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SHIP TRAFFIC FLOW SIMULATION STUDY FOR PORT EXTENSIONS, WITH CASE EXTENSION PORT OF ROTTERDAM

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ABSTRACT

This paper describes the estimation of the capacity of the wet infrastructure of a port system using traffic flow simulation models. Moreover an indication will be given on the estimation of the number of encounters as a key-parameter for internal safety.

The paper deals with the following items:

- *Description of the traffic flow simulation model Harboursim*
  The capacity of a port system can only be determined if the required service level in terms acceptable waiting times or turnaround times is provided. In all ports in the world, a lot of parameters controlling the ship traffic are stochastic of nature. This necessitates the development of probabilistic traffic flow simulation models to estimate waiting times and with that the port capacity. An outline will be given with respect to the functioning of the traffic flow simulation model "HARBOURSIM".
- *Ship traffic rules*
  Many ports in the world do not have strict appointed traffic rules as encounter and overtake possibilities in the different channel sections, traffic rules in turning and mooring basins, safety separation times between vessels and priorities. Nevertheless for safety reasons each port applies traffic rules. Therefore discussions with VTS-operators and the pilot organizations are the basis of the traffic rules applied in a capacity simulation study. The several ship traffic rules are discussed in this paper.
- *A sensitivity analysis within the frame work of a case study for the Port of Rotterdam*
  A sensitivity analysis of the model on safety distances and vessel speeds, applied for the port of Rotterdam, will be presented.
- *Internal safety*
  Moreover an indication will be given to estimate the number of encounters as a key parameter for the internal safety of the port.

SOMMAIRE

Cet article donne une estimation de la capacité d'infrastructure mouillée d'un système portuaire utilisant des modèles de simulation de trafic. Nous donnerons également une estimation du nombre de rencontres comme paramètre clé pour la sécurité intérieure.

Cet article traite des thèmes suivants :

- *Description of the traffic flow simulation model Harboursim*
  La capacité d'un système portuaire ne peut être déterminée que si le niveau de service requis en termes de délais acceptables d'attente ou de battement est fourni. Dans tous les ports du monde, de nombreux paramètres contrôlant le trafic maritime sont de nature stochastique. Ceci nécessite le développement de modèles de simulation de trafic probabilistiques. Nous donnerons une esquisse dans le respect du fonctionnement du modèle de simulation de trafic « HARBOURSIM ».
- *Ship traffic rules*
  De nombreux ports dans le monde ne disposent pas des règles de trafic strictement définies telles que celles concernant les possibilités de rencontres et de dépassement dans les différentes sections des canaux, les règles de trafic dans les zones d'évitage et d'amarrage, les délais de séparation de sécurité entre les navires et les priorités. Néanmoins, pour des raisons de sécurité, chaque port pratique des règles de circulation. Pour cette raison, les discussions avec les opérateurs du système d'organisation du trafic maritime et les organisations des pilotes constituent la base des règles de trafic maritime appliquées dans une étude de simulation de capacité.
- *A sensitivity analysis within the frame work of a case study for the Port of Rotterdam*
  Une analyse de sensibilité du modèle sur les distances de sécurité et de vitesse du navire sera présentée, appliquée pour Maasvlakte1 du port of Rotterdam.
- Internal safety

Nous donnerons également une indication à titre d'estimation du nombre de rencontres comme paramètre clé pour la sécurité intérieure.

Keywords: Port capacity
Traffic flow simulation models

1 INTRODUCTION

For a sound estimation of the capacity of the wet infrastructure a port system in terms of number of ships that can be handled per year with an adequate service level and an adequate safety level, simple methods are not good enough.
A port complex with many terminals and a lot of different fleet types combined with a complex wet infra structure can only be schematized as a complex system.
For the description of such a complex port system the “process description” is considered as an appropriate and efficient method. This method describes the behaviour of each alive component and the interactions with other components in the belonging modules of the model, for example the interaction between the component Ship on arrival and the component VTS for permission to enter the port system. The model simulates the ship movements from arrival buoy to the different terminals.

For this reason Delft University of Technology developed the traffic flow simulation model Harboursim. In the next chapters first the model Harboursim will be discussed after which the application for the extension of the port of Rotterdam is explained broadly.

The structure of this traffic flow simulation model consists of two parts:

a. The definition part
In the definition part the structure of the model in terms of components, attributes of components and the interactions between the components are defined.
b. The dynamic part
This part describes the behaviour of the components in the belonging modules.

Table 1 shows the most important components with the modules.

Table 1: Components and modules of the model HARBOURSIM

Component	Name module	Process description
Generator	Genprocess	Generates the ship traffic and assigns the attributes of the ship
Ship	Shipprocess	Describes the process of the component ship
Quay master	Qmasterprocess	Checks the availability of the quay and assigns a berth to a requesting vessel
VTS	Vtsprocess	Checks tidal conditions and traffic situation
Terminal operator	Termprocess	Determines the service time (dwell time along the quay)
Tidal conditions	Tideprocess	Determines the tidal conditions
Tug	Tugprocess	Registers the number of tugs in operation
Section occupation	Occupationsections	Reserves the occupation of a channel section

2 PROCESS OF THE CLASS OF COMPONENTS GENERATOR

For each fleet the generator creates ship arrivals according to the belonging inter arrival time distribution.
A fleet is defined as a group of ships belonging to the same class with the same destination in the port.
An inter arrival time is the time between two successive arrivals of ships from the same fleet. For instance for the port of Rotterdam in the order of 40 generators generate the ship traffic.

When a ship has been generated the attributes are assigned.
The main attributes are listed below:

1. Ship class
2. Length
3. Draught
4. Destination in the port
5. Incoming route
6. Outgoing route
7. Ship speeds in the various port sections
8. Separation time with respect to other vessels
9. Service time (mooring, unloading, loading and demooring)
10. Tidal windows
11. etc.

Ship class
The ship class is mainly used to specify the traffic rules, for instance to determine whether it is allowed to overtake or to meet another ship in a certain port section.

Ship length
The ship length is important to determine the free quay length and of course the quay occupancy.

Draught and tidal window
The draught of the ship is important when dealing with tidal windows.

Destination in the port and incoming and outgoing routes
When a ship is generated the incoming route as well as the outgoing route is assigned. Moreover the dwell times in the relevant port sections are given and the way (normal sailing or manoeuvring) the ship is passing the port sections is indicated.
Table 2 gives an example of required input data for incoming vessels with a certain destination.

Table 2: Example of an incoming route through the port system

	Incoming traffic to terminal destination 26								
route	**s1**	**s2**	**s4**	**s5**	**s18**	**s19**	**s20**	**s24**	**s26**
	Ship type 2								
sailing times [min.]	26.9	11.3	6.1	2.7	3.8	4.7	4.7	0.5	20.0
sailing / manoeuvring	sailing	sailing	sailing	sailing	sailing	sailing	sailing	sailing	manoeuvring
	Ship type 3								
sailing times [min.]	26.9	15.1	7.3	3.2	7.6	9.5	9.5	1.1	20.0
sailing / manoeuvring	sailing	sailing	sailing	sailing	sailing	sailing	sailing	sailing	manoeuvring
	Ship type 4								
sailing times [min.]	26.9	15.1	9.1	4.1	7.6	9.5	9.5	1.1	30.0
sailing / manoeuvring	sailing	sailing	sailing	sailing	sailing	sailing	sailing	sailing	manoeuvring
	Ship type 5								
sailing times [min.]	44.8	22.7	12.2	5.4	7.6	9.5	9.5	1.1	30.0
sailing / manoeuvring	sailing	sailing	sailing	sailing	sailing	sailing	sailing	sailing	manoeuvring

It is remarked that mooring in section 26 is considered as manoeuvring
When a ship is manoeuvring in a certain area it is forbidden for another ship to be at the same time in this area.

Separation times
Separation times between vessels are based on safety consideration. Separation times are dependent on the vessel type. For instance the separation time between a passenger vessel and a LNG-carrier is much higher than between general cargo vessels.

Service time and inter arrival time distributions
As inter arrival times, service times are determined by taking samples from a distribution function.
Each ship generator is provided with an inter arrival time distribution and a service time distribution.
Based on practical experiences very often Negative Exponential Distributions (NED) can be used to describe the arrival process (see Figure 1) and Erlang-k distributions for the service process.

The density function of a NED distribution is:

$$f(t) = \lambda e^{-\lambda t}$$

Where:
λ= arrival rate and
t=inter arrival time.

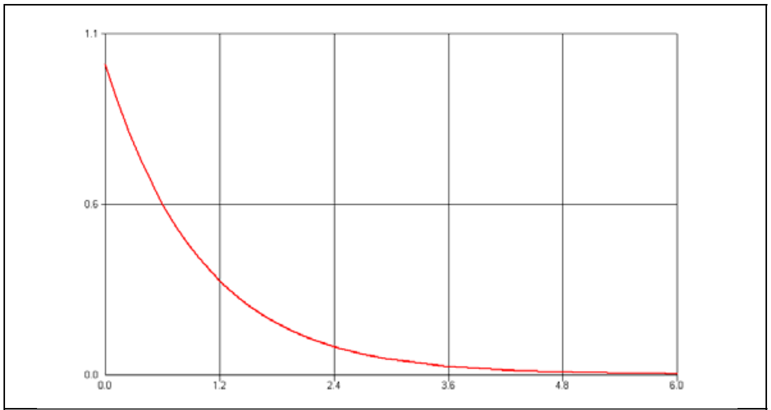


Figure 1: Negative exponential distribution with λ= 1

Mostly the service times can be fitted in an Erlang-k distribution.
The service time is supposed to be subdivided in a number of stages (mooring, unloading, loading and demooring) and this is also the nature of the Erlang-k distribution.

The Erlang-k distribution may be thought to be built up out of k negative exponential distributions (see Figure 2).
The mathematical formulation of the probability density function is:

$$f(t) = \frac{(k\mu)^k t^{k-1} e^{-k.\mu.t}}{(k-1)!}$$

Where:
μ = the service rate,
t = average service time and
k=the shape parameter.

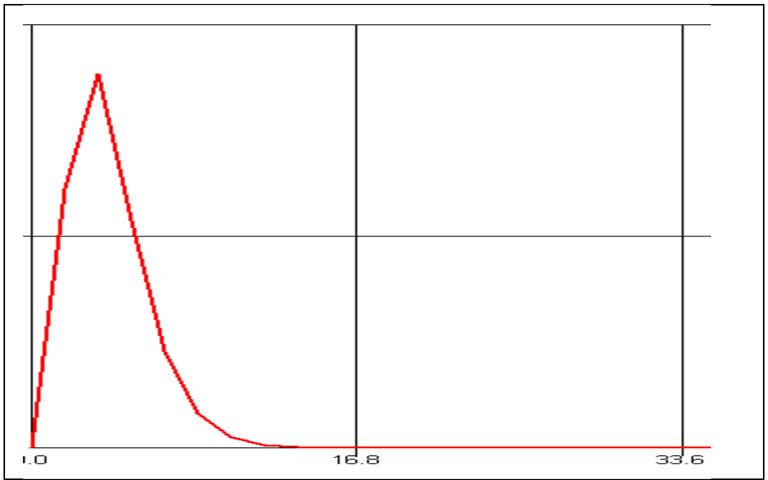


Figure 2: Erlang-k distribution with μ=4 en k=4

3 PROCESS OF THE SHIP

A ship is generated by the corresponding generator and starts her process at the arrival buoy.
On arrival a berth is requested. Next the VTS-component checks currents, water levels and traffic situation. In case a problem exists the ship has to wait and after a few minutes the situation is checked again.
The ship sails to the berth and after the service time again the VTS is asked for permission to leave the port.
The process of the ship and the interactions of the component ship with other components are given in Figure 3.

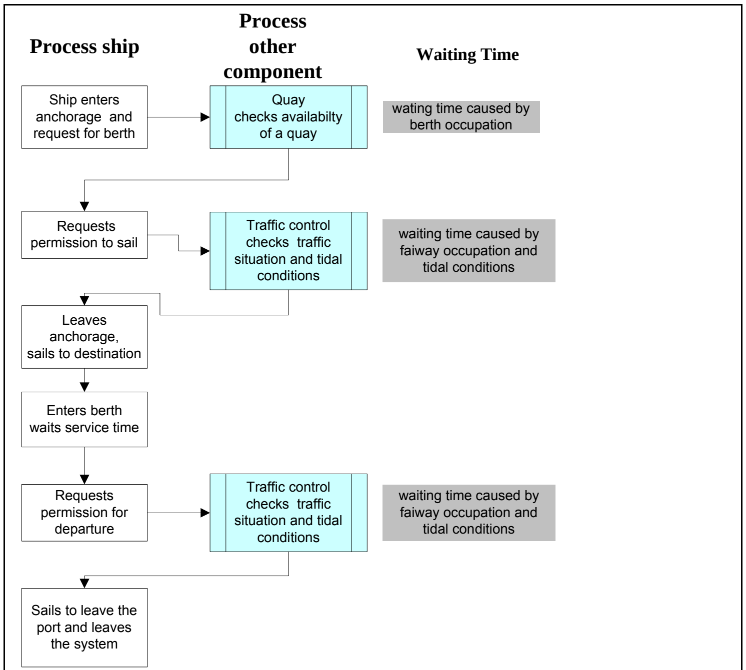


Figure 3: Process of the ship and interactions between component ship with other components

4 PROCESS OF THE VTS-COMPONENTS

As indicated in the process of the ship, the VTS-components are checking the currents, water levels (tidal windows) and the ship traffic.
To check the ship traffic the VTS component uses the ship traffic rules, or user operating rules, specified for each port section.
In principal two sail characteristics are distinguished:

a. Normal sailing
   Depending on the ship classes, ships are permitted to encounter or to overtake each other.
b. Manoeuvring (turning circles and mooring basins)
   In case a ship is manoeuvring no other ship is allowed to enter this area.

Figure 4: Ship traffic rules in manoeuvring areas and straight sections

Table 3: Ship traffic rules in port section

Section 4	Ship class, overtaking							
	1	2	3	4	5	6	7	8
Class 1	1	1	1	1	1	1	0	1
Class 2	1	1	1	1	1	1	0	1
Class 3	1	1	0	0	0	0	0	1
Class 4	1	1	0	0	0	0	0	1
Class 5	1	1	0	0	0	0	0	1
Class 6	1	1	0	0	0	0	0	1
Class 7	0	0	0	0	0	0	0	0
Class 8	1	1	1	1	1	1	0	1

	Ship class, encounter							
Section 4	1	2	3	4	5	6	7	8
Class 1	1	1	1	1	1	1	0	1
Class 2	1	1	1	1	1	1	0	1
Class 3	1	1	1	1	1	0	0	1
Class 4	1	1	1	1	1	0	0	1
Class 5	1	1	1	1	0	0	0	1
Class 6	1	1	0	0	0	0	0	1
Class 7	0	0	0	0	0	0	0	0
Class 8	1	1	1	1	1	1	0	1

As an example Table 3 shows traffic rules for normal sailing in a port section. For example overtaking is not allowed for class 3 and class 4 ships (0), while an encounter between class 3 and class 4 ships is permitted (1). In general traffic rules for overtaking are stricter.

5 CASE STUDY EXTENSION OF THE PORT OF ROTTERDAM

5.1 INTRODUCTION

After a period of stabilization of cargo throughput Rotterdam experiences a significant growth over the last years, which is expected to continue in the coming decades. To accommodate this growth land reclamation with a capacity of 1000 ha terminal area is being developed (see Figure 5).

The traffic flow simulation model HARBOURSIM was used to estimate the capacity of the wet infrastructure. The simulation study has been carried out to registers among other things ship-waiting times and turnaround times as a function of the traffic volume, applied ship traffic rules.

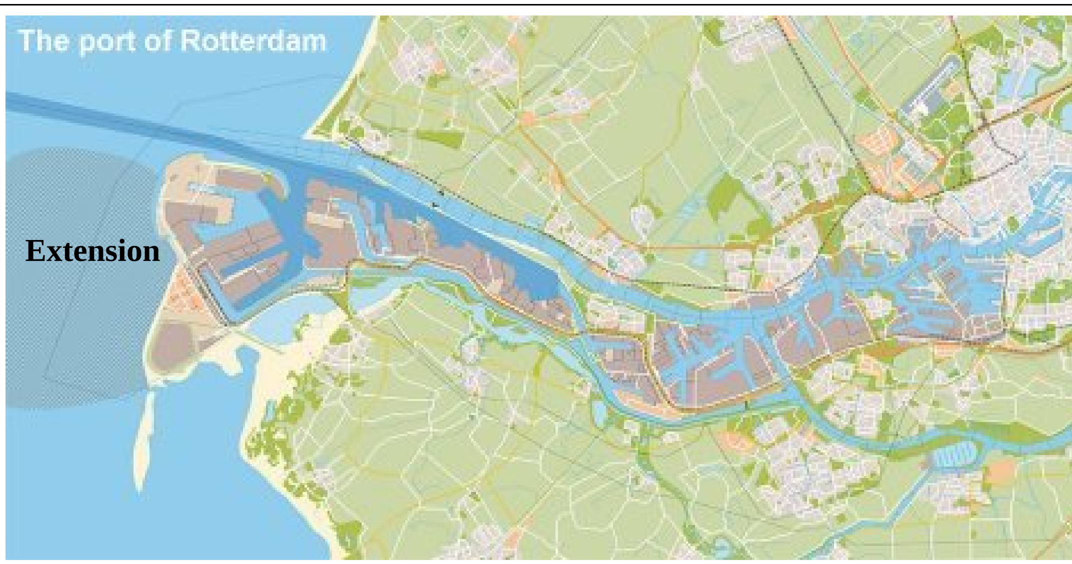


Figure 5: Port extension Port of Rotterdam

5.2 CASE STUDY OBJECTIVE

The objectives of the port of Rotterdam with respect to the port extension are a safe and smooth handling of the marine traffic. This is translated in two main objectives:

1. safe means that that the present safety level should be maintained and
2. smooth means that the service level should fulfill the demands of the ship owners.

The safety level can be secured by maintaining or if necessary by extending traffic rules. The service level, mostly identified with ship waiting times, is influenced by berth occupancy and occupancy of the wet infra structure. As stated if the safety level of the port is too low, traffic rules can be extended but by extending the traffic rules most probably waiting times will go up and with that the service level will go down.

As for most ports in the world a lot of parameters are controlling the ship traffic and many parameters are stochastic of nature. Together with the complexity of the Port of Rotterdam this necessitates the application of probabilistic traffic flow simulation model.

5.3 MODEL SPECIFICATION

Figure 6 gives the artists impression of the extension of the port of Rotterdam.
For the simulation of the marine traffic the wet infra structure should be subdivided in a number of port sections. The subdivision should be done in such a way that one set of ship traffic rules can be applied for a port section. This subdivision of simulated part of the port of Rotterdam (Maasvlakte 1 and Maasvlakte 2) is given in Figure 7.
Two areas were distinguished:
The existing reclaimed area Maasvlakte 1 (completed round 1980, the gray area in Figure 6 and 7)
The proposed extension Maasvlakte 2 (colored area in Figure 6 and 7)

For each terminal destination fleet generators were inserted in the model; Table 4 shows the different fleets per terminal destination for the year 2004.

Table 4: Individual ship generators

Destination	Number vessels per ship class 1	2	3	4	5	6	Total	Generators
Caland kanaal	1500	1250	1000	750	500	0	5000	1 tot 5
MOT	0	0	0	0	40	92	132	6 tot 7
TOR	0	771	86	0	0	0	857	8 tot 9
LYONDELL	182	182	0	0	0	0	364	10 tot 11
APM	0	567	185	207	131	0	1090	12 tot 15
ECT Europa	0	536	175	196	124	0	1031	16 tot 19
ECT Amazone	0	1072	350	392	247	0	2061	20 tot 23
EMO	91	91	259	0	6	36	483	24 tot 28
NEREFCO	140	455	105	0		0	700	29 tot 31
Stad Rott	10310	7896	2752	212	0	0	21170	31 tot 35
Totaal							32888	

To specify the traffic rules ship classes are distinguished; Table 5 shows the different classes for the year 2004.

Table 5: Ship classes

Ship class	Description
6	Channel bound Length>300 m Draft>17.4
5	Semi channel bound, Length>300 m Draft14.3- 17.4 m
4	Length>300, Draft<14,3 m
3	Length 200- 300 m
2	Length 200- 300 m
1	Length <120 m

Figure 6: Artist impression of the extension of the port of Rotterdam

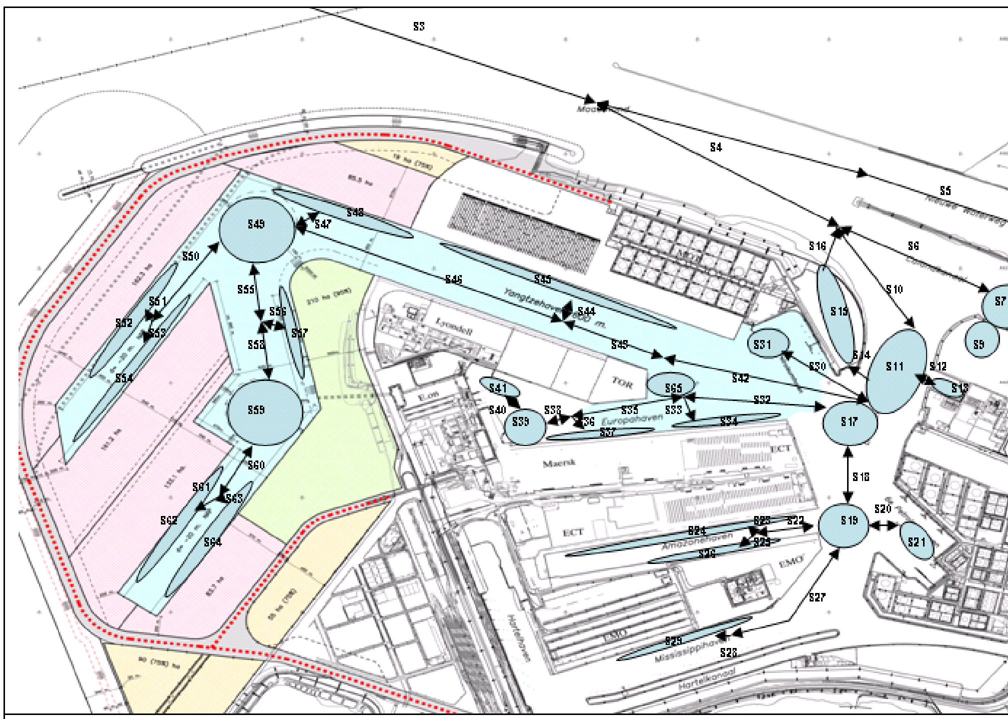


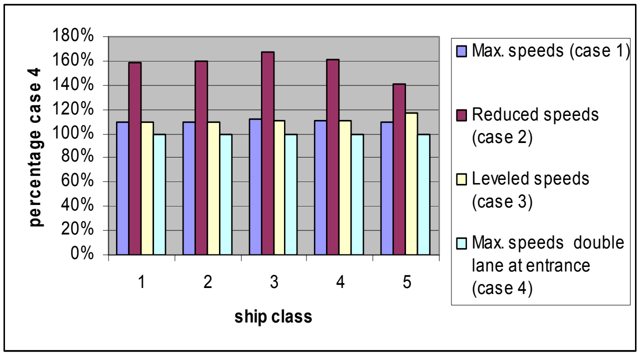
Figure 7: Port sections with manoeuvring areas

5.4 VALIDATION AND SENSITIVITY ANALYSIS

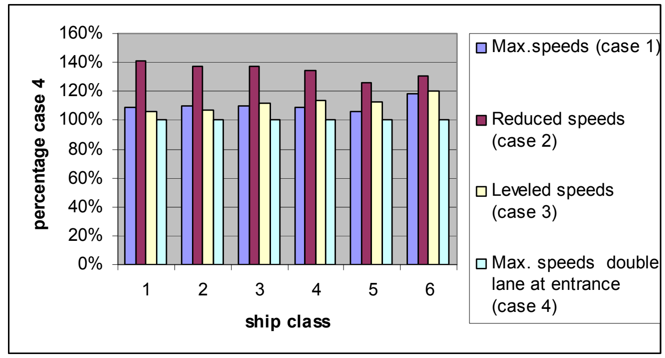
For the validation of the model a sensitivity analysis was carried out with respect to the vessel speeds. The following groups of speeds were simulated:

1. maximum speeds (case 1);
2. reduced speeds (case 2);
3. leveled speeds (case 3, the speed differences when using the maximum speeds were reduced as much as possible);
4. maximum speeds and incase of sufficient width, the possibility to sail beside one another (case 4).

The results are presented in Figure 8.



Dynamic turn around time Europoort



Dynamic turn around times Maasvlakte 1

Figure 8: Sensitivity analysis vessel speeds for model validation

Figure 8 shows the so called “dynamic turn around times” of the vessels spread over 6 classes.
The dynamic turn around time is defined as the sailing time from arrival buoy to the terminal and reverse plus the waiting times caused by occupation of the port sections.
The results of Maasvlakte 1 and Europoort (the more inner part of the port) show the same trends:

1. When going from maximum speeds to reduced speeds an increase can be observed of the turnaround time. This is of course due to the reduced speeds of the vessels but also waiting times due to occupation of port sections are going up.
2. When the speed differences of case 1 (maximum speeds) are levelled the turn around times show only minor deviations. From this it is concluded that the waiting times are not caused by speed differences but for the major part by encounter problems and manoeuvring activities.
3. The maximum speeds combined with the possibility to sail beside one another, case 4, results in a reduction of about 10% of the TAT related to case 1.

The simulated cases show that the model reproduces reality in such detail that various scenarios of changes to the traffic rules could be evaluated by using this model.

6 SAFETY ASPECTS

Traffic flow simulation models, such as presented in the previous section might also be used to evaluate safety aspects.

With respect to the internal safety, potential encounters are registered and have to be converted to encounter densities. A potential encounter is defined as an entry of another vessel in the safety domain of the vessel. It is quite clear that the safety domain around a vessel depends on the vessel type and the location of the vessel in the port. Assumptions have to be made to specify the safety domains.
To register the number of encounters the track of each individual ship has to be determined; therefore also assumptions have to be made with respect to the distribution of the ships over the width of the channel.

Based on historical data with respect to accident rates and the registered number of encounters the number of accidents per year per port area can be estimated.
Figure 9 shows an example of such an encounter density.
From the encounter density conclusions can be drawn with respect to the future risk levels.
If the risk level is too high additional traffic rules could be considered. However it should be realised that more traffic rules mostly leads to increased waiting times and with that a reduction of the service level.

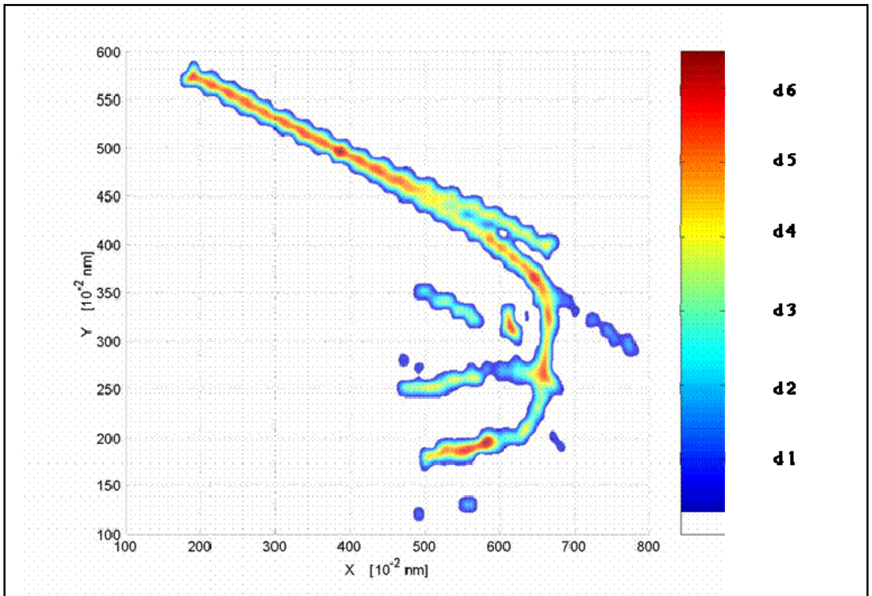


Figure 9: Potential encounter densities, Maasvlakte 1

7 CONCLUSIONS AND RECOMMENDATIONS

1. Capacity models satisfy quite well the demands
   It should be remarked that the accuracy strongly depends on the input data as the arrival pattern, the service time and applied traffic rules. In most ports of the world, traffic rules will always bring about higher ship waiting times. When dealing with low traffic intensities, the contribution to the total ship waiting times, caused by traffic rules is of minor importance when dealing with low traffic intensities.

2. The internal safety estimation in ports using traffic flow simulation models is just starting
   - Estimation of the safety domain around should be improved
   - Estimation of the ship track should be improved
     More data on vessel behaviour depending on infrastructural conditions, environmental conditions, and traffic loads should be collected for a statistical description of vessels tracks. Radar interpretations are suitable for this purpose.
   - More information should come available with respect to encounter frequencies specified per location and per encounter type for each port to be evaluated. Port VTS systems are quite capable to provide this type of information.

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