A possible VTS-Operator Support System based on vessel traffic simulation.

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In this paper a possible Operator Support System (OSS) for vessel traffic management on the basis of vessel traffic simulation is presented. A proposal is made for a tool to give the Vessel Traffic Service (VTS) operator a better understanding in the development of vessel traffic situations and in advance identification of unsafe situations. An indication is given for the safety margins of the ships, indicating the reserves in control and space to cope with unexpected and unsafe situations. This information should enable the VTS-operator to manage and optimise the safety and efficiency of the future vessel traffic situations, without jeopardising the safety in the port of Rotterdam.
Abstract

The Rotterdam Municipal Port Management (RMPM) performs a role in managing the port's safety, i.e. the safety of the people, the vessel traffic and the environment. One of the measures the RMPM has taken is the implementation of a Vessel Traffic Management System (VTMS) to monitor and manage the vessel traffic situations. The evolution of the vessel traffic is on-going and today's operator at the Vessel Traffic Service (VTS) centre needs a better understanding of the development of vessel traffic situations and accompanying safety.

In this paper a possibility for an Operator Support System (OSS) for vessel traffic management on the basis of vessel traffic simulation is presented. A proposal is made for a tool to provide the VTS-operator more insight in the development of vessel traffic situations and in advance identification of unsafe situations.

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Preface

This graduation project was partly performed at the Rotterdam Municipal Port Management and partly at the section Man Machine Systems at Delft University of Technology. This report consists of the submitted article, an abstract and appendices.

The author wishes to thank dr. ir. W. Veldhuyzen and dr. ir. P.A. Wieringa for a year and a half of inspirational academic work and life. I have learned a lot.

Thanks to all my fellow students and the staff of the Man Machine Systems section for the great time on the faculty. Special thanks to all the students who “lived” on the Denktank during the last two years for sharing good and bad times. Also thanks to all people connected to the Rotterdam Youth Council for the necessary distraction during my graduation period. It helps to keep a clear focus on your work by being confronted with the world outside the university, or at least to recharge the battery for a short moment.

Special thanks for my good friends Kenneth and Sander, for all the memorable hours we spend in the evening and at night at the Denktank. Thanks guys, without your help, motivation and vision on my project the building would have been finished before my graduation. Now I know for sure that I will not have to go through the humiliation of actually seeing people work in a building that was not their when I started my graduation project.

Thanks to Kees en Ineke for all their feedback and offering a possibility to escape the university for a moment.

To Karianne for all her love, understanding and patience. Now we are both free to do what we want. Let us go on with our lives.

And last but not least to my parents for always believing in me, keeping their patience all those years. It has not been in vain. Thank you for all the possibilities you have offered me.

Douwe Leguit

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### Abbreviations

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<tr>
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<th>Description</th>
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<tr>
<td>AIS</td>
<td>Automatic Identification System</td>
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<tr>
<td>CPA</td>
<td>Closest Point of Approach</td>
</tr>
<tr>
<td>DHS</td>
<td>Data Handling System</td>
</tr>
<tr>
<td>ECDIS</td>
<td>Electronic Chart Display</td>
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<tr>
<td>ETA</td>
<td>Estimated Time of Arrival</td>
</tr>
<tr>
<td>ETD</td>
<td>Estimated Time of Departure</td>
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<tr>
<td>FTS</td>
<td>Fast Time Simulation</td>
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<tr>
<td>HCC</td>
<td>Harbour Co-ordination Centre</td>
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<td>HO</td>
<td>Human Operator</td>
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<tr>
<td>NAD</td>
<td>Nautical Accident Database</td>
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<td>OSS</td>
<td>Operator Support System</td>
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<tr>
<td>PID</td>
<td>Proportional, Integral and Differential controller</td>
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<td>RCI</td>
<td>Reserve Control Indicator</td>
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<tr>
<td>RMPM</td>
<td>Rotterdam Municipal Port Management</td>
</tr>
<tr>
<td>SBP</td>
<td>Shore Based Pilotage</td>
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<tr>
<td>TEU</td>
<td>Twenty feet Equivalent Unit</td>
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<td>VTMIS</td>
<td>Vessel Traffic Management and Information System</td>
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<td>VTMS</td>
<td>Vessel Traffic Management System</td>
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<td>VTS</td>
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Submitted paper

A possible VTS-operator support system based on vessel traffic simulation.
A possible VTS-operator support system based on vessel traffic simulation.

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Abstract - The Rotterdam Municipal Port Management (RMPM) performs a role in managing the port's safety, i.e. the safety of the people, the vessel traffic and the environment. One of the measures the RMPM has taken is the implementation of a Vessel Traffic Management System (VTMS) to monitor and manage the vessel traffic situations. The evolution of the vessel traffic is on going and today's operator at the Vessel Traffic Service (VTS) centre needs a better understanding of the development of vessel traffic situations and accompanying safety. In this paper a possibility for an Operator Support System (OSS) for vessel traffic management on the basis of vessel traffic simulation is presented. A proposal is made for a tool to provide the VTS-operator more insight in the development of vessel traffic situations and in advance identification of unsafe situations. An indication is given for the safety margins of the simulated ships, which indicate the reserves in control and space to cope with unexpected and unsafe situations. These safety margins give an indication of the safety level of the predicted vessel traffic situation. This information should enable the VTS-operator to manage and optimise future vessel traffic situations on its safety and efficiency, without jeopardising the safety in the port of Rotterdam.

Introduction

The port of Rotterdam is one of the world's main ports. Approximately 30,000 sea-going and 130,000 inland vessels visit the port every year, resulting in respectively 80,000 and 360,000 vessel movements. On behalf of the Dutch ministry of transportation the RMPM is delegated to promote the safety and efficiency of the vessel traffic in the port of Rotterdam. The RMPM uses a variety of traffic measures and rules to guarantee a safe and efficient passage of the vessels. One of the main measures taken was the implementation of a Vessel Traffic Management System.

Vessel Traffic Management System

After over a decade of development and discussion the old shore based radar system, which dated from 1956, was replaced by the VTMS in 1987. The objective of VTMS is to provide a safe and efficient vessel traffic flow in the port of Rotterdam. The system can be divided into two main functions, which are integrated through the Data Handling System (DHS):

- **Traffic co-ordination**: operational management by co-ordination of vessel traffic in the port.
- **Traffic guidance**: monitoring and guidance of sea going and inland vessels.

Traffic co-ordination takes place at the Harbour Control Centre (HCC), supervising the overall development of the vessel traffic situation in the port. Traffic guidance takes place at VTS-centres near the waterway. Each VTS-centre guards the development of the vessel traffic situation in its own area.

VTMS developments

The VTMS is an evolving system. In 1999 a mid-life conversion of the system is carried out. Changes are made to the interface of and information exchange between the various systems of the VTMS and the vessel traffic. However new functionality is not added.

Developments related to VTMS can be divided into:

- **Organisational developments**.

  Developments related to the way information exchange is organised. For instance the development of Vessel Traffic Management and Information Services (VTMIS) to acquire information on the ship status by exchanging VTMS-information with other ports. Or the development of shore-based pilotage (SBP), which relocates the pilot from ship to shore and makes the information exchange between ship and pilot a crucial point. SBP is not (directly) considered to be a task of the VTMS, but it shall effect the way VTMS-information is exchanged and organised.

- **Technological developments**.

  The possibility to assess the ship's status and accompanying traffic situation by using new technological developments. Main developments are the installation of an Electronic Chart Display (ECDIS) and an Automatic Identification System (AIS) on the ship's bridge to determine the positions of ships in a certain area. By doing so
the Human Operator (HO) both on the ship’s bridge, as well as in the VTS-centre, has the opportunity to obtain a better overview of the current vessel traffic situation.

**Nautical developments**

These comprise the developments concerning the knowledge and skills available both on ships and at VTS-centres. An increasing problem is the quality of the staff on board of ships. Their skills are not always up to international standards and nautical English is often not well mastered, which can lead to miscommunication and, in the worst case, dangerous situations. This is partly compensated by the presence of a native pilot that masters the language. Partly, since the presence of a pilot relocates the communication problems from shore to the ship’s bridge, still leaving a possibility for miscommunication between the staff and the pilot.

**Problem definition**

For the management of the vessel traffic flows the VTS-operator will require more insight in the development of vessel traffic situations. Nowadays the VTS-operator relies to a greater extent on his own internal representation of the vessel traffic to perform a vessel traffic prediction, but the time delays and complexity of the vessel traffic makes it hard to predict an overview of the vessel traffic situation. Technological and organisational developments related to VTMS can help the VTS-operator, especially in the event of communication problems, to obtain the necessary information with high accuracy and speed.

For a proper overview the VTS-operator needs to know:
- Was a ship will be in the nearby future.
- Whether there will be other ships that share the same waterway.
- Whether the accumulation of ships in a certain area can lead to an unsafe situation.
- What actions have to be taken to prevent the appearance of these unsafe situations.

This leads to the following questions:
- Is it possible to give the operator more insight in the development of vessel traffic?
- How can the development of vessel traffic situations be judged with respect to safety?
- What does the VTS-operator need to know to prevent the occurrence of unsafe situations?

It is stated that the VTS-operator may benefit from an Operator Support System, which provides the operator with more insight in vessel traffic development and occurrence of possible unsafe situations.

The objective of this study is to determine the possibility to support the VTS-operator in vessel traffic management using an OSS based on vessel traffic simulation, giving a prediction for the vessel traffic development and accompanying safety level.

The OSS should comply with the following requirements:
- It should make a selection of the ships to should simulate.
- It should generate a route plan.
- It should generate a possible traffic schedule.
- The operator should be able to interactively assess different scenarios by adjusting the traffic schedule.
- It should give an overview of the future traffic situation for the time that a ship sails through the shipping lanes until it reaches its destination.
- It should give an indication of the safety level for the future vessel traffic situation.
- The presentation of the traffic situation should be orderly.
- The presentation of the safety indication should give an instant overview of the safety level of the predicted traffic situation.

**Vessel traffic safety**

To obtain insight in vessel traffic safety a definition for nautical safety should be given. From there possible standards for the safety assessment of a ship’s status can be proposed. For the safety assessment of future vessel traffic situations, a prediction has to be made to obtain information concerning the future vessel traffic status.

**Nautical safety**

The way ship accidents are presented in the media has a major influence on the acceptance by the public of nautical risks. The experience of safety by the public is often coupled to the consequences and not the risk of an accident. For that a distinction has to be made between the terms undesired situation, risk and nautical safety. A ship accident -due to grounding, collision, breaking or sinking-, as well as its consequences, can be considered as an undesired situation.

Most ports collect information concerning ship accidents in a Nautical Accident Database (NAD). The probability of a nautical accident can be estimated by using these databases. For the definition of undesired situation a comparison is made with the definition used for nautical accidents in the NAD. An undesired situation is defined as: “a situation, which held considerable damages or losses toward man, environment or material”. The following classification can be used:
- **Man:**
  - (In)direct a considerable amount of injured people.
- (In)direct a considerable amount of dead people.
- Environment:
  - Considerable damage to nature reserve which takes years to recover.
  - High cleaning expenses of the nature reserve for the society.
- Material:
  - Damage to vessels.
  - Damage to infrastructures.
  - Obstruction of the shipping lane.
  - Damage to a neighbourhood.

The risk of an undesired situation can be defined as: "the hazard level and duration combined with the likelihood of leading to that undesired situation^"

On basis of the previous statements the following definition of nautical safety is used: "to what extent the risk of undesired nautical situations can be reduced, i.e. the probability of undesired nautical situations, their hazard level and duration^".

**Standards for safety assessment**

For the design of harbour basins and assessment of vessel traffic situations the RMPM increasingly uses simulators. The subjective assessment of the data obtained by of simulator runs is often considered as a major limitation. The use of safety standards for an objective safety assessment of data acquired by simulator runs has been investigated extensively. Research into objective (mathematical) standards has not lead to an unambiguous and objective assessment method for simulator data.

The safety assessment of the data obtained by simulator runs often focuses on:
- Determination of the probability of crossing the borderlines of the shipping lane by observing the Closest Point of Approach (CPA) during the simulation.
- To what extent the ship's controls rudder, motor, trusters and tugs are used to carry out a specific manoeuvre. The degree of available control during this manoeuvre gives an indication for the resilience of the system to deal with unexpected situations and can be indicated using a Reserve Control Indicator (RCI).

Assumed is that both the pilot and the VTS-operator use an internal model to predict the future vessel traffic situation using similar standards for the safety assessment, i.e. the probability of crossing the borderlines and the available control left to prevent this from happening. It can be considered wise to use similar

This approach can be worked out into:
- Required versus available space.
- Required versus available ship control.

**Required versus available space**

A vessel needs a specific amount of space for a safe passage, assuming an optimal usage of this space by the vessel. When disturbances are acting upon the vessel a correction will be needed to hold the optimal path. At first the required space will increase, followed by a claim on the reserves in control to make sure that the required space will not exceed the available space.

The available space for a clear passage of a certain ship will not only be defined by the physical boundaries of the waterway, but also by the surrounding vessels and buoyage. In this way the relation required versus available space could give an indication for the probability of the occurrence of an undesired situation.

**Required versus available ship control**

In case of disturbances the required space will increase if a correction is not made in time. The effect of a disturbance is related to the degree of correction and to what degree the reserves in control are used. The reserve in control is the difference of the amount of required control and the available control. If disturbances or failures cannot be corrected due to the small available reserves, this can lead to undesired and therefore unsafe situations.

The ratio required versus available control gives a relative indication to what extent the ship's control is used. It is an addition to the standard for required versus available space. It is possible that, while the first standard gives no indication for the probability of the occurrence of an undesired situation, the standard for ship control is decreased to a minimum. At that moment the standard for ship control can gives an indication for a possible unsafe situation, since unforeseen disturbance or events shall lead to a deviation from the desired path for there will be no control left to compensate.

A combination of both standards should give the operator more insight in the vessel traffic safety by observing the status of all ships in a (specific) situation. The combination of both standards seems logical, since in most case a deliberation has to be made upon the control effort versus the deviation of the system.

**Safety assessment of vessel traffic**

The safety assessment of a vessel traffic prediction can be divided into two parts:
- The actual vessel traffic prediction.
- Safety assessment of the vessel traffic prediction on basis of the proposed safety standards.
Vessel traffic prediction by simulation

To obtain a better understanding of the development of vessel traffic safety, a prediction of the future vessel traffic situation can help. This can be done using vessel traffic simulation, which makes it possible to predict in a short time a future vessel traffic situation. Studies on simulation as an OSS have been conducted by TNO-IWECO within the framework of the development of the current VTMS. These studies focused on both a short term (15 minutes) as well as a long term (4 hours) vessel traffic prediction.

Vessel traffic simulation offers the possibility to:
- Simulate various ships for different situations and/or strategies in a short time.
- Study relations between various parameters with relatively low costs.
- Perform an objective evaluation of a situation, by using mathematical standards to assess the simulation data.

The main limitations of vessel traffic simulation are:
- The quality of the results depends on the quality of the models used.
- The estimation of a ship's future speed determines for a greater part the reliability of the prediction.
- The quality of the available (initial) information from the VTMS database determines the quality of the results.

Safety assessment of vessel traffic prediction

For the safety assessment of the vessel traffic prediction, data on the status of the ships is needed for two purposes:
- To acquire data for future use of the safety standards.
- To assess the vessel traffic prediction on its safety.

In both cases vessel traffic simulation is used to fulfill these requests. As mentioned before it gives the opportunity to acquire data on the future vessel traffic status in a short time, which makes fast safety assessment of vessel traffic development within reach of the VTS-operator.

The first purpose concerns the data acquisition for the safety standards. Multiple simulations of all relevant ship types under varying hydrological and meteorological conditions (e.g. current and wind) have to be performed. The environmental conditions are in fact disturbances that cause the ship to deviate from the desired track and demand active control to sail the ship back to its desired path. These two effects result into a distribution of the required space and control under those conditions. The resulting distributions for each ship type under different conditions are stored in a database for future use.

The second purpose is the actual safety assessment of the vessel traffic prediction. By simulation of the vessel traffic data is obtained concerning the vessel traffic situation. The predicted vessel traffic situation can be assessed on its safety by using the proposed safety standards. For this the information stored in the above-mentioned database can be used.

An Operator Support System based on vessel traffic simulation

The intention of the OSS is to give an insight in the vessel traffic development, and to give an indication for the safety margins of a ship to cope with unexpected and unsafe situations.
A distinction is made between the different functions within the OSS, as is shown in Figure 1:

- **Selection and route planning.**
  Selects all relevant ships from the VTMS database and determines the route plan based on the initial position and the destination of the ships according to the information from the VTMS database.

- **Traffic scheduling.**
  Determines the schedule using the information from the VTMS database and the route plan.

- **Vessel traffic simulation.**
  Predicts development of the vessel traffic situations over a certain period of time.

- **Safety assessment vessel traffic prediction.**
  Assess the vessel traffic prediction by means of the proposed safety standards.

- **Presentation vessel traffic prediction and safety indication.**
  Presents the results of the vessel traffic prediction and accompanying safety assessment to the VTS-operator.

By adjusting the schedule the VTS-operator can optimise the predicted vessel traffic situation for its safety and efficiency.

The above mentioned functions will subsequently be described, giving a global indication of the tasks that have to be fulfilled.

### Selection and route planning

The first step of the OSS is to make a selection of all vessels that should be simulated. For this information stored in the VTMS database should be filtered to obtain a list of ships that should be observed. The VTMS database contains:

- Information on the actual vessel traffic status.
- Information on the Estimated Time of Arrival (ETA) and Departure (ETD) of ships.
- Ship (type) related information.
- Information on cargo.
- Hydrological information.
- Meteorological information.

Criteria by which the relevant information can be distinguished from the irrelevant information are:

- Ship type: length, depth and manoeuvrability.
- Cargo: dangerous substances.
- Ship’s position: position within area of interest.

Using these criteria a list of ships can be obtained that should be observed. This ship list combined with the VTMS information is used to determine a route plan. For each ship a route can be obtained using the initial position and the destination as a starting point.

### Traffic scheduling

By combining the information from the route planning and the VTMS-database a traffic schedule can be made up. Effects of vessel traffic interaction on the schedule due to ship encounters are not considered at this point.

However encounters which are considered relevant for the safety assessment of the vessel traffic prediction should be added to a list of potential encounters, for this list will form a starting point for the safety assessment.

The safety assessment of the vessel traffic prediction should emphasise the effects of possible future encounters of ships with other ships or objects, by indicating a drop of the safety level in case of encounters.

The VTS-operator should have the opportunity to interactively adapt the schedule, to be able to optimise the safety and efficiency of the vessel traffic.

### Vessel traffic simulation

The vessel traffic can be simulated over a certain period of time, assuming the proposed schedule. The purpose of the vessel traffic simulation is dual.

First of all it is a possibility to determine the minimal distance between two ships that will have an encounter. An encounter will need further examination if the distance is smaller than a certain predefined threshold for minimal distance, otherwise it can be removed from the list of potential encounters.

The second purpose of the simulation is to predict the vessel traffic situation and in particular the general status of the ship in the future, to decide if a ship can be admitted to a harbour and what its schedule should be.

### Safety assessment

The proposed safety assessment method can be divided into two tasks, corresponding to the distinction made in the traffic simulation:

- Detection of the ship encounters which are below a predefined standard for minimal distance.
- The actual safety assessment of the vessel traffic.

For the first task the threshold for minimal distance determines for a great part the accuracy in detecting undesired situations as a result of ship encounters. A lower threshold will require a greater level of accuracy of the simulation results to cover all possible encounters. This puts a high demand on the quality of the used models and available information. Otherwise a large number of encounters will be falsely set aside. A higher threshold will be less demanding for the quality of the used models and information, but the chance of false alarms will grow with increasing minimal distance.
The second task concerns the assessment of the ship’s safety status for the simulated situation. This safety status depends on various factors. The following factors are reviewed corresponding to the earlier defined safety standards:

- Available space.
- Required space.
- Available control.
- Required control.

The available space and control are related respectively to the track line and subject ship. If there is an encounter between two ships, the available space for the subject ship will be reduced with the value for the required space of the observed ship, for the time an encounter endures, giving an indication for the actual available space for the subject ship. In case of multiple encounters this action has to be repeated several times.

The required space and control of that specific ship is obtained from a database, which contains the distributions for these safety factors. This database is acquired in advance by running multiple simulations under various ship conditions and situations. For the required space and control the 90%-likelihood of the stored distributions is used.

The result of the safety assessment is a safety margin that represents the ship’s resilience to cope with unexpected and unsafe situations. A threshold for the safety-margin can define the degree of allowable intervention due to the local vessel traffic.

<table>
<thead>
<tr>
<th>Safety margin M_s</th>
<th>Safety level</th>
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<tr>
<td>M_s &gt; 0.4</td>
<td>Safe</td>
</tr>
<tr>
<td>0.2 &lt; M_s &lt; 0.4</td>
<td>Acceptable</td>
</tr>
<tr>
<td>0.1 &lt; M_s &lt; 0.2</td>
<td>Unsafe</td>
</tr>
<tr>
<td>M_s &lt; 0.1</td>
<td>Unacceptable</td>
</tr>
</tbody>
</table>

Table 1 Various areas with the same interpretation for the safety level by defining the borders for the safety margin.

To be able to obtain an indication for the safety level of the predicted vessel traffic situation a division has to be made into various categories for the safety margin, as is shown in Table 1. The values in Table 1 are arbitrary, but present a way the results from the safety assessment can be translated to define various safety levels.

**Presentation**

The result of the safety assessment can be used as feedback to optimise the schedule. A low safety margin can be an indication for a bad schedule. This can be a motivation to make a new schedule, especially when a sudden drop of the safety margin is a direct result of a ship encounter. This information and the predicted vessel traffic overview have to be presented to the operator in such a way that he is able to instantly recognise the possible occurrence of undesired situations.

For a complete evaluation of the schedule, the efficiency of the vessel traffic should also be presented. The number of ship movements during the observation time and time that ships have to wait outside the port due to the water level or obstructions of the waterway could give an indication for the efficiency of the schedule.

**Implementation of the OSS**

The Operator Support System presented in the previous chapter is implemented in MATLAB®, which is a software programme for analysing systems of sets of linear equations. The vessel traffic is simulated for various situations and conditions over a certain period of time. By comparing the acquired results with those presented in literature the used simulation models are validated.

**Assumptions and limitations**

Considering the objective of this study: demonstrating the possibility of vessel traffic simulation as an OSS
for vessel traffic management, a number of choices had to be made concerning the way the models and conditions are implemented. The quality of the used models determines to a great extent the accuracy of the prediction, i.e. the correctness of the presented traffic overview.

For the objective of the OSS a rough vessel traffic prediction, which gives the opportunity to use simple models. A complete model of the system ship and the disturbances acting upon it is needed. A model for the Human Operators (HO) on board of the ship's bridge is also needed, to obtain a control model for the system ship.

In this demonstration only the effect of wind disturbance is taken into account. Other effects like current, bank suction and ship-ship interactions are left out of consideration to obtain a simple and clear simulation model, suitable to demonstrate the possibilities of the proposed method.

A distinction can be made between the assumptions concerning the vessel traffic and those concerning the ship speed.

For the vessel traffic the following assumptions have been made:
- Assuming the main interest being the vessel traffic flows, all activities in the harbours basins are neglected. The entrances of the harbours basins define the boarders of the system. Special manoeuvres like mooring are left out since these take place within the harbours. The area of interest is defined from 10 miles outside the port to the beginning of the Botlek area, since most sea ships pass this region.
- Interactions of the vessels due to the schedule are left out of consideration, since possible conflicts due to these encounters should be indicated by the proposed utility. The simulation time is restricted to an hour. This is considered to be sufficient to demonstrate the possibilities of the proposed OSS.

For the ship speed the following assumptions have been made:
- The minimal desired ship speed is defined as 6 knots. This makes the simulation of trusters or tugs unnecessary, considering that these are only efficient at speeds below 6 knots.
- The minimal allowable distance between two ships that have an encounter can be related to the ship speed. For the demonstration a fixed distance threshold of one nautical mile is defined, approaching the travelled stop distance in case of an emergency stop at full ahead speed for vessel of over 200 meter.
- Assuming that the maximum number of revolutions of the propeller will not be reached during the simulation, only the rudder angle is taken into account for the standard of ship control. The effect of ship speed will indirectly be taken along by observing the required space and rudder angle, since in most cases these shall increase with a decrease of the ship speed.

Models

A short description of the implementation of every function of the OSS will be given, conform the aforementioned design.

Route planning and scheduling

The route plan is predefined, since in most cases no alternatives for the routes are available due to the restrictions of the traffic lanes. For the specification of the routes a reference track line system is defined, as shown in Figure 3.

![Figure 3 Reference track line network for the area of interest. The dotted lines represent the reference track lines.](image)

Each reference track line has its own identification number. This makes it possible to define the ship's route by indicating the track line numbers that should be followed. Additional information like the desired speed, water depth and maximum boarder line is assigned to the track line, which gives the opportunity to take the local situation into account.

The schedule is scanned on the presence of possible ship encounters. Three types of encounters can be recognised:
- Overtaking situations: the subject and the observed vessel are sailing on the same track and (almost the same) course, while the latter is in front of the first vessel sailing at a lower speed.
- Head-on situations: the subject and the observed vessel have an opposite course while sailing on the same track.
- Crossing situations: the tracks of the subject and the observed vessel cross.

To determine if the traffic schedule contains possible conflicts, a comparison is made between the proposed route plans. If two ships shall use the same track line during their journey, an encounter is added
to the list of possible encounters. This approach covers only the overtaking and head-on encounters. The encounters due to crossing are left out at this stage, for these require another approach for their detection.

**Vessel traffic simulation**

The basis for the simulation is founded by the reference track line network, along which the ships are simulated.

As shown in Figure 4 the system ship can be divided into three subsystems, on which disturbances act:

- **Navigator**
- **Helmsman**
- **Ship dynamics**

![Figure 4 System ship and the disturbances](image)

The navigator on board of the ship defines a desired heading by comparing the actual position of the ship with the desired path. The helmsman in turn compares the desired heading with the actual heading and defines a desired rudder angle. In case of special manoeuvres the navigator can also define a desired rudder angle.

The navigator and helmsman are both modelled by a PID-controller. A PID-controller uses the error, the integral and flux of the error to determine a control action. For the modelling of the navigator this error is defined as the difference between the actual and desired position relative to the track line. For modelling of the helmsman the error is defined as the difference between the actual and desired heading.

The desired ship speed is related to the reference track line. The navigator adjusts the speed according to the desired speed, by changing the telegraph position. In the case of large rudder angles (>20 degrees), the telegraph position is altered -by the navigator- to create more rudder pressure and hence a better ship control.

The ship dynamics of the presented simulation model can be subdivided into four sub models:

- **Hull**
- **Rudder**
- **Propeller**
- **Wind**

All sub models are implemented in modules, using relative simple models for the actual simulation models and more extensive models for the estimation of the ship parameters. The latter have a major influence on the ship dynamics and are only calculated at the start of the simulation, thus resulting in a small increase of the calculation time. While the first mentioned models are continuously used in the simulation and determine to a greater extent the calculation time. More extensive models shall lead to a dramatic increase of the calculation time. The same reasoning can be applied for the control models.

**Safety assessment**

The safety assessment of the predicted traffic overview is realised using the aforementioned safety margin.

The safety assessment consists of two parts:

- Generation of a database containing information concerning the distribution of the required space and control (only once).
- The actual safety assessment of vessel traffic situation to give an indication of the vessel traffic safety development.

For the first part all relevant ships have to be simulated under different (initial) conditions, to collect data to obtain a distribution for the required space and control for those specific conditions. These distributions are stored in a database, which will be used for the safety assessment of the predicted vessel traffic image. The entries of the database are formed by the telegraph position, the wind speed and wind direction.

For the safety assessment of the predicted vessel traffic image information is needed about the telegraph position, the wind speed and the relative wind direction of every observed ship during the simulation. Using this information the distributions of required space and control can be retrieved from the database, which are used to calculate the safety margins of the ships for every time step. The 90 % likelihood of these distributions is used, since the tail ends contain excessive values with a low likelihood.

The available space and control are related to respectively the track line and the observed ship.

Since the available space is related to the track line, the length of the track lines determines the level of accuracy by which the traffic lanes are modelled. Shorter lanes mean more detail on the characteristics of the traffic lane, like width and depth.

By observing the distance between two ships during the simulation and comparing it with a predefined threshold, a distinction can be made between the relevant and the non-relevant encounters.

If there is an encounter between two ships, the available space for the subject ship will be reduced with the value for the required space of the observed ship, giving an indication for the actual available space for the subject ship. In case of multiple encounters this action has to be repeated several times.
Presentation

The results of the vessel traffic prediction and safety assessment have to be presented in an orderly way to prevent confusion of the VTS-operator.

A way of sorting out the information is by presenting the results in time blocks. A time block of a quarter of an hour is handled in this project for the presentation. A shorter time block can result in a loss of overview, while a larger time block can result in an overload of information for the VTS-operator.

Another way of sorting out the information is by combining the results of both the vessel traffic prediction and safety assessment in one figure. In this way an indication of (the safety of) the vessel traffic development can be obtained in an instant. Coupling the value for the safety margin to the accompanying ship can do this.

A possible solution is to vary the colour of a ship as an indication for the safety margin. The colour could for instance vary from white to red, in which red could indicate a low safety margin, ergo, a high chance for the occurrence of an undesired situation as a result of a ship accident. Examples of this method can be found on the internet for the visualisation of traffic jams\(^1\). This approach is used for the presentation of the results to the VTS-operator.

Situation and conditions

For the validation of the used simulation models and generation of the database necessary for safety assessment various alternatives are simulated:

- **Different vessel size:**
  - 1700 TEU container vessel (Abel Tasman).
  - 6000 TEU container vessel (Regina Maersk).
  - 9000 TEU container vessel (Maxicon).

- **Different ship speeds:**
  - All engine-room telegraph positions ahead, resulting in ship speeds from 5 to 25 knots.

- **Different conditions:**
  - 3 wind speeds: 0 / 10 / 20 m/s
  - 8 wind directions: 0 to 315 degrees.

For the generation of the database all (initial) conditions were varied, while the desired track line remained unchanged, in order to acquire the distributions of required space and control for all possible situations.

Validation of the models

For a first validation of the used ship models two characteristic parameters are observed: the turning circle and the maximum ship speed. The results of the simulation are compared with the values found in literature, as shown in Table 1.

Both characteristic parameters correspond to a large extent with the values found in literature\(^2,3\). The deviation is small and considered as acceptable for the objective of this study.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Abel Tasman</th>
<th>Regina Maersk</th>
<th>Maxicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship capacity (TEU)</td>
<td>1700</td>
<td>6000</td>
<td>9000</td>
</tr>
<tr>
<td>Length over all (meters)</td>
<td>225</td>
<td>318</td>
<td>350</td>
</tr>
<tr>
<td>Turning circle Literature (meters) by maximum speed</td>
<td>780</td>
<td>1260</td>
<td>1038</td>
</tr>
<tr>
<td>Turning circle Simulation (meters)</td>
<td>840</td>
<td>1300</td>
<td>1175</td>
</tr>
<tr>
<td>Deviation (%)</td>
<td>7.7</td>
<td>9.3</td>
<td>13.2</td>
</tr>
<tr>
<td>Maximum ship speed literature (knots)</td>
<td>22.0</td>
<td>25.0</td>
<td>24.3</td>
</tr>
<tr>
<td>Maximum ship Speed simulation (knots)</td>
<td>21.7</td>
<td>24.6</td>
<td>23.7</td>
</tr>
<tr>
<td>Deviation (%)</td>
<td>1.4</td>
<td>1.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 1 Validation of the models for ship dynamics by comparing the maximum simulated ship speed and turning circle with the values found in literature.

Results

The results obtained from the vessel traffic prediction and the safety assessment by means of the previously defined standards are presented conform the proposed presentation.

Vessel traffic prediction

The proposed presentation of the vessel traffic in blocks of a quarter of an hour over the area of interest is retained, with the possibility to zoom in into specific traffic situations. To determine the usefulness of the prediction the results are compared to results found in simulator research\(^4\).

Figure 5 Vessel traffic prediction during a period of 15 minutes for four vessels.
The predicted traffic image is generally similar, taking into account the mentioned assumptions and limitations. In Figure 5 an example of the presentation of the vessel traffic prediction is given.

**Safety assessment of the vessel traffic prediction**

The proposed safety assessment of the predicted vessel traffic gives a rough indication for the safety of the future vessel traffic situation. Although it gives a better understanding of what can become critical situations due to ship encounters or the effect of disturbances. The accuracy of the input and the assumptions have a great impact on the results of the safety assessment, making it only possible to give an general indication. The result of an assessment of a vessel traffic prediction is given in Figure 6.

![Figure 6 Safety margins of two simulated vessels. The points indicated with T represent the transition of track line, resulting in a new value for available space. The points indicated with E represent the moment the effect of a ship encounter is taken along.](image)

By defining a threshold an indication can be given for the minimal safety margin that should be obtained. This threshold should guarantee a safe passage for the simulated vessel traffic as well as for the (local) vessel traffic that is kept out of the simulation. It guarantees a certain level of resilience of a ship to cope with the occurrence of unexpected and undesired situations.

By presenting the vessel traffic prediction and the safety margin in one figure the VTS-operator can acquire information on the future vessel traffic safety in an instant. An example of this presentation is given in Figure 7.

![Figure 7 Presentation predicted traffic image and accompanying safety margins in one figure by changing the colour of the vessels as an indication for the safety margin. In this example the light grey fill indicates a reduced safety level due to the ship encounter.](image)

The combination of this information in one single display makes it easier for the VTS-operator to optimise the situation for the safety, for it gives the direct relation between the presented safety margins and the traffic prediction.

**Discussion**

A distinction can be made between the applicability of the vessel traffic prediction and the safety assessment of the predicted vessel traffic. Both subjects are discussed to evaluate the results.

**Vessel traffic prediction using simulation**

Simulation as prediction tool gives the operator the opportunity to gain insight in the vessel traffic development and to assess different scenarios at high speed.

The quality of the used ship models is satisfying for the objective of the simulation, which is giving an indication for the vessel traffic development.

The accuracy of vessel traffic simulation is subjected to:
- The estimation of ship speed.
- The quality of the models for the ship dynamics.
- The quality of the models for the HO’s.

The estimation of the ship speed has a great influence on the reliability of the predicted vessel traffic development. The estimation should improve by:
- Using historical information concerning the ship speed acquired during monitoring of the vessel traffic.
- Better communication and understanding between the VTS-centre and the vessel concerning the predicted ship speed.
Imposing a desired ship speed by the VTS-operator.

The last option gives the opportunity to improve the accuracy of the vessel traffic prediction, but circumscribes the freedom of the pilot on the ship's bridge in determining the desired speed. The profit for the pilot should be a passage guaranteed to be without (unexpected) dangerous encounters.

The models for the ship's dynamics satisfy, for now, the objectives of the application. Adding the disturbances that were left out will give a more realistic vessel traffic prediction, in particular due to the effect of current and limitations due to the ship's depth.

More extensive models for the HO on the ship's bridge can improve the accuracy of the simulation results compared to the reality, but at the cost of computer capacity. The addition of modules for specific manoeuvres, that take place within the system boundaries, can also improve the accuracy of the results from the vessel traffic prediction. In most cases special manoeuvres can be simplified as a temporal obstruction of the waterway for a certain period of time.

**Safety assessment vessel traffic using vessel traffic simulation**

The safety assessment gives the VTS-operator insight in the safety margins of predicted vessel traffic. With this information he can try to optimise the efficiency, taking into account the vessel traffic safety.

The usefulness of the safety assessment is related to:
- Accuracy of the vessel traffic prediction.
- Used standards and thresholds to determine ship encounters.
- The accuracy of the acquired distributions for required space and control.
- Comprehensiveness of the database for safety assessment.

The accuracy of the vessel traffic prediction is discussed in the previous section. The assumptions, which are made for the vessel traffic prediction, are of major influence on the accuracy of the simulation results, which makes it hard to judge the safety assessment for its reliability. The safety assessment has to be evaluated on its usefulness, disregarding any inaccuracy related to the vessel traffic prediction.

The way the ship encounters are observed and processed has a major impact on the safety assessment. Wrong assumptions and standards can sort out a great part of the encounters, which ought to be evaluated on their safety, thus resulting in a incorrect -high- value for the safety margin.

The accuracy of the results obtained by simulation has an impact on the reliability of the distributions for required space and control. Nevertheless, it satisfies for the purpose of serving as input for the safety assessment, since no severe demands are formulated for these distributions.

A restriction of the database is the limited number of conditions that can be processed, since an increase of the number of entries results in a decrease of the manageability of the database. A solution to get around this limitation can be the method developed by PIANC for the preliminarily design of harbours. This method calculates the width of a passageway by summarising various width-factors as a function of the examined situation and conditions. These factors are the result of an investigation of various fast time simulations and simulator runs. A limitation of this method is the lack of data on control usage, but a great advantage is the translation of the required space in a formula, which makes safety assessment better manageable.

**Conclusions**

Vessel traffic simulation as an operator support system can be a useful tool for the VTS-operator to gain insight in the vessel traffic development and to evaluate different scenarios at a high speed.

The sensibility of the simulation results for the input restricts the usefulness of the vessel traffic prediction as is presented in this paper. The reliability of the simulation results is to a greater extent related to the estimation of the ship speed.

By using modules for the various parts of the simulation, adjustments and extensions can be easily implemented. As well as that new ships easily can be introduced due to the modular structure.

By means of simple standards a safety indication, on basis of the proposed safety margin, can be given for the observed vessels, which gives the opportunity to identify unsafe situations at an early stage using vessel traffic prediction.

By combining the vessel traffic prediction and the safety indication in one figure, the operator can instantaneously obtain an overview of the vessel traffic development.

Adding modules for optimisation of safety and efficiency of vessel traffic schedules should give the VTS-operator the opportunity to determine an optimal schedule - interactively- at high speed.

**Recommendations**

A possibility for better results is to define (or impose) a desired speed for the participating vessels, which could result in a better correspondence of the estimated (simulated) ship speed with the actual ship speed.
Assumed is that the application of extensive control models for the navigator and the helmsman can improve the accuracy of the prediction results. A study on the effects of extensive control models on the results of the VTS-OSS should give an answer to this question.

An expert, e.g. a VTS-operator, should verify the proposed safety assessment method. This can for instance be done during interactive simulator runs at which VTS-support is taken along. This is not done in this study, due to a lack of time.

The distributions for space and control stored in the database should be verified by the results of simulator research and, if desired, adjusted to obtain a correct distribution.

A study on the conversion of the database into a formula, corresponding to the method described in PIANC\(^1\), should be conducted to determine the feasibility of such a conversion.

Adding a module for the efficiency of the vessel traffic can help the VTS-operator in managing the traffic flows.

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Appendix A: Proposed VTS-Operator Support System

This appendix describes the objectives and the design of the proposed VTS-OSS.
The objective of the VTS-OSS

The objective of the VTMS is to provide vessel traffic a safe and efficient passage through the waterways and an optimal use of port facilities. In the ideal case ships should always be able to maintain their planned speeds and should always have enough room for their planned manoeuvres, such as entering a harbour basin. The VTMS should function in such a way as to satisfy these demands as far as possible.

For this the VTS-operator needs a better understanding of the vessel traffic development and its effects on the safety in the port. The VTS-operator nowadays uses his internal models of the vessel traffic to predict the vessel traffic development. Due to the complexity of the vessel traffic the mental workload for the operator can be high. By supplying the VTS-operator with additional tools to predict the future vessel traffic situation the mental workload should decrease, in effect leading to a reduction of the risk for misjudgement and thus increases the overall safety. In order to do so the OSS should comply with the following requirements:

1. All relevant vessels should be distinguished from the vessel traffic.
2. A route plan needs to be generated for each relevant ship.
3. A possible traffic schedule should be generated.
4. The operator should be able to interactively assess different scenarios by adjusting the traffic schedule.
5. The OSS should give an overview of the future traffic situation
6. The OSS should give an indication of the safety level for the future vessel traffic situation.
7. The presentation of the traffic situation should be orderly.
8. The presentation of the safety indication should give an instant overview of the safety level of the predicted traffic situation.

The objective of the VTS-OSS is to give the operator a better understanding of the vessel traffic (safety) development, by presenting a vessel traffic prediction and a safety assessment of this prediction.
Design of the OSS

The proposed operator support system consists of five modules, each responsible for one of the following processes:

- Selection and route planning
- Traffic scheduling
- Vessel traffic simulation
- Safety assessment
- Presentation

These modules can be found in Figure 1. First a selection of relevant ships is made to obtain a list of ships that should be simulated. From the initial vessel traffic situation combined with the information on the destination of a ship, a route plan can be obtained using a reference track line network to set out the track lines that have to be followed. The route plan combined with the initial vessel traffic situation and the Estimated Time of Arrival (ETA) (for incoming ships) or the Estimated Time of Departure (ETD) (for outgoing ships) give a traffic schedule, which serves as input for the vessel traffic simulation. The simulation calculates the status of all ships within the system boundaries, i.e. the ship’s position, orientation and speed. The ship dynamics, the human operators and the disturbances acting upon each ship are modelled in order to obtain a simulation model of the system ship. All ship movements combined lead to a vessel traffic prediction, which forms the input for the safety assessment.

The safety status of each ship is obtained by using a safety assessment method that predicts the safety margin of a specific ship at every step in time. By assessing all ships an indication can be given for the overall safety level of the predicted vessel traffic situation.

The vessel traffic prediction combined with the safety indication of each ship is presented to the VTS-operator. This presentation can be used by the VTS-operator to gain insight in the vessel traffic safety development, by locating the possible occurrence of undesired situations. By adjusting the schedule the operator can prevent the occurrence of these undesired situations. Adding an extra module to the structure of the presented OSS for the efficiency of the vessel traffic, an optimisation can interactively be performed by the VTS-operator for both the efficiency and safety of the vessel traffic.
Figure 1 Overall design of the OSS. The five consecutive processes in the OSS are presented: selection & route planning, traffic scheduling, traffic simulation, safety assessment and presentation of vessel traffic (safety) prediction.
Selection and route planning

The first step in predicting vessel traffic is to determine a route plan for each ship, i.e. the route a ship has to sail to arrive at its destination.

Before the actual route planning can be started, a selection has to be made of all ships that sail or are going to sail, according to the VTMS-database, in the area of interest during the simulation time.

Information can be obtained from the VTMS database, concerning:
- The initial vessel traffic situation;
- The Estimated Time of Arrival (ETA) and Departure (ETD) of ships;
- (Historical) information related to the various ships, e.g. expected speed, manoeuvrability and depth;
- The ship’s cargo;
- Hydrodynamic information;
- Meteorological information;

The information stored in the VTMS database has to be filtered to obtain a list of ships that should be observed, by:
- Selecting all relevant ships in the VTMS database.
- Discarding ships that are not nor will be within the area of interest during simulation time.

At this moment all ships that have to announce themselves to the VTMS conform the current regulations are considered as relevant, since these ships are either limited in their manoeuvrability or carry dangerous goods. Hence, these ships have inherent an increased risk for undesired situations, thus should be considered as relevant for simulation.

This results in the following categories:
- All seagoing vessels
- All inland vessels longer than 110 metres
- All inland vessels with dangerous cargo
- Special transports.

This means an exclusion of "normal" local vessel traffic and small inland vessels without dangerous cargo are excluded from the VTMS database. Taking along all present ships will make the simulation complex and unreliable, since the routes of smaller inland vessels are often unknown and subjected to continuous revision.

The presence of ships in the area of interest during the simulation depends on the initial position of the ship and the ETA (or ETD). On the basis of this information and historical information concerning ship speed an estimation can be done for the future ship position and the probability of a journey through the area of interest during the simulation time. All ships - which qualify for simulation - are stored in a temporal ship list, as is shown in Figure 2.

For the actual route planning a set of reference track lines is predefined along which the simulated ships will sail. This reference track line network includes relevant nautical information such as water depth, width and maximum speed. Using this reference track line network a route plan can be defined for each ship, by generating a list of track lines that should be followed. This is done for all ships in the temporal ship list, as is shown in Figure 3, and results in a ship route list.
Figure 2 The route planning: obtain a route plan for all ships on the temporary ship list.

Figure 3 The selection: obtain a list of ships that should be simulated.
Scheduling

The schedule, i.e. the expected start position of a ship and the expected time certain points of the route plan are passed during the journey, can be set up using the information from the VTMS-database and the route plan.

The VTMS-database comprehends information on the initial vessel traffic situation and the Estimated Time Arrival/Departure (ETA/ETD) of all ships. By combining this information with the previously obtained route plan a schedule can be calculated, as is shown in Figure 4.

This schedule is assessed for the presence of possible encounters, as is shown in Figure 5.
For each encounter a subject and an observed vessel can be defined. The subject vessel is the vessel under consideration, while the observed vessel is assumed to be the vessel the subject vessel has an encounter with.

Three types of encounters can be recognised:
- Overtaking situations: the subject and the observed vessel are sailing on the same track and course, while the latter is in front of the first vessel sailing at a lower speed
- Head-on situations: the subject and the observed vessel have an opposite course while sailing on the same track.
- Crossing situations: the tracks of the subject and the observed vessel cross.

These encounters are considered relevant for the safety assessment of the vessel traffic and are listed to a list of possible encounters. Interactions due to these encounters are at this stage neglected, assuming an optimal journey without any obstructions. The effects of encounters will become clear in the safety assessment, as the safety level of ships involved drops dramatically as a result of such an encounter. By changing the strategy and adjusting the schedule, the operator can try to eliminate the possible occurrence of undesired situations due to encounters, resulting in an "optimal" journey for the simulated vessels.

The list of possible encounters forms a starting point for the safety assessment of the predicted vessel traffic.
Figure 5 Obtain a schedule for all the ships in the ship route.

Figure 4 Assessment of the schedule for the presence of possible encounters.
**Vessel traffic simulation**

The vessel traffic simulation uses the information available from the schedule and the VTMS-database as a starting point. By using models for the ship dynamics, the human operators on the ship's bridge and the disturbances acting on the ship the vessel traffic can be simulated along reference track lines. The simulation is started after each scheduling. When the simulation time elapses, the vessel traffic simulation is stopped.

During this simulation information is stored concerning the status of all simulated ships. This information is needed for the presentation of the vessel traffic development as well as for the safety assessment of this prediction.

The flow chart for the vessel traffic simulation is shown in Figure 6.
Figure 6 Vessel traffic simulation using the previously obtained route plans and traffic schedule.
**Safety assessment**

To assess the safety level of the vessel traffic prediction, the safety margins of the observed ships have to be determined. The safety margin gives an indication for the resilience of the ship to cope with unexpected and undesired situations.

Firstly the list of ship encounters has to be filtered to determine all relevant ship encounters, i.e. the encounters that have a high probability for occurrence. This is done by comparing the distance between two ships that have an encounter with a distance threshold for the minimal distance, a (qualitative) statement can be made on the probability of occurrence of that specific encounter. See Figure 7. If the distance between two ships is lower than the threshold the encounter is considered as a potential encounter, while exceeding this threshold may authorise elimination of the encounter from the list. The threshold should be a function of the type of encounter and the ship's speed, since the time between two ships before having an encounter is a result of the (relative) speed of and the distance between these two ships.

Next an indication can be given for the safety margin of a ship by taking into account the required space and control of a ship in a certain situation. The safety margin can be obtained by calculating the ratio required versus available space and the ratio required versus available control. The available space for the subject vessel in case of an encounter can be calculated by reducing the available space with the required space of the observed vessels.

The flow chart for the safety assessment is shown in Figure 8.
Read data vessel traffic status

Read in list of potential ship encounters

Get first ship encounter from list

Determine distance threshold according to type of ship encounter

Calculate distance between ships

Distance smaller than threshold

Yes

Store information on vessel traffic status during encounter

No

All ships done?

Yes

F

No

Next ship on ship encounter list

Figure 7 Filtering the list of ship encounters to acquire all relevant encounters.
First timestep

First ship on list

Read in required space and control from database

Determine available space

Ship encounters

Yes

Read in relevant ship encounters

Determine observed ships

Reduce available space subject ship with required space observed ships

No

Determine available control

Calculate and store safety margin

Safety margin simulated ships

All ships done?

Yes

Time exceeding simulation time

Yes

G

No

Next ship on list

Next timestep

Figure 8 Calculation of the safety margin of the simulated ships
Presentation

The results from the vessel traffic prediction as well as the results from the safety assessment have to be presented to the VTS-operator. For this an interface between the computer and the operator is needed.

The results can be combined in one figure, giving the operator the opportunity to observe the relation of the vessel traffic prediction and the safety margins in one figure. This gives the VTS-operator a better understanding of the presented results for the prediction of the vessel traffic (safety) development.

By presenting the data in time blocks the operator maintains an overview of the situation, preventing an overflow of information.

The flow chart for the presentation is given in Figure 9.
Figure 9 Presentation predicted vessel traffic image and accompanying safety indication.
Appendix B. Proposed Safety Assessment Method

In this appendix a description is given for the motivation and design of the proposed safety assessment method.
Motivation safety assessment method

The safety assessment of vessel traffic simulation results was performed by adopting an approach based on safety indicators used for safety assessment of data obtained by simulator runs. The use of safety indicators for an objective safety assessment of data acquired by simulator runs has been investigated extensively\textsuperscript{1,2}.

The safety assessment of the data acquired by simulator runs often focuses on:
- Determination of the probability crossing the borderlines of the shipping lane, e.g. by observing the Closest Point of Approach (CPA) of a ship to the borderline during the simulation.
- To what extent the ship’s controls, i.e. rudder, motor, trusters and tugs, are used to carry out a (specific) manoeuvre. By using a Reserve Control Indicator (RCI) an indication can be given for the degree of available control left over during this manoeuvre, indicating the resilience of the system to deal with unexpected situations.

For the assessment of simulation results this approach is worked out into standards for:
- Required versus available space.
- Required versus available ship control.

For both standards a short description is given.

**Required versus available space**

A vessel needs a specific amount of space for a safe passage, assuming an optimal usage of this space by the vessel. When disturbances act on a vessel a correction will be needed to hold the optimal path. At first the required space will increase, followed by a claim on the reserves in control to make sure that the required space will not exceed the available space.

The available space for a clear passageway of a certain ship will not only be defined by the physical boundaries of the waterway, but also by the surrounding vessels and buoyage. In this way the relation required versus available space could give an indication of the probability for the occurrence of an undesired situation, since the probability for exceeding the borderlines of the traffic lane will increase if the amount of required space approaches the amount of available space.

The required space is a function of the ship’s width and dynamics, the disturbances acting upon the ship and the vessel traffic situation. The effects of human or technical failure are left out in the calculation of required space, since failures can be considered as exceptional situations and thus cannot be seen as regular effects acting on the system ship.

The ratio required versus available space should give an indication for the resilience of the system ship to deal with these kind of unexpected situations.
Required versus available ship control

In case of disturbances acting on the vessel the required space will increase if a
correction is not made in time. The effect of a disturbance is related to the degree of
correction and to what degree the reserve in control is used. The reserve in control is
the difference of the amount of required control and the available control. Disturbances or failures that cannot be corrected, due to the small available reserve,
can lead to an unsafe and therefore undesired situations.

The ratio required versus available control gives a relative indication to what extent
the ship’s control is used. It is an addition to the standard for required versus
available space. It is possible that, while the first proposed standard gives no
indication for the occurrence of an undesired situation, the standard for ship control
is decreased to a minimum.

Disturbance or unforeseen events can lead to a deviation from the desired path for
there will be no control left to compensate. This can result in the crossing of a
borderline. At that moment the standard for ship control gives an indication for a
possible unsafe situation.

The required control is a function of the ship’s dynamics, the disturbances acting
upon the ship and the vessel traffic situation. Human or technical failures are left out
due to the above-mentioned reason.
Proposed safety assessment method

The assessment of the ship's safety status for the simulated situation depends on various factors. The following factors are reviewed corresponding to the earlier defined safety standards:
- Available space.
- Required space.
- Available control.
- Required control.

Since interest lies in the relation of these factors, the ratio of these factors should be calculated. For each ratio the factors, as a function of various input, are described.

Space ratio

The available space \( (S_a) \) is a function of:
- Width of the traffic lane, taking into account restrictions due to the water level.
- Buoyage, e.g. for the separation of traffic lanes.
- Space required for other vessels in the same area.

The required space \( (S_r) \) is a function of:
- Ship's width.
- Ship dynamics, i.e. the easiness of the system to correct deviations from the desired path.
- Disturbances acting on the system ship, resulting in a deviation from the desired path.

Control ratio

The available control \( (C_a) \) is a function of:
- The ship's available control, i.e. maximum engine power, rudder angle, truster power.
- The vessel traffic situation, i.e. the reduction of the control due to the ship speed (loss of truster efficiency) or location (restriction to the number of propeller revolutions).

The required control \( (C_r) \) is a function of:
- The vessel traffic situation, e.g. restrictions on ship speed.
- Disturbances acting on the system ship, i.e. the control needed to correct the effects of current of wind.
**Safety margin**

A combination of both standards should give the operator a better understanding of the vessel traffic safety development by observing the status of all ships in a (specific) situation. The combination of both standards seems logical, since in most case a deliberation has to be made upon the control effort versus the deviation of the system output.

The standards must be combined in such a way that the resulting relation, referred as: the safety margin, can act as a proper safety indicator.

Under the assumption that:
- Both standards are equally important to the safety status of a ship.
- Safety is only ensured if the space and control ratios are both higher than a certain predefined safety threshold.

The following formula for the safety margin is proposed:

$$M_s = \left(1 - \frac{S'}{S_a}\right) \times \left(1 - \frac{C'}{C_a}\right)$$

The safety margin $M_s$ is a function of the ratio for space and control of a ship: $M_s(S', C')$, in which $S'$ and $C'$ stands for the ratio required versus available space respectively control of a ship. $S_a$ and $S_r$ symbolise respectively the available and required space, while $C_a$ and $C_r$ symbolise respectively the available and required control for a ship.

The safety-margin is shown in Figure 1. The lines represent the iso-safety margin lines, i.e. the lines representing a constant safety margin for a ship as a function of the ratio for space and control.

The safety margin runs from zero to one, representing a low respectively high safety level.

![Figure 1 The iso-safety margin lines representing the lines for which the safety margin is constant under varying ratio for space and control.](image-url)
The extreme points in Figure 1 can be interpreted as follows:

- \( M_s(0,0) = 1 \)
  The safety margin is one, the highest safety margin possible. The required space and control are zero. Although this is not a realistic situation, since the required space is always greater than zero due to the ship's width, it shows that if no disturbances act on the ship this leads to the greatest safety margin possible.

- \( M_s(0,1) = 0 \)
  The safety margin is zero, the lowest safety margin possible. The required control is equal to the maximal available control, resulting in a control ratio of one. This means a critical situation with respect to control. However the space ratio \((S^*)\) is zero which means nothing of the available space is not used. This is considered as not realistic since less control will not (directly) lead to an undesired situation, due to the fact that enough space is available for a safe passage.

- \( M_s(1,0) = 0 \)
  The safety margin is zero, the lowest safety margin possible. The required space is equal to the maximal available space, resulting in a space ratio of one. This means a critical situation with respect to space. However the control ratio \((C^*)\) is zero which means full control is available but not used.

- \( M_s(1,1) = 0 \)
  The safety margin is zero, the lowest safety margin possible. The required space and control are maximal with respect to respectively the available space and control, resulting in a space and control ratio of one. This situation is critical for both the space and control, and can be considered as totally unacceptable.

Note that although the extreme points are in fact not realistic situations, they show the theoretical boundaries of the safety assessment method.
The result of the safety assessment is a safety margin that represents the ship's resilience to cope with unexpected and unsafe situations. A threshold for the safety margin can define a degree of allowable intervention due to the local vessel traffic.

By defining borders for the various safety margins, safety levels can be distinguished. In Table 1 a possible classification is given.

<table>
<thead>
<tr>
<th>Safety margin</th>
<th>Safety level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s &gt; 0.4$</td>
<td>Safe</td>
</tr>
<tr>
<td>$0.2 &lt; M_s &lt; 0.4$</td>
<td>Acceptable</td>
</tr>
<tr>
<td>$0.1 &lt; M_s &lt; 0.2$</td>
<td>Unsafe</td>
</tr>
<tr>
<td>$M_s &lt; 0.1$</td>
<td>Unacceptable</td>
</tr>
</tbody>
</table>

Table 1 Distinction of various areas with the same interpretation for the safety level by defining borders for the safety margin.

The proposed borders for the safety margin are arbitrary, but give an indication of the way the results from the safety assessment can be interpreted. As can be seen in Figure 2.

Figure 2 The iso-safety margin lines distinguishing the various safety levels according to the proposed classification in Table 1.
References:
1. Paassen, van, M.M en Wieringa, P.A., Ontwikkeling van indicatoren voor de veiligheid van havenmanoeuvres (in Dutch), TUDelft, Delft, the Netherlands, August 1997.
3. Veldhuyzen, W., Nautische veiligheid (in Dutch), Gemeentelijk Havenbedrijf Rotterdam, Rotterdam, the Netherlands, 1999.
Appendix C. Exemplary VTS-Operator Support System

This appendix describes an exemplary VTS-OSS to demonstrate how an OSS can be built, and what the possibilities and limitations of an OSS are.
**General**

The exemplary operator support system (OSS) has the same set-up as the proposed OSS described in the paper and Appendix A.

However, this exemplary OSS is a simplification of the proposed OSS, keeping in mind the purpose of this project: exploring the possibility of an OSS based on vessel traffic simulation for managing vessel traffic situations.

For the implementation of the models for vessel traffic simulation, safety assessment and presentation of the findings MATLAB® is used. MATLAB® is a matrix software program for the assessment of sets of equations.

For a demonstration of the proposed VTS-OSS the following requirements are defined:
- It should give a prediction of the vessel traffic development, by which the operator can obtain a better understanding of the vessel traffic development.
- It should give an indication of the possibilities of the proposed safety assessment method.

**Simplifications**

The main simplifications are:

1. There is no direct link to information from the VTMS database, so data was collected to represent the VTMS database.
2. Ships in this OSS sail predefined routes. These routes closely represent routes ships actually sail.
3. The routes ships sail extend from the Botlek area to 10 km outward.
4. All activities in the harbour basins are excluded.
5. No restrictions for depth are made.
6. Wind is the only disturbance acting upon vessels.
7. The minimum desired speed is above 6 knots
8. No usage is made of trusters or tugs.
9. Operators can only choose three different simulated ships (the Abel Tasman, Regina Maersk, and Maxicon).
10. Ship-ship encounters caused by crossing track lanes are not assessed.
Route planning

The route planning and scheduling functions are combined into one module. Both functions are described separately to make a clear distinction between them.

To specify the routes simulated vessels follow a reference track line network has to be defined, in which the reference track lines (IT) represent the traffic lanes of the port of Rotterdam. In Figure 1 an example is given of the reference track lines corresponding with the area near the port entrance, which is assumed to be the area of interest. This area offers various traffic situations that can be simulated and assessed on its safety.

![Diagram ofReference track line network for the area of the port entrance, which also defines the area of interest. The dotted lines represent the reference track lines.](diagram)

The reference track lines are aligned with the middle of the traffic lanes or –if they are present– the leading lines. Each reference track lines has two numbers:
- An odd number, representing the track line pointing inland.
- An even number, representing the track line pointing seaward.

Additional information like desired speed, water depth, minimum and maximum boarder line is assigned to each reference track line.
A route plan (ITP) for the simulated ships, consisting of several track lines, is predefined. The predefined route plans represent several journeys through the port, which can be used to create various traffic situations. Each route plan is defined by indicating the track line numbers that should be followed.

At the moment a ship passes the end gate of a track line (GXTE), the navigator model will adapt its relative position to the new (next) track line on the route plan.

For a realistic and subtle track transition an adaptation is made to define a desired track between the end and begin gate (GXTB) of respectively the old and new track. The adjustment of the transition is done by using a predefined turn radius by which the begin and end gate are defined, as shown in Figure 2. This turn radius is defined as 4 times the ship's length.

![Figure 2 Transition of reference track line.](image)

The position of a ship \((X_0,Y_0)\) is defined relative to the earth-fixed co-ordinate system. By transforming the earth-fixed axis to a lane-fixed axis a relative position of the ship \((X_r,Y_f)\) to the lane-fixed co-ordinate system is obtained. As is shown in Figure 3. The desired distance in transverse direction \((Y_{TD})\) determines the desired track of the ship. The difference between the desired and real distance in transverse direction is defined as the position error of the ship \((Y_{TE})\).

The desired position of the ship relative to the track line is in reality defined by restrictions due to:
- Width of the traffic lane, i.e. the distance between the borderlines.
- Obstructions in the traffic lane, e.g. due to moored vessels.
- Buoyage in the traffic lane.
- Depth of the traffic lane (trench)
In this simulation only the width of the traffic lane is used as a restriction, by defining the maximum \( Y_{\text{TMX}} \) and minimum \( Y_{\text{TMIN}} \) width. The desired position is determined to be on one quart of the mean width of a track line, since no additional information is retrieved from the desired position except for the indication of the future ship position.

Figure 3 \( P_t \) represents the heading of the track line relative to the fixed co-ordinate system, \( P_w \) the heading of the ship relative to the track line co-ordinate system and \( P \) the heading of the ship relative to the fixed co-ordinate system. \( P_w \) is the wind direction and \( U_w \) the wind speed.
**Traffic scheduling**

The schedule is a direct result of the predefined route planning and a chosen start point in time. By adjusting the starting point (ITA) in the route plan of a ship various route schedules can be obtained, giving the opportunity to create various traffic situations in time.

For every reference track line a desired speed (UDT) is defined, which depends on the location of the track line. Assumed is a minimal desired speed of 6 knots. This assumption can be justified by observing only the vessel traffic situations in the traffic lanes, setting aside all activities in the harbour basins, like mooring for which additional controls like tugs are needed. Special manoeuvres within the waterway, e.g. turning, are left out at this stage. The speed assumption implies an elimination of trusters and tugs, since these only work at low ship speed, i.e. below 6 knots.

At this point interaction of vessel traffic is left out of consideration, assuming a passage without obstructions or limitations for all vessels. The effect of ship encounters should come forward in the results of the OSS, giving an indication for the safety margin of all related ships and the safety level of the predicted vessel traffic situation. The interaction of the vessel traffic is, in this way, taken along in the VTS-OSS by presenting the operator possible side effects of ship encounters, i.e. a decrease (or sudden drop) of available space for a safe passage. The VTS-operator can, by adjusting the route schedule, interactively try to optimise the vessel traffic prediction for its safety.

For the safety assessment information on all possible encounters should be gathered, in order to be sure that the effects of vessel traffic interaction on the safety level will come forward.

Three types of encounters can be distinguished:

- Overtaking situations: the subject and the observed vessel are sailing on the same track and (almost the same) course, while the latter is in front of the first vessel sailing at a lower speed
- Head-on situations: the subject and the observed vessel have an opposite course while sailing on the same track.
- Crossing situations: the tracks of the subject and the observed vessel cross.

In this demonstration only the encounters due to overtaking and opposite courses are implemented, for these are assumed to be sufficient to present the possibilities of the proposed OSS. This means that encounters due to crossing track lines are left out.

A list of ship encounters can be obtained by filtering the schedule on overtaking or opposite courses of all vessels. By observing all overlapping track lines -opposite and equal- possible encounters can be filtered out. This will result in a list of possible encounters, which forms the starting point in safety assessment of vessel traffic prediction.
Simulation vessel traffic

The accuracy of the simulation results depends mainly on three issues:
- The quality and availability of information on the initial vessel traffic situation.
- The quality and availability of information on ship characteristics.
- The quality and availability simulation models for the system ship.

It is assumed that for the implementation of the system ship and its dynamics all available information is limited to a short list of basic parameters. This represents the actual situation, in which only limited information on ships characteristics is available. Other parameters necessary for simulation are calculated using embedded models.

Extensive simulation models for the system ship with a high accuracy will be unnecessary, since the restrictions on the available information concerning the ship's parameters determine for a larger part the simulation results. The choice is made to use simple simulation models, as these satisfy for the objective of the study and do not distress the computing capacity.

The usage of simple simulation models results in:
- A faster update of the traffic prediction.
- More ships that can be taken along in the simulation.
- A restriction on the accuracy of the simulation results.

The last point makes that only roughly a traffic prediction can be calculated, but at the time being this will fulfil the predefined requirements.

The system ship can be divided into three subsystems, as is shown in Figure 4:
- Navigator
- Helmsman
- Ship dynamics

Figure 1 System ship and the disturbances acting upon it.

The disturbances act on the ship dynamics. In this case only wind is taken in account, leaving other disturbances like banking and current out of consideration.
Navigator:

The navigator on board of the ship's bridge is responsible for the route planning and scheduling, which results in a desired track. In case of a position error, due to a difference between the desired and actual position relative to the track, a new desired heading is calculated to correct this deviation. In the event of special manoeuvres like turning, the navigator can also define a desired rudder angle.

For the implementation of the navigator function a PID controller is proposed. PID stands for:
- Proportional
- Integral
- Differential

The PID controller proposed uses the position error, its derivative and its integral to calculate a desired heading (PDN). A great advantage of the PID controller compared to other models described in literature is the simplicity of the controller, i.e. no use of (complex) internal models to estimate the future state of the ship. This can also be interpreted as a limitation since no anticipation takes place for foreseeable events, which can lead to a deviation of the desired path while in reality no deviation are noticed. In the light of this project a PID controller is considered as acceptable, since there are no hard demands prescribed on the accuracy of the simulation output.

The navigator actions due to special manoeuvres are left out of consideration at this stage. The values for the PID controller is assumed to be the same for all simulated ships.

Helmsman:

The helmsman on board of the ship is responsible for the translation of the desired heading into a desired rudder angle. If a heading error (PEH) between the actual (P) and desired heading is observed, a control action is taken by defining a desired rudder angle (DDH). In case of large angles (>20) the telegraph position (ITGA) is altered –by the navigator- to create more rudder pressure and hence a better ship control.

For the implementation of the function helmsman the same controller is proposed as for the navigator. The PID controller for the helmsman uses the heading error to calculate a desired rudder angle. The desired rudder angle will only be changed if the difference between the actual rudder angle (Delta) and the desired rudder angle (DDH) exceed 3 degrees, to prevent an unrealistic number of rudder calls.
Models for ship dynamics

The ship dynamics can be divided into four sub-modules:

- Hull forces
- Rudder forces
- Propeller forces
- Wind forces

The used models for ship dynamics are based on the models for the Abel Tasman as described in [5], in which a description of a model for the simulation of the steering- and manoeuvring characteristics of a second-generation container ship is given.

To start the simulation information has to be gathered concerning the basic set of ship parameters, from which all other ship parameters can be calculated. For every ship the values for this basic set of parameters differs. In this simulation three ships are taken along, demonstrating the possibility to introduce a new ship without putting much effort in the implementation of the ship. The values for the basic set of parameters of these three ships are shown in Table 1.

<table>
<thead>
<tr>
<th>Basic parameter</th>
<th>Abbreviation</th>
<th>unit</th>
<th>Ship Abel Tasman</th>
<th>Regina Maersk</th>
<th>Maxicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all</td>
<td>LOA</td>
<td>Meter</td>
<td>225,8</td>
<td>318,2</td>
<td>350</td>
</tr>
<tr>
<td>Length waterline</td>
<td>L</td>
<td>Meter</td>
<td>210</td>
<td>302,3</td>
<td>332,5</td>
</tr>
<tr>
<td>Width</td>
<td>B</td>
<td>Meter</td>
<td>30,5</td>
<td>42,8</td>
<td>46</td>
</tr>
<tr>
<td>Depth</td>
<td>D</td>
<td>Meter</td>
<td>16,4</td>
<td>12,2</td>
<td>14,5</td>
</tr>
<tr>
<td>Cavity</td>
<td>T</td>
<td>Meter</td>
<td>11,55</td>
<td>25</td>
<td>26,1</td>
</tr>
<tr>
<td>Block coefficient ship</td>
<td>CB</td>
<td></td>
<td>0,517</td>
<td>0,675</td>
<td>0,682</td>
</tr>
<tr>
<td>Maximum ship speed</td>
<td>UMX</td>
<td>Knots</td>
<td>22</td>
<td>24,6</td>
<td>24,3</td>
</tr>
<tr>
<td>Maximum engine power forwards</td>
<td>WEFMX</td>
<td>Watt</td>
<td>54000</td>
<td>54800</td>
<td>61050</td>
</tr>
<tr>
<td>Maximum engine power astern</td>
<td>WEAMX</td>
<td>Watt</td>
<td>53000</td>
<td>53300</td>
<td>60000</td>
</tr>
<tr>
<td>Maximum number of rev. propeller</td>
<td>NMX</td>
<td>Rev./minute</td>
<td>110</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td>Number of propellers</td>
<td>NP</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Diameter propeller</td>
<td>DP</td>
<td>Meter</td>
<td>7</td>
<td>9,2</td>
<td>9,2</td>
</tr>
<tr>
<td>Pitch propeller</td>
<td>PP</td>
<td></td>
<td>0,935</td>
<td>0,97</td>
<td>0,97</td>
</tr>
<tr>
<td>Area propeller</td>
<td>FP</td>
<td>Square meters</td>
<td>0,78</td>
<td>0,8</td>
<td>0,8</td>
</tr>
<tr>
<td>Number of propeller blades</td>
<td>BP</td>
<td></td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Efficiency propeller-shaft</td>
<td>CQFR</td>
<td></td>
<td>0,025</td>
<td>0,025</td>
<td>0,025</td>
</tr>
<tr>
<td>Maximum rudder angle</td>
<td>DMX</td>
<td>Degree</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Maximum flux rudder angle</td>
<td>DFMX</td>
<td>Degree/second</td>
<td>3,5</td>
<td>3,5</td>
<td>3,5</td>
</tr>
<tr>
<td>Time delay steering engine</td>
<td>TD</td>
<td>Second</td>
<td>1,5</td>
<td>1,5</td>
<td>1,5</td>
</tr>
<tr>
<td>Number of rudders</td>
<td>NR</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 1 Basic set of parameters for the three container ships implemented in the simulation.

Model hull forces:

For the implementation of the hull forces the aforementioned models proposed for the Abel Tasman are used as a starting point. The various ship parameters are calculated using the basic set of parameters and the models as described in Kijima\(^4\) for lateral forces and moments. The models proposed by Clarke as described in Van Manen\(^5\) are used to implement the effects of added mass due to the inertia of water.

Model rudder forces:

The models to calculate the rudder forces originate from Inoue\(^6\). The rudder area (\(A_{RUD}\)) is estimated as 2 % of the ship area, i.e. the product of the ship’s length (L) and cavity (T).
Model propeller forces:

For the calculation of the propeller forces the desired number of propeller revolutions ($N_{ DN}$) has to be determined by dividing the desired ship speed ($U_D$) with the maximum ship speed ($U_{MX}$). The desired ship speed can be obtained from the desired (maximum) track speed ($U_{DT}$). The desired number of propeller revolutions calculated is adjusted so it approaches the number of propeller revolutions ($N_{TG}$) related to the various telegraph positions ($I_{TG}$). This is done by a simple control that defines for each telegraph position a threshold equal to the 90%-value of the accompanying number of propeller revolutions, starting at zero. If the desired number of propeller revolutions is smaller than the threshold belonging to the telegraph position, the telegraph position is altered to one position higher. This is repeated until the correct telegraph position is obtained. Since the VTS-OSS aims at a passage of the simulated vessels without any restrictions, no slowing down by reversing the propeller revolution is assumed, leaving the control for telegraph positions astern out.

Since in reality the number of mutations in the ship speed is limited, the adjustment of the ship's speed is limited to the transition of track line and the alteration of the telegraph position in case of large rudder angles. The models used to calculate the actual propeller forces are described by LAP in Van Manen⁹.

The telegraph position corresponding with the maximum number of revolutions is left out of consideration, since this position is only applicable at sea (sea speed) and not in nor nearby ports.

Model wind forces:

Only wind is taken along as disturbance on the ship. The Davenport spectrum as described in Brix¹⁰ is used to model wind disturbance. In the simulation various wind speeds and directions are simulated, to obtain data necessary for the database used in the safety assessment.

The following wind conditions are simulated:
- 3 wind speeds: 0 / 10 / 20 m/s
- 8 wind directions: 0 to 315 degrees.
Safety assessment vessel traffic prediction

The safety assessment of the OSS can be divided into two modules:
- A module for the calculation of the distance between ships that may have an encounter, according to the schedule, to determine the relevancy of the previously obtained entries in the list of encounter by filtering out all "irrelevant" encounters.
- A module for the calculation of the safety margins of all simulated ships, taking into account the results of the first part of the safety assessment: the list of relevant ship encounters.

For the first part of the safety assessment a number of simplifications have been made. The main simplification comprehends the defining of a fixed distance threshold for ship encounters. If the distance between two ships that have an encounter is below the distance threshold, the encounter is added to a definitive list of encounters. Information concerning the (simulation) time and place (reference track line) as well as the participating ships is stored in the same list. The distance threshold is in this case defined as one nautical mile, which approaches the stop transfer at full ahead manoeuvrability speed for most ships above 200 meters ship length. The central idea is that the stop length represents the minimal distance needed to prevent a collision in case of a sudden obstruction of the traffic lane.

The second part of the safety assessment calculates the safety margins of the simulated vessels. For this information for every time step is necessary on the required space and control of each simulated vessel, as well as information on the available space and control. The required space and control is read out of a database, containing information on the distributions for these parameters under different wind and speed conditions. The entry for speed is defined by the telegraph position, resulting in a considerable reduction of the database entries. Assumed is that the effects of the disturbances on the speed are not relevant.

This database is acquired by running multiple simulations for all vessels for the above mentioned conditions. The 90% likelihood is calculated for the required space and control, leaving out the tail ends containing excessive values with a low likelihood.

In this demonstration only the effects of rudder angle are considered as relevant for the ship control. Assumed is that the effects of ship speed will come forward in the distributions for required space and rudder angle, as well as that the number of telegraph alterations (thus speed changes) will be limited. The last remark is based on the assumption that the ship speed will only change due to the transition of track lines and in case of large rudder angles. This reduces the direct effect of the speed on the required control, which makes that the ship speed can almost be considerate as static during certain time periods.

The available space and control are related to respectively the track line and subject ship. If there is an encounter between two ships, the available space for the subject ship will be reduced with the value for the required space of the observed ship, for the time an encounter endures, giving an indication for the actual available space for the subject ship. In case of multiple encounters this action has to be repeated several times.
Presentation vessel traffic prediction and safety indication

The way the results are presented to the VTS-operator has a great influence on the interpretation of them. Illogical presentation will distract the operator and thus reducing the value of the OSS.

The results of the simulation and the safety assessment can be presented in various ways. In this demonstration two options are presented:

- The presentation of the vessel traffic prediction and the associated safety assessment in two different screens.
- The presentation of the vessel traffic prediction and the associated safety assessment combined in one screen.

A great advantage of the last presentation is the possibility for the VTS-operator to gain insight in the vessel traffic development and associated safety in a glance. A way of presenting the combined information is by colouring the simulated vessels, in which the colour gives an indication for the safety margin of a ship. A similar presentation can be found on the internet for the presentation of traffic jams on highways, in which the colour varies from red to white representing the traffic speed from respectively zero to maximum speed. This approach is also applied for the implemented VTS-OSS.

All vessel traffic predictions are presented with the contour of the port of Rotterdam as background, to facilitate the VTS-operator in its orientation of the predicted vessel traffic situation.

The results of the simulation and the assessment are presented in time blocks of 15 minutes.
References

2. Noë, P.P. and Veldhuyzen, W., The use of simulation techniques as a tool for vessel traffic management, TNO, Delft, the Netherlands, March 1981.
3. Heinen, H.G. and Veldhuyzen, W., Short term vessel predictions as an aid to vessel traffic guidance, reportno. 5161055-83-1,TNO-IWECO, Delft, the Netherlands, February 1983.
Appendix D. Results vessel traffic simulation and safety assessment

In this appendix the results of the vessel traffic simulation and the safety assessment based on the predicted traffic overview will be presented. The results can be divided in:

- Results used to validate the used models for ship dynamics.
- Data on the distributions of required space and control for ships to generate the database necessary for the safety assessment
- Predicted vessel traffic situation
- Safety margins as a result of the safety assessment of the predicted vessel traffic situation by means of the proposed safety standards
Validation models ship dynamics

For a first indication for the accuracy of the implemented models, two characteristic ship parameters are validated. The results for these simulated characteristic parameters are compared with the values found in literature, as can be seen in Table 1. The turning circle and the maximum ship speed are chosen as characteristic parameters, since these are generally considered, besides the results of the zig-zag manoeuvre, as the manoeuvring characteristics for ships.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Abel Tasman</th>
<th>Regina Maersk</th>
<th>Maxicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship capacity (TEU)</td>
<td>1700</td>
<td>6000</td>
<td>9000</td>
</tr>
<tr>
<td>Length over all (meters)</td>
<td>225</td>
<td>318</td>
<td>350</td>
</tr>
<tr>
<td>Turning circle literature (meters) by maximum speed</td>
<td>780</td>
<td>1260</td>
<td>1038</td>
</tr>
<tr>
<td>Turning circle simulation (meters)</td>
<td>840</td>
<td>1300</td>
<td>1175</td>
</tr>
<tr>
<td>Deviation (%)</td>
<td>7.7</td>
<td>9.3</td>
<td>13.2</td>
</tr>
<tr>
<td>Maximum ship speed literature (miles/hour)</td>
<td>22.0</td>
<td>25.0</td>
<td>24.3</td>
</tr>
<tr>
<td>Maximum ship speed simulation (miles/hour)</td>
<td>21.7</td>
<td>24.6</td>
<td>23.7</td>
</tr>
<tr>
<td>Deviation (%)</td>
<td>1.4</td>
<td>1.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 1 Validation of the models for ship dynamics by comparing the maximum simulated ship speed and turning circle with the values found in literature.

Both characteristic parameters correspond to a large extent with the values found in literature\(^1\)\(^2\). The deviation is small and is, at this stage, considered as satisfying for the purpose of the simulation at this stage: exploring the possibility of the proposed VTS-OSS.

For a feasibility-study of the proposed OSS a more fundamental validation has to be performed, which means all characteristic ship parameters should be validated, including the zig-zag manoeuvre. Also the sensibility of the used models for varying values of the (basic) parameters should be determined, since a high sensibility of the results for changes made to the basic set of parameters can be an indication for the usefulness of the implemented models.

Due to the restricted time available the validation is kept to the validation of two characteristic parameters.

The addition of other disturbances and restrictions that act on the ship dynamics shall result in a more realistic behaviour of the system ship, resulting in new values for the characteristic parameters.
Data acquisition for safety database

For the safety assessment of the vessel traffic prediction information is needed on the distribution of the required space and rudder angle for a ship under various conditions. For this a database is used containing the distributions for required space and rudder angle under specific conditions. To fill the database data acquisition is performed by running multiple simulations for various conditions, resulting in a distribution for the required space and control.

The required space is a function of the maximum positions of the corners of a ship. This means the required space is a function of the position, the heading and width of a ship. This is taken along in the acquisition of the distribution for required space.

The distributions are stored in the database under various entries, subjected to the number of disturbances that are taken along in the simulation and the influencing factors. In this proposal only wind as disturbance is simulated, which results in the following entries:
- Ship speed
- Wind direction
- Wind speed (mean)

Since the ship speed is directly related to the telegraph position, the ship speed is replaced by the telegraph position, which implies that the distributions are also directly related to the telegraph position. By doing so, a simplification is made which has a major impact on the size of the database. After all, the number of telegraph positions is limited and discreet, while the ship speed varies continuously over a large range. The effect of disturbances on the ship speed is irrelevant, since at this point only the distributions for space and rudder angle are considered relevant, while the effect of disturbances on the ship speed will come forward in the vessel traffic prediction.

For the acquisition of data multiple simulations are executed along a predefined track line under varying predefined initial conditions while the telegraph position and wind condition remained the same. This results, after deviations due to the initial conditions are corrected, in a distribution for the of the ship position across the width of the shipping lane (required space) and rudder angle (required control) is given. In Figure 1 a set of histograms for the distribution of the ship position is presented for four successive moments in time, in time steps of 25 seconds. The distribution is assumed to be normal.

The stored distributions should actually represent the (simulated) reality, assuming that the results from the simulations to be accurate. For this the characteristics of the distributions are observed in time. If the characteristic values of the distribution at a certain point in time remains the same, the distributions is considered to be a correct representation of the (simulated) reality.

For the application, for which the distributions are required, only the 90%-likelihood is considered as relevant, disregarding the values for mean and deviation. By obtaining the 90% likelihood the tail ends are eliminated, by doing so large values with a low probability are removed leaving better applicable values.
For the Maxicon the required space is approximately 92 (meters) and required rudder angle is 10 (degrees) for telegraph position full ahead, a mean wind speed of 10 (m/s) and wind direction of 90 (degrees). The acquired value for required space approaches the required space according to the pilot, which is determined as 96 meter to obtain an acceptable situation. Assumed is that the distributions in the database give a realistic value for the required space.

![Histograms presenting the distribution of the ship's position of the Abel Tasman relative to the track line. The simulated conditions are telegraph position full ahead manoeuvrability (ITG= 9), wind direction transverse on the ship (Pw= 90 degrees) and wind speed (Uw) 10 meter/seconde. The histograms run from time step 601 to 976 in steps of 25 seconds. The vertical axis represents the number of hits, while horizontal the ship's position is presented, in which the position is determined relative to the centre of gravity. For the calculation of the required space the ship's position should be corrected by the heading and width of the ship, resulting in an increase of the required space. At first sight the distributions seem to be normal distributed, which is also assumed in the further process.](image)

In case of severe wind conditions or low the ship speed the required space will increase, altering all characteristic values for the distribution. This is not considered to be relevant, since the interest lies purely in the value for 90%-likelihood, i.e. the total required width to cope with 90% of the case.
Vessel traffic prediction

The results of the simulation give an indication of the vessel traffic development, as is shown in Figure 2. To determine the usefulness of the prediction the results a comparison is made with the results found in simulator research\textsuperscript{15}. This is done by simulating the described journeys made during simulator runs and comparing these results at first sight. The predicted traffic image is, in general, considered to be similar, taking into account the previously mentioned assumptions and limitations.

The results obtained by the simulation are considered useful to gain a first impression of the possibilities of the proposed OSS. Still the behaviour of the control models can become a restriction if special manoeuvres are executed or in case of exceptional situations, due to the simplicity of the control models. This can, for instance, result in a deviation of the desired path.

The proposed presentation of the vessel traffic in blocks of a quarter of an hour over the area of interest is retained, with the possibility to zoom in into specific traffic situations.

The results of the vessel traffic simulation depend on:
- Accuracy of the input.
- Accuracy of the ship models.
- Accuracy of the estimations for ship speed.
- Accuracy and extensiveness of the HO models.

In this study no extensive survey has been conducted on the sensibility of the results for the accuracy of the above-mentioned points, for the main point has been the exploration of the proposed VTS-OSS.

\textbf{Figure 2} Vessel traffic prediction for four ships during 15 minutes.
Safety assessment of the vessel traffic prediction

The first step of the safety assessment is the selection of potential ship encounters from the ship encounter list, by selecting all encounters that fall below the distance threshold. A fixed distance threshold was used, resulting in a list of potential encounters, depending on the traffic schedule the simulation started with.

The proposed safety assessment of the predicted vessel traffic gives a global indication of the possible future safety status. It gives an insight of what can become critical situations due to ship encounters or disturbances by taking into account the lack of free waterway or reserve in control. A safety assessment of a vessel traffic prediction for two ships is given in Figure 3.

![Safety margin for two ships that have an encounter. The points indicated with T represent the transition of track line, while the points indicated with E represent the ship encounter.](image)

By defining a threshold an indication can be given for the minimal safety margin that should be obtained. This threshold should guarantee a safe passage for the simulated vessel traffic as well as for the (local) traffic that is kept out of the simulation. It copes with the occurrence of unexpected and undesired situations by maintaining a certain level of resilience of the vessel traffic to be able to handle these situations. The used threshold for the safety margin is conform the categorisation of the safety levels as is presented in the paper. Thus implying a threshold of 0.4 for the safety margin to obtain an acceptable safety level.

The sudden drop of the safety margin due to the transition of track line is a result of the available space coupled to each track line. A refinement of the transition can be obtained by reducing the length of the track lines, thus making it possible to model the environment precisely.
By presenting the vessel traffic prediction and the safety margin in one figure the VTS-operator can acquire information on the future traffic safety in a glance. An example of this presentation is given in Figure 4, for the same situation as is presented in Figure 3.

The combination of this information in one single display makes it easier for the VTS-operator to optimise the situation for the safety, for it gives more insight in the direct relation between the presented safety margins and the traffic prediction. A problem with this way of representing the obtained results is the fact that not always a direct relation is visible between ships that experience the same encounter.

Figure 4 Presentation vessel traffic prediction and safety assessment in one figure. The effect of the encounter on the vessel traffic safety is made visible by varying the colour of the ships. A light grey colour means, in this specific case, a decrease of the safety margin.
In Figure 5 the safety margins are given for the prediction of five ships. The accompanying vessel traffic prediction is given in Figure 6.

Figure 5 Safety margins for five simulated vessels. 1 and 4, 2 and 1 have an encounter starting at respectively 175 and 790 seconds.
Figure 6 Vessel traffic prediction belong to the safety margins in Figure 5. Since in this image the prediction for 20 minutes is presented, the image can become crowded and disorderly.
References:

