents the most realistically scenario, Indy gives total evacuation times ranging from just over 22 hours to 24 hours. The EC calculates nearly the same results: 22 to 24 hours. Again it should be noted here that in both models the crossing flows of traffic are not simulated at all; because of this the evacuation times are expected to be somewhat higher than those given.

Differences in the outcome can be seen when there is looked at an optimized assignment (and again using all exits). The EC shows its best result of 12 hours, and its worst of 21 hours. Indy however declares that the evacuation cannot be done quicker in any case than approximately 22 hours. The reason for this difference could be explained by the fact that EC does not really simulate the propagation of the traffic. It estimates evacuation times based on the capacities of the different links together with a priori estimated average travel speed. Indy does predict a lot of congestion, especially when applying the 8 hour departure profile. This slows down the traffic significantly, and therefore lengthens the evacuation time.
2.5 Some alternative scenarios using Indy

Various extensions to the basic scenarios were investigated using INDY. Some of these extensions aimed to minimize the evacuation time. These included application of a different departure profile structure, the use of shelters, and the use of the tunnel as an escape route. Other extensions attempted to simulate in more detail the behavior response of inhabitants in the case of an evacuation. Below is a description of the extensions that were applied:

- **Linear departure profile**: Instead of using realistic S-curves, it may be more advantageous for the throughput of traffic to use a linear departure profile.
- **Tunnel**: The Schelde tunnel that serves as the link between Terneuzen and Zuid Beveland is added to the list of exit links.
- **Shortest path**: While INDY tries to spread the evacuees over multiple routes, in reality most people will tend to use the shortest route known to them. Therefore the exit assignment shortest path was added.
- **Dynamic Optimal INDY Assignment**: This is the same procedure as the Optimal Assignment, only the assignment is done during the simulation.
- **Shelters**: By assigning shelters in certain parts of the area (safe spots, critical areas) the number of cars that need to evacuate can be reduced, and thus also the evacuation time.
- **Coupled to a flood scenario**: Delft Hydraulics is able to give prognoses on possible dike breakthroughs and their consequences. By determining the most probable flood scenarios, the evacuation process can be altered such that the most critical areas are evacuated first. It is also possible to alter it such that the time available for evacuating can be extended to even during the actual flooding.

These extensions were applied and evaluated by comparing them to one or more of the basic scenarios.

**Linear departure profile**

Although the S-curves used in the basic scenarios represent a more realistic departure profile, the people are entering the network in a non-linear way. For example, in the case of the 16-hour S-curve departure profile, approximately 80% of evacuees depart over a span of six hours (see Figure 9). It seems logical that when a more linear departure profile is applied this will lead to a more balanced use of the network and thus a reduction in the evacuation time. Therefore two linear departure profiles, an 8-hour and a 16-hour, were created. Figure 11 presents the 16-hour linear and S-curve departure profiles. The comparison of the evacuation times are presented in Table 7.
The use of a linear departure profile results in a decreased evacuation time. This is because with a linear departure profile, the load of traffic is transferred onto the available infrastructure in a more balanced way than when using the S-curve. However, a linear departure profile is impossible to achieve whereas the S-curve represents a realistic (uncontrolled) departure profile.

Use of the Westerschelde tunnel

Figure 12 shows a photograph of the Westerschelde tunnel. In the evacuation simulation done with the models of EC and Escape, the exit possibility of the Westerschelde tunnel was not explored. This is because the possibility of inundation while within the tunnel is considered too dangerous at the moment flooding begins. However, it can be argued that the use of bridges or roads along dams is more dangerous due to the fact that storm weather conditions, such as heavy rain and strong winds, can make it difficult for drivers to maintain control of their vehicles. Within the tunnel drivers are sheltered from storm conditions. Furthermore, the entrance and the exit of the tunnel are located at higher elevations, making the tunnel no more vulnerable to flooding than an average road. Additionally, the tunnel leads to an area south of Terneuzen which is safer than Noord-Beveland and Noord Brabant. Thus it is considered realistic to add the tunnel to the set of exit links. The network including the Westerschelde tunnel as an exit point, with the optimized exit assignment used, is shown.
in Figure 13. The evacuation times resulting from the INDY simulation with and without the tunnel as an exit link are compared in Table 8:

Figure 12: Entrance Westerschelde tunnel at Terneuzen

Figure 13: OmniTrans network with the Westerschelde tunnel (optimized assignment)
Table 8: Outcomes of INDY with the addition of the tunnel

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Assignment</th>
<th>Exits used</th>
<th>Evacuation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-curve over 8h</td>
<td>Optimized</td>
<td>All exits used (excluding tunnel)</td>
<td>21h45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>All exits used (including tunnel)</td>
<td>19h15</td>
</tr>
</tbody>
</table>

The evacuation time is reduced with the inclusion of the tunnel, as the added exit allows for a better spread of traffic. However, given that the tunnel has the second largest capacity (3,200 vehicles per hour), which considerably lessens the load of traffic on the other exit points, the reduction in evacuation time (~11%) was less than expected.

**Shortest path**

In the event that inhabitants are assigned an exit point, but no specific route is assigned, it is likely that the shortest route, which is often the fastest route, will be chosen by the evacuees. INDY attempts to improve the individual travel times by assigning them to alternative routes. The user defines how many of these routes are explored with the iteration parameter. In the current study, this parameter was set to ten meaning that at most ten different routes are considered. If this parameter is set to one, only the shortest route is available to the drivers. Thus, the case in which the iteration parameter is set to one is considered representative of actual conditions in the event that no route is assigned to the evacuees, while the case in which the parameter is set to ten represents conditions in the event that routes were prescribed along with the exit point. These two scenarios were investigated with INDY and the resulting evacuation times are presented in Table 9.

Table 9: Outcomes of INDY with the shortest path

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Assignment</th>
<th>Exits used</th>
<th>Scenario</th>
<th>Iteration Parameter</th>
<th>Evacuation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>8h S-curve</td>
<td>Optimized</td>
<td>All exits</td>
<td>Prescribed Routes</td>
<td>10</td>
<td>21h45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No Prescribed Routes</td>
<td>1</td>
<td>23h15</td>
</tr>
</tbody>
</table>

The shortest-route simulation, in which no routes were assigned to the evacuees, resulted in a longer evacuation time than the case in which ten alternative routes were employed. This is because in the shortest-route simulation, the traffic is confined to one route per exit point, instead of ten. This leads to more congestion which results in a longer evacuation time. This confirms the importance of prescribed routes in the evacuation process.

The degree of improvement is dependent on the road use in the study area. In the area of Walcheren and Zuid-Beveland, most of the traffic uses the highway as part of their route. Even if more paths are considered, a large portion of the traffic will eventually make use of this highway. Thus the advantage of employing multiple routes may be somewhat limited. Traffic conditions 15 hours after evacuation began, for the case of multiple routes and shortest route only, are presented in Figure 14 and Figure 15, respectively. Routes shown in red indicate congestion in the network and routes shown in green indicate traffic moving at almost the speed limit. It can be seen that during an evacuation, the highway serves as the bottleneck in the area, remaining congested until approximately 15 km before the exit points, when it splits into multiple paths. Thus it may be concluded that because of the use of the highway in so many of the alternate routes in the study area, an increased number of routes does not significantly affect the evacuation time. In the case that there are multiple (independent) paths leading toward the exit points, the effect of increasing the number of alternate routes will be more significant.
Optimal INDY exit assignment

Until now the assignment of the vehicles to the exit points has been done outside the INDY simulation. Using one of the exit assignment methods (reference, nearest, optimized) the routes are generated and stored within the OD matrix, which serves as input to INDY. In the following example, INDY is used to assign the zones to the exits. To accomplish this we connect all the exit points with one virtual point. These connections have unlimited capacity and a distance of zero. In the new OD matrix each zone is just assigned to this new point. Thus INDY will now simulate the traffic to this point. Each vehicle will reach this point coming along one of the exit points, because these are the only options for reaching their destination. After the first iteration this will be the closest exit point (initial INDY solution), but later on when new paths are explored the spreading of the traffic is more optimized. Thus INDY will be assigning the zones to the exit points itself. This is shown in Figure 16 and Table 10.
The results show no better results than before. The reason may be that not enough paths are being looked at during the simulation. What INDY will do is generate new paths by looking at the ones already generated. These paths may have quite an overlap. As told before the first path looked at is the shortest one. Since the newly generated paths are more or less variations on the shortest path, it is very unlikely that the new path differs in the used exit point compared to the previously generated paths. In this simulation 10000 paths are generated initially. More generated paths will probably give better results but it also complicates the simulation and thus the running time. For the settings used now, this simulation already took approximately 48 hours to finish. Ideally all available paths must be taken into consideration, but this makes the simulation too complex.

**Shelters**

This extension serves to investigate if the sending of evacuees to shelters significantly reduces the total evacuation time. During the evacuation process, evacuees may be advised to go to nearby safe locations within the risk area if the time is too limited to for everyone to evacuate. Examples of such locations are taller buildings (four or more floors), dunes, secondary embankments or non-flooded areas. Because flood events typically coincide with storm conditions, remaining out of doors for an extended period of time presents a danger for evacuees. As a result it is considered better and safer to send people to shelters such as schools, apartment buildings or hospitals, instead of dunes and embankments where they have no protection against the weather. It should be known by the decision makers where these shelters are located and what their capacities are. These shelters must be prepared with food, water and facilities (e.g. beds). For the organisation process prior to the evacuation (assignment of exit points, etc.) these shelters play an important role. The more people are sent to shelters, the less traffic there is on the road network. This means that people are only routed to shelters in their direct neighbourhood; they must be able to reach them without the use of a car. Because of the relief shelters provide to the road network, the use of shelters should reduce the total evacuation time.

Table 11 presents a list of the shelters used in the simulation. Vlissingen has the largest shelter capacity due to a large number of apartment buildings located along the coast. A total of 9500 people can be directed to the shelters. This is approximately 4.5% of the total number of inhabitants in the
The resulting evacuation times in the case with and without shelters are compared in Table 12.

Table 11: Overview of the available shelters

<table>
<thead>
<tr>
<th>City</th>
<th>Total capacity of shelters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vlissingen</td>
<td>6000</td>
</tr>
<tr>
<td>Middelburg</td>
<td>2000</td>
</tr>
<tr>
<td>Goes</td>
<td>1000</td>
</tr>
<tr>
<td>Kapelle</td>
<td>500</td>
</tr>
<tr>
<td>Total</td>
<td>9500</td>
</tr>
</tbody>
</table>

Table 12: Results the simulations with/without the shelters

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Assignment</th>
<th>Exits used</th>
<th>Remark</th>
<th>Evacuation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-curve over 8h</td>
<td>Optimized</td>
<td>All exits used</td>
<td>No shelters</td>
<td>21h45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Shelters used</td>
<td>20h45</td>
</tr>
</tbody>
</table>

The resulting evacuation time is reduced in the case where shelters are employed. The 4.5% decrease in evacuees using the road network resulted in a comparable decrease in the total evacuation time. Thus, it is expected that to achieve a significant reduction in the evacuation time, the shelter capacity would need to be significantly larger.

**Coupling the model to a flood scenario**

If flooding occurs due to an embankment failure, a part of the area will become flooded. Which area becomes flooded depends on the breach location and the amount of water which flows through the breach. Figure 17 shows possible flooded areas due to a large number of failure locations along the Westerschelde Estuary. In most circumstances only one or a few of these locations will breach at the same time. However in case of a serious flood threat, it is not known where the first breach will be. Figure 17 also shows the importance of the secondary embankments. These secondary embankments limit the flood extent, leaving large parts of the area to remain dry.

![Figure 17: Possible flood scenario](image)

Therefore, it might not be necessary to evacuate the whole area if part of it is expected to remain dry. The critical areas, denoted Figure 17 by red and blue colours, should be evacuated in case of a real
flood threat. In this extension only these critical areas are evacuated and the evacuees are routed outside the research area using the same four exits as before. Approximately 107,000 people reside in the critical areas, representing 53.5% of the total population of the study area. Table 13 presents the evacuation time for the case of only the critical area being evacuated compared with the evacuation time for the entire study area.

Table 13: Results of the partial evacuation

<table>
<thead>
<tr>
<th>Departure profile</th>
<th>Assignment</th>
<th>Exits used</th>
<th>Remark</th>
<th>Evacuation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-curve over 8h</td>
<td>Optimized</td>
<td>All exits used</td>
<td>Whole area</td>
<td>21h45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Only the critical area</td>
<td>12h00</td>
</tr>
</tbody>
</table>

Evacuating only the critical area reduces the total evacuation time by 45%, comparable to the reduction in the number of evacuees. When time available for evacuation is limited, it is advisable to begin evacuating inhabitants from the critical areas first.
3. Optimizing evacuations

In the final chapter of this thesis a method from the area of Operation Research area is applied to the evacuation process. Using a maximum flow algorithm the departure times and the assignment of zones to exits are optimized. This can then serve as new input for Indy in order to find out whether the propagation of traffic does perform better.

In the first sections the maximum flow problem is introduced as well as an algorithm to solve it. Thereafter the program where this algorithm is applied to the evacuation process is explained. Next the results of this program as well as the results of the new Indy simulations are discussed. The chapter will be completed with the conclusions and recommendations for future research.

3.1 Introduction

For the previous chapters a number of simulations were done on evacuation modelling using the dynamic traffic assignment model of Indy. Throughout different scenarios it was seen that the evacuation process was never without problems. Congestion seemed to appear at the same places in nearly all of the cases causing a delay in the overall evacuation. Indy does aim for an optimal propagation of the traffic over different routes to their destinations. But the OD matrices as well as the departure profiles are already set in the preparations of the Indy simulation. In the OD matrix the assignment of zones to exit points is captured. In one of the alternative scenarios Indy was used to search for a better assignment. The arguably non-optimal assignment done prior was thereby taken away. This turned out not to work since the routes that Indy considered were not diverse enough. Therefore exit points lying significantly further away than the nearest exit were never looked at during the simulation. The departure profile on the other hand was based on studies done before on evacuations with hurricane in the United States of America [van der Doef et al. 2006]. But for an optimal spread of the traffic this important factor must be more individualised to improve the total evacuation time. This means a huge organisational effort must be delivered. But if the evacuation time does decrease significantly it may well be something to consider.

Therefore it was chosen to apply another algorithm in order to optimize the previous mentioned assignment of zones to exits and the departure profile. This algorithm was likely to be found in the area of the Operation Research. The maximum flow algorithm seemed to be the most appropriate.

3.2 The maximum flow problem

In this section the general maximum flow (max flow) problem is introduced as well as its relation to the evacuation modelling. Thereafter an existing algorithm is proposed for solving the max flow problem.

3.2.1 Problem definition

In the maximum flow problem, we are given a directed or undirected graph, most commonly directed in real world applications, where one vertex is considered a source and another is the
destination or commonly referred to as the sink. Some object then flows along the edges of the graph from the source to the sink. Each edge along the path is given a maximum capacity that can be transported along that route. The maximum capacity can vary from edge to edge in which case the remainder must either flow along another edge towards the sink or remain at the current vertex for the edge to clear or be reduced. The goal of the maximum flow problem is to determine the maximum amount of throughput in the graph from the source to sink. In real world applications determining the maximum throughput allows the source to know exactly how much of something to produce and send along the path without creating waste.

**Mathematical formulation**

Let \( G = (V, E) \) be the directed graph with the vertex set \( V \) and the edge set \( E \). The size of \( V \) is denoted by \( n \) and the size of \( E \) by \( m \). We assume that \( m > n - 1 \). A graph \( G = (V, E) \) is a flow network if it has two distinguished vertices, a source \( s \) and a sink \( t \), and a positive real-valued capacity \( c(v, w) \) for each edge \( (v, w) \in E \). This capacity function is extended to the other vertex combinations by defining \( c(v, w) = 0 \) if \( (v, w) \not\in E \). A flow on \( G \) is a real valued function on vertex pairs satisfying the following constraints:

\[
\begin{align*}
    f(v, w) &\leq c(v, w) \quad \text{for all } (v, w) \in V \times V \quad \text{(capacity constraint)}, \\
    f(v, w) &= -f(w, v) \quad \text{for all } (v, w) \in V \times V \quad \text{(antisymmetry constraint)}, \\
    \sum_{u \in V} f(u, v) &= 0 \quad \text{for all } v \in V - \{s, t\} \quad \text{(flow conservation constraint)}. 
\end{align*}
\]

The value \( |f| \) of the flow \( f \) is the net flow into the sink:

\[
|f| = \sum_{v \in V} f(v, t)
\]

A maximum flow is a flow of maximum value.

Additionally the definitions of a preflow and excess flow are introduced. The algorithm, discussed in the next section, solves the maximum flow problem by manipulating this preflow on the network. A preflow is a real-valued function on vertex pairs satisfying the capacity and antisymmetry constraints, as well as the following constraint:

\[
\sum_{u \in V} f(u, v) \geq 0 \quad \text{for all } v \in V - \{s\} \quad \text{(nonnegativity constraint)}. 
\]

That is, the total flow into any vertex \( v \neq s \) is at least as great as the flow out of \( v \). Excess flow \( e(v) \) of vertex \( v \) is defined as \( \sum_{u \in V} f(u, v) \), the net flow into \( v \).

The maximum flow problem has been studied for over fifty years. The first classical method for solving this problem was the Ford-Fulkerson augmenting path method. This algorithm is based on the fact that a flow is a maximum flow if and only if there is no augmenting path. That is, there is no path possible from the source to the sink, such that for each edge (or link) in the path there is capacity left. The algorithm repeatedly finds an augmenting path and augments along it, until no augmenting path exists. This simple generic method need not terminate if the network capacities are irrational numbers, and it could take exponential time if the capacities are integers represented in a binary format.

Other classical methods for solving the maximum flow problem are the blocking flow method of Dinic and the push-relabel method developed by Goldberg and Tarjan [GOLDBERG 1988]. The latter will be used in this thesis and is explained in the next section.
3.2.2 The push/relabel algorithm

The push/relabel algorithm has been developed in 1986 by Andrew V. Goldberg and Robert E. Tarjan [GOLDBERG 1988]. With respect to the running time compared to earlier algorithms they managed to improve this to $O(n^2m)$. This means that the running time of the algorithm depends on the square of the number of vertexes times the number of edges in the network.

In this section their version of the push/relabel algorithm is outlined. The algorithm works by examining vertices other than $s$ and $t$ with positive flow excess and pushing excess from them to vertices estimated to be closer to the sink $t$. The goal here is to get as much excess as possible to $t$. If the sink is not reachable from a vertex with a positive excess, the algorithm pushes this excess to vertices estimated to be closer to the source $s$. Eventually the algorithm reaches a state in which all vertices other than $s$ and $t$ have zero excess. At this point the preflow has become a flow, in fact, it has become the maximum flow.

Two issues are addressed now more extensively: how to move flow excess from one vertex to another and how to estimate the distance from a vertex to $s$ or to $t$.

Coming to the first issue, a new variable is introduced: residual capacity $r_f(v,w)$ of a vertex pair $(v,w)$. It is defined as $c(v,w) - f(v,w)$. If a vertex $v$ has positive excess and pair $(v,w)$ has positive residual capacity, then an amount of flow excess up to $\delta = \min(e(v), r_f(v,w))$ can be moved form $v$ to $w$ by adding $\delta$ to $f(v,w)$, and subtracting $\delta$ from $f(w,v)$. There are two ways a pair can have positive residual capacity. Either $(v,w)$ is an edge with flow less than its capacity, or $(w,v)$ is an edge with positive flow. In the first case, moving excess from $v$ to $w$ increases the flow on edge $(v,w)$. In the latter case, it decreases the flow on $(w,v)$. A vertex pair is called a residual edge if $r_f(v,w) > 0$. The residual graph $G_f(V,E_f)$ for a preflow $f$ is the graph whose vertex set is $V$ and whose edge set $E_f$ is the set of residual edges.

For the second issue (estimating the distance from a vertex to the source or the sink) a valid labelling $d$ is defined as a function from the vertices to the nonnegative integers and infinity, such that $d(s) = n$, $d(t) = 0$ and $d(v) \leq d(w) + 1$ for every residual edge $(v,w)$. The intent is that, if $d(v) < n$, then $d(v)$ is a lower bound on the actual distance from $v$ to $t$ in the residual graph $G_f$, and if $d(v) \geq n$, then $d(v) - n$ is a lower bound on the actual distance to $s$ in the residual graph.

Finally an additional definition is needed before outlining the algorithm step by step. A vertex is called active if $v \in V \setminus \{s,t\}$, $d(v) < \infty$, and $e(v) > 0$.

The maximum-flow algorithm starts with the preflow $f$ that is equal to the edge capacity on each edge leaving the source and zero on all other edges, and with some initial sink labelling $d$. The algorithm then repeatedly performs the basic operations push and relabel:

**Push**($v, w$)

*Applicability:* $v$ is active, $r_f(v,w) > 0$ and $d(v) = d(w) + 1$

*Action:* Send $\delta = \min(e(v), r_f(v,w))$ units of flow from $v$ to $w$ as follows:
Relabel(v,w)

**Applicability:**  v is active and \( \forall w \in V \rightarrow r_f(v, w) > 0 \) and \( d(v) \leq d(w) \)

**Action:**  \( d(v) = \min\{d(w) + 1 \mid (v, w) \in E_f\} \)

When there are no active vertices, the algorithm terminates. A summary is given in the scheme below:

**Procedure**  \( \text{Max-Flow}(V, E, s, t, c) \)

Starting from an initial pre-flow

<loop>

While there is an active vertex

Choose an active vertex  v

Apply \( \text{Push}(v,w) \) for some  w  or \( \text{Relabel}(v) \)

The previous will now be illustrated with an example.

**Example**

The algorithm just described is now applied to the simple network shown below. Between the source and the sink lie two other vertexes. The capacities of the edges between the four vertexes are mentioned in the figure. Before any preflow is pushed through the network from the source, none of these capacities are used yet.

![Network Diagram](image)

**Figure 18:** The example network with the link capacities

In the next step an initial preflow, as large as the capacities of the first link(s) allow it to be, is pushed into the network. Also the first labelling is done: the source is given a label equal to the total number of nodes in the network.
In the next step the first active node is selected: a node where the flow into this node is not equal to the flow moving out of this node. In this case, the node right of the source is selected as active node (see Figure 20).

In the following step the excess of flow of the active node is pushed through the network where possible. In this case a flow equal to 1 is pushed further towards the sink since the third node has a lower label than the active node has.
In the next step a new active node is selected, and this node is relabelled again to a number that is 1 higher than its previous label. This time this active node is the third one in the network (Figure 23).

Now the excess flow of the selected node is pushed further down the network, in this case towards the sink (see the figure below). Again this is the only direction it may go because of the lower label number.

Again a new active node is selected. The only one remaining with an excess flow in this network is the second node. This node is now relabelled (with steps of 1) until the excess flow can be pushed away from it. Since the capacity of the edge between this second and third is saturated, this will eventually causes the flow to return to the source (see Figure 25).
Thus the algorithm finds a flow equal to 1; the maximum flow. This maximum flow in the network is shown below:

Figure 26: The maximum flow is found
3.3 Applying the max flow algorithm to evacuation modelling

Projecting the maximum flow problem onto traffic modelling is quite straightforward. The network corresponds with the available road network. The capacities within the flow network are now those of the individual roads. The source and the sink correspond respectively to the origin and destination of the traffic. In evacuations the latter correspond respectively to the zone and exit point.

The aim now is to seek for traffic flows during the evacuation process such that the network is used most efficient. Capacities of roads should never be exceeded. This will lead to congestion and thus slow down the evacuation. The application of the max flow algorithm, which is outlined below, searches for a maximum flow between zones and an exit per chosen time interval.

For the evacuation modelling the push/relabel algorithm is applied iteratively. A step-wise instruction is given on how to apply it to the evacuation. The steps are programmed as follows:

1. Choose a time-interval in which the sub problems per exits are to be solved. In the simulations done, an interval of 15 minutes is chosen.
2. Choose the exit point with the nearest non-empty zone still available bases on the shortest path distances.
3. Solve the max-flow problem for the combination of the chosen exit point and his nearest non-empty zone.
4. Update capacities on the link of the network, and solve the max-flow problem for the next nearest non-empty zone.
5. Repeat step 4 until no more flow is found for a number (user-input) of zones. Move to step 2 until all exits have been solved for this time-step. For the network the residual network is used with the remaining capacities for each link.
6. Update the time with the chosen time interval and repeat the process again (with the original network capacities) until no demand is left in any zone. All inhabitants are now given a time interval in which they are supposed to leave.

A couple of notes should be made motivating some of the steps made in this implementation of the max flow algorithm. First of all the flows of traffic are not simulated anywhere in the program. Thus at the time of the next interval there is still traffic using the network released in previous time intervals. To minimize conflicts in road usage, the nearest zones are unloaded first. The idea is that traffic coming from a certain zone will not yet use the parts of the network where other earlier released traffic is still driving. Conflicts are tried to be kept at a minimum, but may well be there. For instance, the max flow algorithm may find routes for certain traffic flows which may seem cumbersome. These routes may be directed along zones which are unloaded at a later time instant and thus cause conflicts with the newly released traffic.

At the start of each interval, the exit with the nearest non-empty zone is looked at. This will make certain that the traffic does not take unnecessary long routes, especially at the end of the program.

The implementation of the program has been done using the mathematical software of Matlab. For the push/relabel algorithm the code of [GLEICH 2006] is used.
### 3.4 Results and discussion

The max flow algorithm application from the previous section has been used for the research area (Zuid-Beveland and Walcheren, as introduced in 2.3.1). The assumptions made before also hold for this case. It is also assumed that the initial four exits are available for use. The estimated evacuation time is calculated as follows: With 15 minutes set as the interval, the max flow application calculates the time needed to let all inhabitants depart from their homes. Once all inhabitants have left their homes, the evacuation is only finished when the last inhabitant reaches his exit point. Thus an estimation is made of the travel time of the people leaving in the final intervals which have the longest travel time. This estimation is added to the time of the last departure. The result is listed in the following table:

<table>
<thead>
<tr>
<th>Time till last departure</th>
<th>Estimated time till last arrival</th>
<th>Indy check</th>
</tr>
</thead>
<tbody>
<tr>
<td>14h00</td>
<td>14h35</td>
<td>18h00</td>
</tr>
</tbody>
</table>

The output of the max flow application, the origin/destination matrices per interval, can serve as input for Indy. Since Indy really simulates the traffic on the network in contrast to the max flow application, it is interesting to see what results are given when using this new input. This is also shown in Table 14. Compared to the initial estimation, it is significantly longer (~23%). With help of the software program OmniTRANS, one can review the traffic flows of Indy. It can be seen that at some locations there is still congestion appearing.

As said before the max flow application does not take the time factor into account. Thus it might be that earlier released vehicles conflict with later released vehicles on certain roads. By releasing traffic from the zones in order of their travel distance to the exit points, this has been prevented as much as possible. However, the max flow application may have found paths that are significantly longer than the shortest paths available. Thus, traffic on these longer paths may still conflict other traffic flows released at a later time instant when their paths join each other. Also the generated routes in Indy still have their limitations. In contrast to Indy, the max flow algorithm can make use of any possible route.

The mentioned results can also be compared to the ‘best’ result of the simulations done by Indy earlier. When choosing the 8 hour linear profile together with an optimized assignment of zones to exit points, a simulated time of 20h45 was found. Thus with the newly found input there is an improvement of nearly 7 percent. It is interesting to find out what causes this improvement by comparing the different inputs. Below respectively the departure profile and the assignment of zones to exits, found by the max flow application, are pictured.
The departure profile appears to be almost linear. Releasing the traffic evenly spread over a time period seems to reduce the congestion. The assignment pictured in Figure 28 is difficult to compare to the optimized one Figure 8: lines between two points of the first one may mean that only part of that particular zone is assigned to that exit. In the optimized assignment, zones are
assigned entirely to one exit. Conclusions on the assignment can be better drawn from the table below. It shows, in numbers, how many people are assigned to each exit:

Table 15: Number of people assigned to the available exits

<table>
<thead>
<tr>
<th>Exit:</th>
<th>Secondary road to the North of Brabant</th>
<th>Highway A58 to the North of Brabant</th>
<th>N57 Middelburg to Noord-Beveland</th>
<th>N256 Goes to Noord-Beveland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priori Optimized assignment</td>
<td>16633</td>
<td>37892</td>
<td>17555</td>
<td>17501</td>
</tr>
<tr>
<td>Max flow</td>
<td>20441</td>
<td>25925</td>
<td>21659</td>
<td>21559</td>
</tr>
</tbody>
</table>

As can be seen, there are significantly less people sent to the exits in the direction of Brabant (first two exits in the table). It was shown before that indeed at these exits the most congestion appeared.
3.5 Conclusions and recommendations

In this chapter a new approach of the evacuation modelling was investigated. With the application of maximum flow algorithm one aims to use the available infrastructure as efficient as possible. Congestion needs to be avoided as much as possible, because it slows down the evacuation of the traffic.

It was shown, using only the outcome of the max flow application, that an evacuation of Zuid-Beveland and Walcheren could be done within 15 hours, where previous simulations showed no better results than 20 hours.

However there are some shortcomings in the max flow application, the most important one being the absence of the time factor. The evacuation problem is only solved statically with the new application, and the traffic is never simulated dynamically. A check of the input generated by the application with help of the dynamic traffic assignment model of Indy showed less optimistic results (18 hours), nevertheless still being better than any of the other earlier results.

Another shortcoming is the number of routes used in the evacuating. The max flow algorithm tries to find all possible routes for its maximum flow without looking at travel time of those routes. The number of routes in a network grow exponentially in the number of vertices. Thus it may be that it sends traffic via routes that take a significantly longer time to travel compared to other shorter routes. Not only will people refuse to go via these routes being aware of the longer travel times, also vehicles given significantly longer routes may conflict with other vehicles leaving at a later time instant.

For future research on this topic, routes and the time factor are ones to look at. Incorporating time dynamically in the model, one must try to follow the different traffic flows. Knowing where and when these flows are, one can reconsider releasing traffic from other zones at a later time instant if they might conflict with other flows.

Concerning the routes, it might be better to restrict them to those not deviating too much from the shortest path. One way to get around this is to use the so-called path formulation of the max flow problem. This is however a linear programming approach and needs a different way of solving. This formulation is based on the fact that any flow can be decomposed into a finite number of subflows each corresponding to a path from $s$ to $t$.

The number of edges in our network is still $m$. Let $e_1,..,e_m$ denote all the edges in the network. Now suppose there $r$ distinct paths in the network that may be used for evacuation. It could for instance be that for each used zone exit combination 3 non-overlapping routes are selected. All these paths are enumerated as $P_1,..,P_r$. Now the so-called arc-path incidence matrix $D = [d_{ij}]$ is introduced. It is defined by

\[\text{Error! Objects cannot be created from editing field codes.}\]

Define the column $m$ vector $c = [c_i]$ where $c_i$ is equal to the capacity of edge $e_i$. Furthermore, let the column $r$ vector $f = [f_i]$ denote the amount of flow which is sent from $s$ to $t$. The path formulation of the maximum flow problem is now:

\[
\begin{align*}
\text{maximize} & \quad z = \mathbf{uf} \\
\text{subject to} & \quad D\mathbf{f} \leq \mathbf{b} \\
& \quad \mathbf{f} \geq 0
\end{align*}
\]

After converting this problem to standard form it may be solved used some linear programming package.
4. Overall conclusions and recommendations

The outcome of the Indy application was compared to two other specialized models: ESCAPE and the EC. The results of the model ESCAPE gave significantly other numbers with respect to evacuation times compared to Indy and EC. The results of Indy and EC were almost equivalent to each other. However Indy performs a precise simulation of the traffic movement on the road network in contrast to the EC. The latter only gives a relatively simple estimation time, based on a couple of road characteristics. Hence Indy is far more suitable for analysing the bottlenecks if the user requires.

Maximum flow application
It was shown that, purely based on the outcome of the max flow application, an evacuation of Zuid-Beveland and Walcheren could be done within 15 hours, where previous simulations showed no better results than 20 hours.

However there are some shortcomings in the max flow application, the most important one being the absence of the time factor. The evacuation problem is only solved statically with the new application, and the traffic is never simulated dynamically. A check of the input generated by the application with help of the dynamic traffic assignment model of Indy showed less optimistic results (18 hours), nevertheless still being better than any of the other earlier results done with Indy.

For future research factor of time needs to be incorporated in the max flow application. Now it is possible to follow the different traffic flows. Knowing where and when these flows are, one can reconsider releasing traffic from other zones at a later time instant if they might conflict with other flows.

Another shortcoming is the number of routes used in the evacuating. The max flow algorithm tries to find all possible routes for its maximum flow without looking at travel time of those routes. Thus it may be that it sends traffic via routes that take a significantly longer time to travel compared to other shorter routes. Not only will people refuse to go via these routes being aware of the longer travel times, also, model-wise, vehicles given significantly longer routes may conflict with other vehicles leaving at a later time instant.

Recommendations on this topic would be to restrict the number of routes to those not deviating too much from the shortest path. However it works against the whole idea of the max flow application. It different approach would be the solution: the path formulation of the max flow problem was given in section 3.5.

Recommendations
The research is based on a theoretical background. For practical use there are many more factors which should be taken into account.

The outcomes of the models are very hard to implement in practice. For example more individualized departure times as well as advised evacuation routes are sometimes hard to understand for the inhabitants. Many will refuse to follow up these assigned advises and this will contribute to chaos during the evacuation. Moreover at the time of an imminent disaster panic takes over the control.

For a realistic simulation of evacuations this human behaviour needs to be modelled as well. So a social study has to be done on these effects in addition to the advanced traffic simulation models.

Another example is incorporating road blocks due to natural and human causes. A storm surge can cause trees to fall down on the roads and cars can collide due to panic situations. Emergency services should instantly be prepared to take care of this problem. And alternative routes, if necessary, should be assigned.

On top of this the individual advises, especially as a result of the max flow application, are hard to communicate before and during the evacuation. In the future this could be done via their mobile phones and navigation systems in cars. In addition, cars can be tracked by their mobile phone, which helps regulating the traffic flow. In this way the evacuation plan can be altered at any time instant according to the current situation.
5. References


