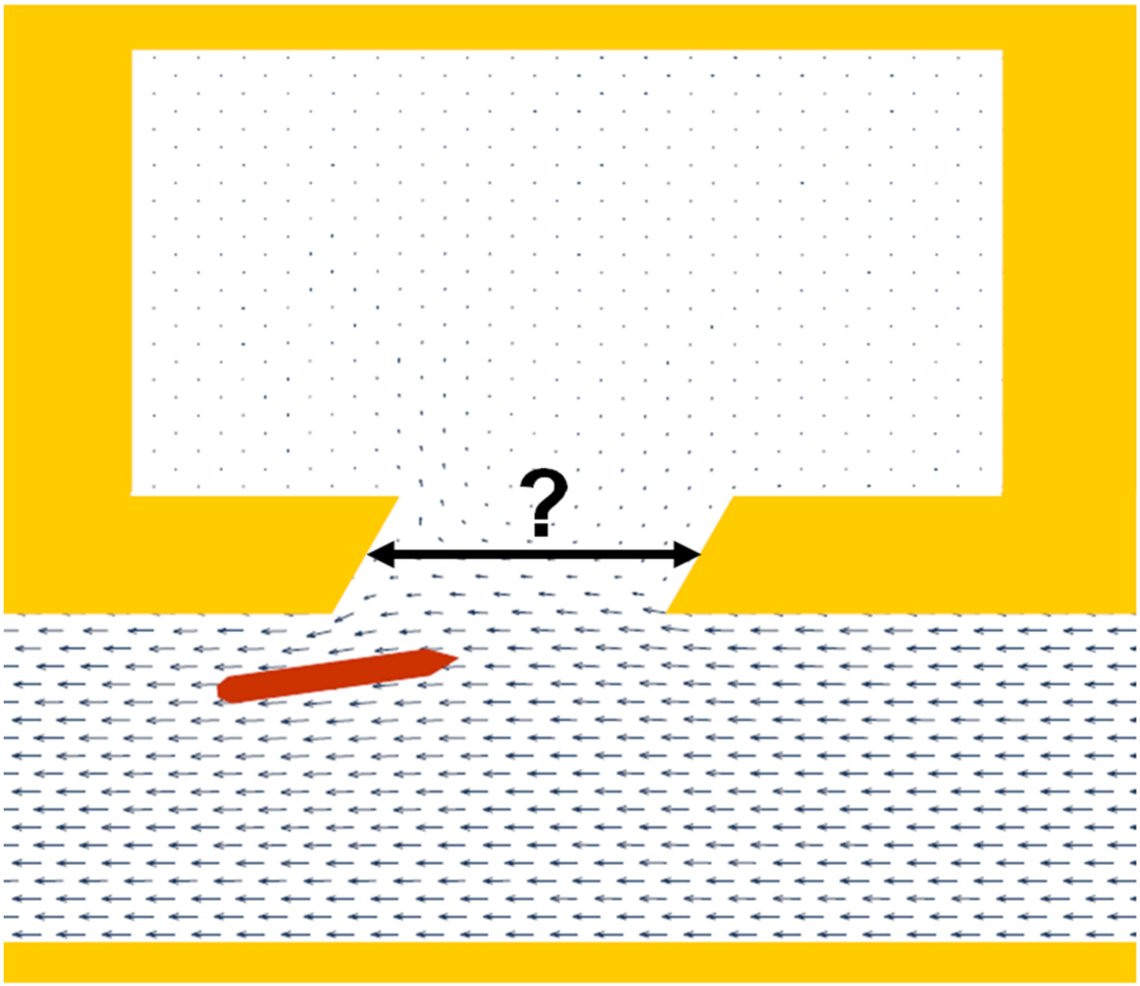
Minimum entrance width for inland ports



Master thesis

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June 2017

Minimum entrance width for inland ports

By

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to obtain the degree of

Master of Science

in Hydraulic Engineering

Faculty of Civil Engineering and Geosciences
Delft University of Technology
The Netherlands

To be defended publicly on
Monday June 26, 2017 at 14.00 PM

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Project duration:	October 3, 2016 – June 26, 2017	
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Preface

This thesis presents my graduation work to conclude my Master Hydraulic Engineering and specialisation Rivers, Ports and Waterways at the Delft University of Technology. The topic of this research is to determine the minimum nautical safe entrance width for inland ports. In this study the influence of different design parameters on the required entrance width are studied. I conducted this research as an intern at MARIN.

First of all, I would like to show my gratitude towards the members of my graduation committee for their input and guidance. I would like to thank Tiedo Vellinga for his feedback during the official meetings and Dirk Jan Peters for reviewing my work in the final phase of my thesis. Special thanks to Henk Verheij and Dick ten Hove. Henk, thank you for the feedback and discussions throughout my entire thesis. Dick, thank you for providing a workplace at MARIN and for making time to answer all my questions.

Secondly, I would like to thank the colleagues from MARIN for providing information and the assistance during my thesis. In particularly, I would like to thank Rien Goedegebuure and Alicja Bilinska for their assistances with the SHIPMA model. Martin van der Wel, thank you for reviewing my report and your help during my thesis. Furthermore, I would like to thank the MARIN students for an enjoyable time at MARIN.

Finally, I would like to thank my fellow students, friends, family and girlfriend for their support during my entire study.

Menno Buckers
Delft, June 2016

Summary

A port entrance should provide nautical safety and it is often desired to minimise the sedimentation in the port. The nautical requirements for designing a port entrance are often opposite of the preferences regarding minimising the siltation. In general, a wider entrance enlarges the ease for navigation through the entrance and a smaller entrance reduces the siltation. In the Netherlands a large variety exists in the used widths of inland port entrances. In addition, multiple entrance layouts are applied.

Currently, guidelines are missing for the design of inland port entrances along flowing waters with flow velocities larger than 0.5 m/s. In the near future, Rijkswaterstaat wants to provide guidelines for inland port entrances along these flowing waters in the Netherlands. In the past, several entrances of inland ports along flowing waters have been studied in order to optimise the entrances with respect to nautical and morphological aspects. However, these studies were performed on specific local situations. A more generic insight into the minimum required nautical safe entrance width and most efficient entrance layout can reduce the design costs and time.

The objective of this research was to find the minimum required nautical safe entrance width for generic situations for inland ports along flowing waters in non-tidal areas. To find this minimum safe entrance width, the most efficient entrance layout was determined. The influence of different design parameters was studied to provide the most efficient situation. Moreover, an insight into the influence of these parameters was needed to determine the effect on the most efficient situation when changing these parameters. Besides the optimisation with respect to nautical safety, siltation aspects were taken into account to provide an entrance layout that is also realistic with respect to minimising sedimentation in the port. The following main research question was formulated: *What is the minimum required nautical safe entrance width and what is the most efficient entrance layout for an inland port along non-tidal waterways?*

This research focused mainly on the nautical safety of inland port entrances for commercial shipping. Optimising the entrance with respect to minimising the siltation was included, but to a smaller extent. The research was performed for waterways with flow velocities between 1.0 and 2.5 m/s, because this range was most common for the flowing waters in the Netherlands. Moreover, only one-way traffic through the entrance was taken into account.

First, literature was studied to obtain an insight in different design aspects which influence the layout of an inland port entrances. Several recently conducted studies were analysed. Furthermore, conducted research on the geometry of non-tidal river ports in relation to minimising siltation was used to outline the differences and similarities for optimising an inland port entrance with respect to nautical safety and minimising sedimentation. Besides the provided insight into the nautical and morphological aspects, the conclusions of the literature study were used to set up a ship manoeuvring simulation study.

A simulation study can provide insight into the different design parameters regarding nautical safety and can be used to compare different scenarios. A fast-time simulation system was chosen, because these systems are suitable for comparing different scenarios, provide quick feedback and enabling quick assessment of the simulations. The fast-time simulation program SHIPMA was used to perform the simulation study.

In the simulation study a mathematical ship model comparable with a loaded CEMT class Va ship was used. From a simplified current and wind force calculation, it was concluded that the unloaded Va ship and container Va ship were less decisive. The simulation results were assessed based on established safety criteria. These criteria make it possible to compare different run results objectively with each other. Furthermore, realistic manoeuvres and ship behaviour should be used to get results which are as reliable as possible. To provide these reliable outcomes, it was attempted to set up every run in such a manner that it satisfied the established safety criteria. It should be mentioned that for each scenario a port basin

was used that provided sufficient distance for a realistic stopping manoeuvre. The influence of the port basin on the required entrance width was not taken into account in this research.

In total, 66 scenarios were simulated with SHIPMA. This simulation model is not suitable for detailed design, taking into account human interference and manoeuvres in which the interaction of two skippers should be taken into account. As a consequence, these aspects were not included in the acquired results. As mentioned before, SHIPMA is suitable for comparing different scenarios. In addition, the conducted runs are set-up in a similar manner and by the same user. Therefore, it is expected that the observed trends, such as the most efficient entrance angle, are reliable.

Based on the simulation study results, conclusions were drawn. The minimum required entrance widths for flow velocities between 1.0 and 2.5 m/s are shown in table 0-1. Only arrival scenarios were taken into account.

Table 0-1: Overview of required entrance widths for entrance angle of 120 degrees and length of 60 meters.

Current	Forward manoeuvre, arrival sailing upstream	Backward manoeuvre, arrival sailing downstream
1.0 m/s	54 m	70 m
1.5 m/s	62 m	78 m
2.0 m/s	71 m	87 m
2.5 m/s	79 m	-

As a result of the performed simulation study, it was concluded that the minimum safe entrance width is provided for an entrance angle of 120 degrees and an entrance length of 60 meters. In figure 0-1 is shown how the design parameters, which are included in the simulation study, are defined. For the determined most efficient layout, the forward manoeuvres into the port when sailing downstream were replaced by backward manoeuvres. A backward manoeuvre was conducted by first stopping downstream of the entrance, then sailing through the entrance against the current direction with the stern of the ship first. Backward manoeuvres were not possible to conduct for flow velocities larger than 2.0 m/s. Hence, for larger flow velocities a ship should turn downstream of the port entrance and enter the port with a forward manoeuvre sailing upstream.

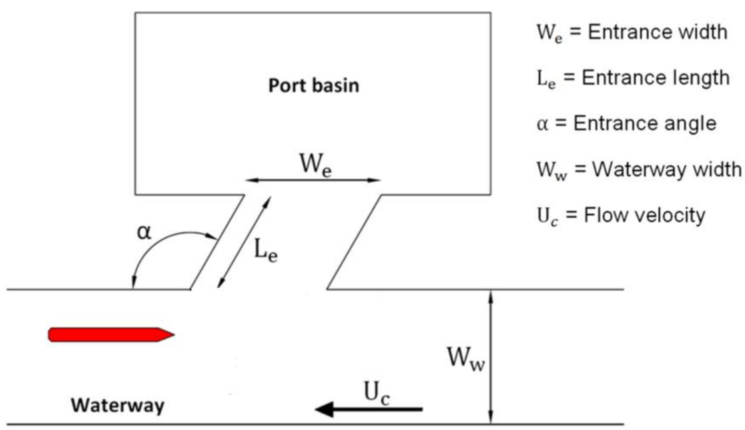

Figure 0-1: Overview of design parameters included in simulation study.

In addition, the sensitivity of several design parameters was analysed for the most efficient layout. It was found, that the flow velocity is the most important parameter which is affecting the required entrance width. A linear relation was observed. As is visible in table 0-1, a deviation of plus (minus) 0.5 m/s in flow velocity increases (decreases) the required entrance width with circa 8 meters. Moreover, it was found that the sensitivity of the entrance width, length and angle is small.

In addition, the most efficient angle of 120 degrees is also favourable regarding minimising the siltation in the port. Previous research found that an entrance angle of 120 degrees reduces the siltation in the port considerably compared to angles of 90 degrees or smaller. Furthermore, the literature study showed that a rectangular shape of the cross-sectional area is more desired than a trapezoidal shape, taking a similar width at the bottom of the entrance into account.

As described above, the sensitivity of the entrance angle, length and width for the determined most efficient layout is small. Moreover, the results for the nautically optimised entrance angle do not conflict with the most efficient angles regarding minimising siltation. Purely based on these results, it should be possible to create a design rule that is applicable for many inland ports along flowing waters. These design rules should be related to different design flow velocities, whereas the flow velocity has a considerable influence on the required entrance width. It should be mentioned that not all the design parameters, which can possibly influence the required entrance width, were studied in this research. Therefore, additional research is required before design rules can be created.

The simulation study showed that for an available waterway width larger than 90 meters, the arrival manoeuvres sailing upstream are more decisive than the departure manoeuvres sailing downstream. Between available waterway widths of 50 to 90 meters, a transition point is expected, in which the departures and arrivals are equally important. Since only arrival scenarios were taken into account to determine the most efficient entrance, the presented minimum entrance widths in table 0-1 are only valid if the available waterway width is larger than 90 meters. Additional simulations are required to establish the transition point more precisely. Then, the validity range of this research can be enlarged. In addition, it was determined that the arrivals sailing downstream are more decisive than the departures sailing upstream, for every waterway width.

The influence of the wind was not included in the simulation study. For the most efficient entrance layout, it was determined, based on simplified current and wind force calculations, that the wind forces are less than 5% of the current forces on the loaded Va ship. Although the expected wind forces are small, wind gusts can influence the ship manoeuvres. However, this aspect cannot be simulated with SHIPMA.

A water depth/draught (h/T) ratio of 1.3 was used in the simulation study. Normally, for large flow velocities these ratios are also larger. Note that when the river discharge increases the flow velocity increases, but also the water level rises. A larger h/T ratio will improve the manoeuvrability of a ship. Hence, the provided results are conservative with respect to the chosen h/T ratio.

Scenarios with an entrance layout comparable to a lock approach harbour, located parallel to the waterway axis, were simulated. Manoeuvres sideways through the port entrance were used. The obtained entrance widths are less favourable than presented results in table 0-1.

It is recommended to perform additional ship manoeuvring simulations to study several aspects more accurately. A better insight is required in the influence of different h/T ratios, different ship types and the wind on the required entrance width. Moreover, by performing real-time simulations for the determined minimum entrance widths, it can be established how the results of this research are related to scenarios in which human interference is included. In addition, in the simulation study only a rectangular shaped entrance was used. This layout was chosen, because this provides the best orientation for the skippers and thus contributes to safe navigation. However, other entrance shapes can also be applied. Additional research, regarding nautical and morphological aspects, is required to study the possibilities of other layouts.

This research mainly focussed on the optimisation with respect to nautical safety. Although the determined most efficient entrance angle of 120 degrees is favourable regarding minimising siltation, additional research to the siltation of inland ports can contribute to a further optimisation regarding minimising siltation.

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Nomenclature

Acronyms

CEMT	Conférence Européenne des Ministres des Transports
RWS	Rijkswaterstaat
WG2011	Waterway Guidelines 2011

Glossary

Bank suction	When a ship sails eccentrically with respect to the waterway axis, this induces an asymmetrical return current pattern. The discharge of the return current is equally on both sides of the ship. As a consequence of the smaller distance between the ship and the near bank, the flow velocities and water level depression are larger at this side of the ship. The increased flow velocity between the ship and the near bank, in combination with the decreased flow velocity between the ship and the far bank, causes a force which draws the ship towards the nearest bank. Moreover, a moment tending to yaw the bow of the ship towards the far bank is created (Verheij et al., 2008).
Nautical safety	Safety related to ships and navigation.
Power burst	Short periods of more propeller revolutions to increase the steering capacity of a ship.
Swept path	The swept path is the envelope of the travelled path by the sailing ship. An example of a swept path is shown in figure 3-20.
Thijsse Egg	Port entrance with an elliptical basin between the entrance at the waterway side and the entrance at the basin side, see figure 1-1.

Symbols

Symbol	Unit	Description
A	(m^2)	Cross-sectional area of the harbour mouth
A_c	(m^2)	Cross-sectional area of ship in current
A_L	(m^2)	Longitudinal cross section of the above water area
A_T	(m^2)	Lateral cross section of the above water area
B	(m)	Beam of ship
c_a	(kg/m^3)	Sediment concentration in the river water
C	$(m^{1/2}/s)$	Chézy coefficient
C_c	(-)	Current force coefficient
C_{xc}	(-)	Longitudinal current force coefficient
C_{xw}	(-)	Longitudinal wind force coefficient
C_{yc}	(-)	Transverse current force coefficient
C_{yw}	(-)	Lateral wind force coefficient
d_1	(m)	Bottom level in the middle of the waterway
d_2	(m)	Bottom level near banks
F	(kN)	Force
F_{bow}	(kN)	Bow thruster force
F_{rud}	(kN)	Force caused by using rudder angle
F_x	(kN)	Force in longitudinal direction
F_y	(kN)	Force in lateral direction
g	(m/s^2)	Acceleration due to gravity
h	(m)	Water depth
h_b	(m)	Basin water depth
H_w	(m)	Elevation above ground or water surface

$H_{w,L}$	(m)	Average height of the longitudinal cross section of above water area of the ship
$H_{w,T}$	(m)	Average height of the lateral cross section of above water area of the ship
L_b	(m)	Length of port basin
L_{bp}	(m)	Ship length between perpendiculars
L_e	(m)	Port entrance length
L_{oa}	(m)	Overall length of ship
$L_{sheltered}$	(m)	Length of sheltered area in front of port
M_{cur}	(kNm)	Moment on ship caused by current forces
n	(-)	Manning's roughness coefficient
n_{crit}	(rev/min)	Machine criterion
n_p	(rev/min)	Propeller revolutions
p	(-)	Trapping efficiency
Q_h	(m^3/s)	Discharge through the entrance
Q_r	(m^3/s)	Water exchange rate between harbour basin and waterway
R	(m)	Hydraulic radius
T	(m)	Draught amidships
T_h	(s)	Horizontal residence time in the harbour
u_b	(m/s)	Average basin velocity
u_c	(m/s)	Critical velocity for sedimentation
U_c	(m/s)	Flow velocity in waterway
v	(m/s)	Water velocity around ship's hull
v_w	(m/s)	Wind velocity at elevation H_w
V	(m^3)	Water volume in harbour basin
$V_{rel,water}$	(m/s)	Relative water velocity around ship
$V_{rel,wind}$	(m/s)	Relative wind velocity around ship
$V_{rel,x,wind}$	(m/s)	Relative wind velocity around ship in longitudinal direction
$V_{rel,y,wind}$	(m/s)	Relative wind velocity around ship in lateral direction
V_{wind}	(m/s)	Average wind velocity
W_1	(m)	Entrance width at the waterway side
W_2	(m)	The entrance width at the port basin
W_b	(m)	Width of port basin
W_d	(m)	The waterway width on the bottom of the waterway
W_e	(m)	Port entrance width
$W_{e,avg}$	(m)	Average entrance width: $(W_1 + W_2)/2$
$W_{e,port}$	(m)	Entrance width at the port side of the Thijsse Egg basin
$W_{e,req}$	(m)	Required entrance width
$W_{e,TE}$	(m)	Entrance width at the waterway side of the Thijsse Egg basin
W_s	(m/s)	Sediment settling velocity
$W_{sheltered}$	(m)	Width of sheltered area in front of port
W_{sp}	(m)	Width of swept path in port entrance
W_{used}	(m)	Used waterway width by ship
W_w	(m)	Waterway width (in the keel plane of a loaded ship)
$W_{w,req}$	(m)	Required waterway width
α	(deg)	Entrance angle, see figure 1-2 for how the entrance angle is defined
Δx	(m)	Distance in x-direction
Δy	(m)	Distance in y-direction
δ	(deg)	Rudder angle
δ_{crit}	(deg)	Rudder angle criterion
ρ	(kg/m^3)	Density
ρ_{air}	(kg/m^3)	Density of air
ρ_{water}	(kg/m^3)	Density of water

1 Introduction

The entrance of an inland port links the port basin with the waterway. A port entrance should provide nautical safety. Besides providing safe navigation, it is often desired to design the entrance in a way that it minimises the sedimentation in the port.

An important aspect in the design of an inland port is the entrance width. In the Netherlands, a large variety exists in the used entrance widths for inland ports. Roughly, entrance widths within a range of four to nine times the beam of the design ship are used (Lee, 2014). Moreover, different entrance shapes are applied. In particular a rectangular entrance, funnel shaped entrance or Thijsse Egg entrance are layouts which are used. These three entrance layouts are illustrated in figure 1-1. A Thijsse Egg entrance is an elliptical basin that is located between the entrance to the port basin and the entrance at the waterway.

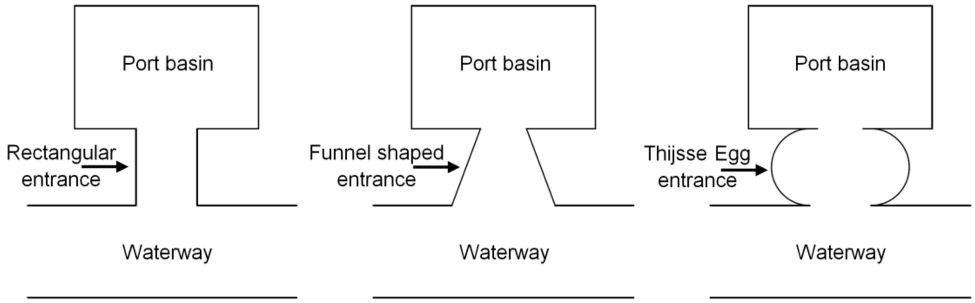


Figure 1-1: Schematisation of rectangular entrance (left), funnel shaped entrance (middle) and Thijsse Egg entrance (right).

In general, the nautical requirements for designing a port entrance are often the opposite of the preferences with respect to hydraulic and morphological aspects (Ten Hove et al., 2015). For example, a wider entrance enlarges the ease of navigation through the entrance, but increases the siltation rate. As a consequence, the maintenance dredging costs will increase. Hence, to limit these costs, a smaller entrance width is desired.

In order to design a port entrance efficiently with respect to nautical safety, several design parameters should be taken into account. Besides the port entrance layout, the layout of the port basin and the waterway are important aspects. Furthermore, the wind, water depth, current and bank suction are environmental aspects which can influence the manoeuvrability of the ships.

In addition, human interference is important to include when designing an entrance (MARIN, personal communication, 2017). Besides, visibility aspects should be considered (RWS, 2011a). Moreover, previous studies found out that the ease for the skippers to orientate themselves is also related to the provided entrance layout (De Jong et al., 2002c; Van Heel & Verheij, 2011).

In the past, entrances were designed based on the judgement of experts. More recently, guidelines were introduced to design port entrances. In the Netherlands, the Waterway Guidelines 2011 (RWS, 2011a) are used for designing waterways with a maximum flow velocity of 0.5 m/s. These guidelines, referred to as

WG2011, state that a minimum entrance width of 4B is required, with B is the beam of the design ship. Lee (2014) revealed that this design rule is not valid for larger flow velocities. For these situations wider entrances are required to provide nautical safety.

In the near future, Rijkswaterstaat wants to provide guidelines for waterways with flow velocities larger than 0.5 m/s (Ten Hove et al., 2015). These guidelines should also contain rules for the design of inland port entrances. In this generic research, an insight is given into the most efficient layout for inland port entrances along flowing waters.

1.1 Problem description

Currently, guidelines are missing for the design of inland port entrances along flowing waters with flow velocities larger than 0.5 m/s. According to Ten Hove et al. (2015), an entrance width equal to the overall length of the design ship is often applied for inland port design along flowing waters. However, it is questionable whether this design rule is the right choice for every local situation. Normally, this rule is used to prevent the possibility of ships becoming stranded across the entrance in case of an incident (PIANC et al., 2014). Therefore, it is unlikely that this rule provides the minimum required safe entrance width for every inland port entrance.

In the past, multiple entrances of inland ports along flowing waters have been studied in order to optimise the entrances with respect to nautical and morphological aspects. However, these studies were performed on specific local situations. A more generic insight into the minimum required nautical safe entrance width is needed to design the entrance of an inland port efficiently. Consequently, a less extensive study is required for the optimisation of an inland port entrance for a local situation. This can reduce the costs and needed time to design the entrances of inland ports.

1.2 Research objective and questions

The objective of this research is to find the minimum required nautical safe entrance width for generic situations for inland ports along flowing waters in non-tidal areas. To find this minimum safe entrance width, the most efficient entrance layout should be determined. The influence of different design parameters should be studied to provide the most efficient situation. Moreover, an insight into the influence of these design parameters is needed to determine the effect on the most efficient situation when changing these parameters. Besides the optimisation with respect to nautical safety, siltation aspects should be taken into account to provide an entrance layout that is also realistic with respect to minimising sedimentation in the port.

The objective will be addressed by answering the following main research question:

What is the minimum required nautical safe entrance width and what is the most efficient entrance layout for an inland port along non-tidal waterways?

The most efficient entrance layout depends on two aspects. Firstly, the most efficient entrance regarding minimising the siltation in and around an inland port and thus reduces the maintenance dredging costs as much as possible. Secondly, the most efficient layout regarding the minimum required nautical safe entrance width. So, in order to provide an answer on the main research question, the following two sub-questions should be answered:

1. What entrance layout is efficient with respect to limiting the siltation in and around an inland port in non-tidal areas?
2. What is the influence of the different design parameters on the minimum required nautical safe entrance width?

In addition, this research should provide an insight into the possibilities of making generic design rules for inland port entrances along flowing waters. Hence, the following sub-question should be answered:

3. Is it possible to create generic design rules for inland port entrances along flowing waters in non-tidal areas?

1.3 Scope

This research focuses mainly on the nautical safety of inland port entrances in non-tidal areas. Figure 1-2 shows how several design parameters are defined in this research. The waterway width (W_w), entrance width (W_e), entrance length (L_e), entrance angle (α) and the flow velocity (U_c) are illustrated. The influence of these design parameters is studied by performing a ship manoeuvring simulation study. Furthermore, a scenario with flooded entrance dams is simulated to analyse the difference with dry entrance dams. The entrance of a lock approach, harbour positioned parallel to the waterway axis, is also included in the simulation study. Several other design aspects are discussed in this report, but are not included in the simulation study. These are: funnel shaped entrance layout, Thijsse Egg entrance layout, port basin layout, water depth and wind. These aspects are also discussed in this report, but to a smaller extent than the aspects mentioned above.

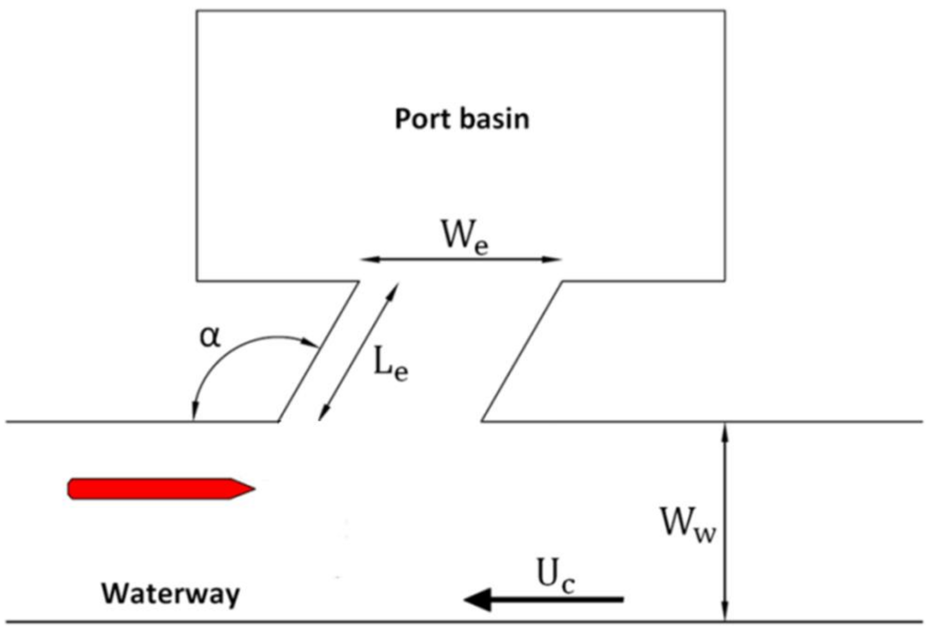


Figure 1-2: Overview of design parameters included in simulation study.

In the Netherlands the waterways are indicated with a CEMT class number. This number indicates the maximum ship dimensions (length, beam and draught) which are allowed on a waterway. A higher CEMT class number represents larger allowed ship dimensions. Based on personal communication with MARIN (2017), it was decided to use a CEMT class Va ship for the simulation study in this research. For several waterways in the Netherlands ships from larger CEMT classes are allowed. Normally, for these situations the largest ship is taken as the design ship. However, inland ports along flowing waters in the Netherlands receive more frequently CEMT class Va ships than ships from higher ship classes. Therefore, it is decided to use the class Va ship to make the simulation results more applicable to the major part of the inland ports in the Netherlands. In addition, the optimisation of the port entrance for pushed convoys is outside the scope of this research.

Furthermore, the following starting points are used for this research:

- Flow velocities between 1.0 and 2.5 m/s are taken into consideration. A range between 0 and 2.5 m/s covers the occurring flow conditions in the Netherlands for most situations (MARIN, personal communication, 2017). Port entrances along waterways with a flow velocity up to 0.5 m/s are described in WG2011. Hence, this research focuses on the velocities between 1.0 and 2.5 m/s.
- No distinction is made between ports located at the left or right side of a waterway, because in the Netherlands it is allowed to sail at the port side of the waterway when approaching a port entrance (RWS, 2011b).
- The influence of the port basin on the required entrance width is not studied in this research. However, a small basin can influence the manoeuvres through the port entrance.
- Only one-way traffic through the port entrance is taken into consideration. In general, only one ship is sailing through the inland port entrances in the Netherlands at the same time.
- This research is limited to commercial shipping; the optimisation of a marina entrance is outside the scope of this research.

Although the focus of this research is on the optimisation of an inland port entrances regarding nautical safety, the optimisation with respect to minimising the siltation is also taken into consideration. However, this part is limited to a literature study and is therefore taken into account to a smaller extent.

1.4 Research methodology

This research is performed by taking different methodological steps. This paragraph outlines the steps that were taken to answer the research questions and achieve the objective of this research.

First, literature about the influence of different design aspects that influences the layout of an inland port entrance was studied. As mentioned before, limited design rules for inland port entrances are available. Therefore, several recently performed studies on inland port entrances were analysed. The results of these studies with respect to nautical safety were used in this research. In addition, the conclusions with respect to minimising siltation were also analysed. Furthermore, research on the geometry of non-tidal river ports in relation to minimising siltation was used to outline the differences and similarities for the optimisation of an inland port entrance with respect to nautical safety and minimising sedimentation.

The conclusions followed from this literature study were used to set up a ship manoeuvring simulation study. During this study different scenarios were simulated in order to study the influences of different design parameters. The main focus during this simulation study was to answer the main research question. Hence, every new group of simulations should provide a better view on the minimum safe entrance width and most efficient layout. The ship manoeuvring simulations were conducted with the fast-time simulation model SHIPMA.

Every conducted run was assessed with respect to the established safety criteria. The used criteria are introduced in section 3.4.1 of this report. These criteria make it possible to compare the different run results objectively with each other. In order to provide as much useful results as possible, it was attempted to set up every run in such a manner that it satisfied the established safety criteria.

Subsequently, the results of the simulations study were analysed. The influences of different design parameters on the required entrance width were investigated. The conclusions based on the simulation study were compared to the results that followed from literature.

1.5 Limitations of the research

For the simulation study the fast-time simulation system SHIPMA was used. This simulation model does not take human interference into account, since the ship is steered by an automatic pilot instead of an actual human operator. As a consequence, the human factor is not included in the research results. Besides, the model is not suitable for detailed waterway or port design. Furthermore, the model is not suitable for manoeuvres in which the interaction of two ships and skippers should be taken into account (MARIN & Deltares, 2015). As a consequence of these limitations the required entrance widths provided in this research are not accurate enough for a final design. Therefore, the results give only an indication of the minimum required nautical safe entrance width.

Furthermore, only a fictional entrance and waterway layout are studied. The chosen layouts are a schematisation of real situations. As a consequence, when using the results of this research for a local situation, the differences between the local situation and the used schematisations for this research should be compared. These differences can influence the results. For example, in the used schematisations no discontinuities are available in the water depth and waterway width. For local situations, it is more common that at least small discontinuities are available in these design parameters. These differences can influence the current pattern around the port entrance. As a consequence, this can cause differences between a local situation and the acquired research results.

In addition, only flow velocities between 1.0 and 2.5 m/s are taken into account in this research. Extrapolating the research results can provide wrong results, because the ship behaviour is not simulated for these larger flow velocities. For flow velocities up to 0.5 m/s, WG2011 can be used. It should be noted that for the Netherlands the flow velocities in the waterways generally occur between a range of 0 and 2.5 m/s (MARIN, personal communication, 2017). Therefore, for inland port entrances in the Netherlands it is generally not necessary to extrapolate the research results for larger flow conditions.

1.6 Report outline

This section provides an overview of the structure of this report. The report is constructed in line with the used research methodology. A visualisation of the report structure is shown in figure 1-3. Sub-questions 1, 2 and 3 are associated with respectively chapter 2, 5 and 7.

In chapter 2, an overview is given of the results of the literature study. This chapter discusses the available guidelines for port design and the results of recently performed entrance studies. Moreover, it provides an overview of performed research on the most efficient entrance geometry of river harbours with respect to minimising siltation. In addition, the existing different ship manoeuvring simulators are briefly explained.

Chapter 3 describes the set-up of the ship manoeuvring simulation study. The used simulation model, the simulation approach and the simulation input is described. Besides, the used safety criteria for the assessment of a run and the evaluation method for the run output are described.

In chapter 4 the nautical safety of the simulated scenarios is assessed. In addition, several conclusions are drawn that follow directly from the assessment. In chapter 5, the assessed simulation results from chapter 4 are analysed in more detail. The influence of different design parameters on the required entrance width is discussed. A reader which is not interested in the safety assessment of the conducted simulated scenarios can continue reading chapter 5 after chapter 3. It is not necessary to read chapter 4 to understand the analysis of the model results in chapter 5.

In chapter 6 the acquired results will be reviewed. First, the interpretation of the simulation results is discussed. Thereafter, the simulation results are compared to the literature results from chapter 2. Moreover, this chapter discusses the possibilities of other entrance layouts than the most efficient entrance layout presented in this research.

Chapter 7 presents the conclusions and recommendations of this research.

In appendix G the output plots of the conducted runs with the fast-time simulation model SHIPMA are shown. This appendix with output plots is available at *http://researchdata.4tu.nl*.

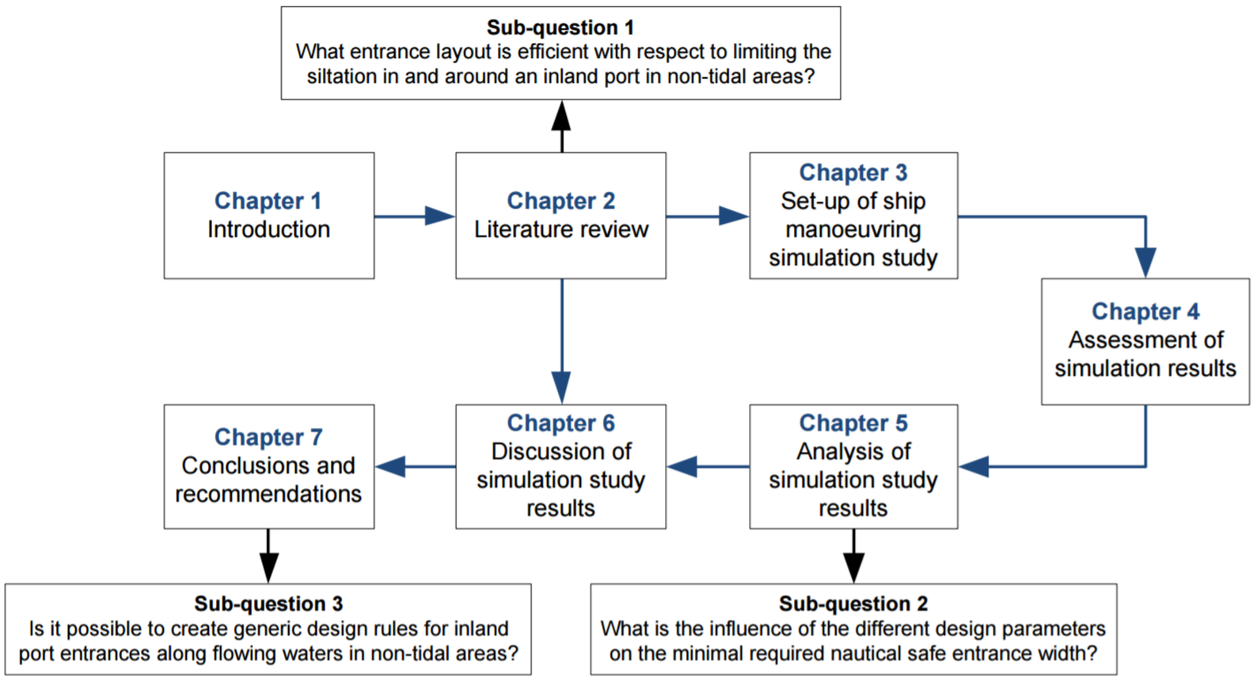


Figure 1-3: Overview of report structure.

2

Design aspects of inland port entrances

Regarding inland ports, many aspects can be studied in order to optimise the entrance width and layout. First in paragraph 2.1 the available guidelines for the design of an inland port entrance are summarised. Next, in paragraph 2.2 an overview is given of relevant aspects from recently performed navigation studies around inland ports. Several aspects with respect to minimising siltation were also included in these studies. This paragraph gives an insight into the available knowledge for the optimisation of an inland port entrance.

Besides the nautical safety of a port entrance, the geometry of an entrance influences the siltation in the port and around the entrance. General siltation processes that can be applied for this generic research are presented in paragraph 2.3. The geometry of the entrance layout is discussed based on these generic siltation processes.

According to PIANC et al. (2014) ship manoeuvring simulation systems can be used to evaluate and optimise the horizontal dimensions of a port. In paragraph 2.4, an overview is given of different ship manoeuvring simulation systems. The differences between these simulation models are briefly discussed.

Finally, in paragraph 2.5 the conclusions of this chapter are presented. In this paragraph also an overview is given of the similarities and differences for optimising an inland port entrance width respect to nautical safety and minimising siltation. Moreover, the starting points to set-up a ship manoeuvring simulations study are presented. In chapter 6 of this report the conclusions of this chapter are used to discuss the results of the conducted ship manoeuvring simulation study.

2.1 Available guidelines for port entrances

In the Netherlands, the Waterway Guidelines 2011 (WG2011) are used for designing inland waterways (RWS, 2011a). These guidelines also contain design rules for inland ports. WG2011 states that the entrance width of an inland port should be at least 4B, whit B is the beam of the design ship. These guidelines are only valid for waterways with flow velocities up to 0.5 m/s.

Furthermore, WG2011 mentions that preventing insufficient visibility should be taken into account during design. WG2011 states that the shape of the harbour mouth should be similar as that of a junction. An unimpeded angle of vision with a length of 5 times the overall length of the ship (L_{oa}) in the axis of the main waterway and a length equal to the overall length of the ship to the theoretical shoreline should be available. This is illustrated in figure 2-1. The bank between the line of sight and the waterway should be kept free of obstructions higher than 2.5 meters above the average water level. At busy ancillary harbours, the corners of the mouth should be rounded off with a radius of at least 1.5 times the overall length of the ship.

In addition, it is mentioned by WG2011 that it should be safe to sail in or out of a port, even with a large flow velocity in the waterway. Moreover, preventing negative effects of wind drift on ship manoeuvrability should be taken into account during design. Although it is mentioned to take these aspects into consideration, no design rules are provided with respect to wind and flow velocities larger than 0.5 m/s.

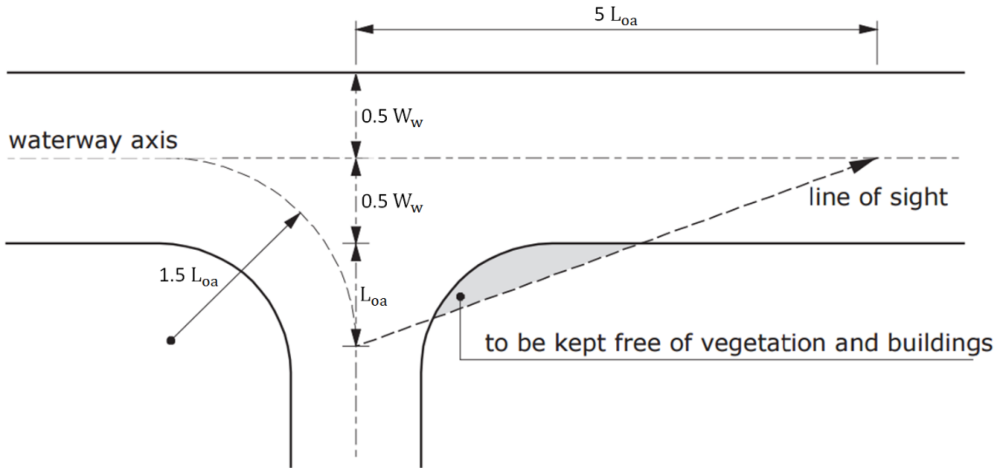


Figure 2-1: Overview of line of sight at a junction. Figure adapted from WG2011 (RWS, 2011a).

According to PIANC et al. (2014), the entrance width of a port should be at least equal to the overall length of the design ship. However, this guideline is made to prevent the possibility of a ship becoming stranded across the entrance in case of an incident. This design rule is not necessarily made from a viewpoint of minimising siltation, or the minimum required width with respect to normal ship manoeuvres when sailing in or out of the port. Besides, the PIANC report is focussing on sea ports and was not made for inland waterway design. However, as mentioned in section 1.1, the length of the design ship is often used for the width of the port entrance mouth along flowing waters (Ten Hove et al., 2015).

2.2 Previous nautical studies on inland port entrances

In the past, multiple inland port entrance studies were performed in order to evaluate the nautical safety around an inland port entrance. Findings of these different studies are presented in this paragraph. Studies to the overnight stay harbour of Haaften, the overnight port of Lobith, the Waalhaven in Nijmegen (all in the Netherlands) and the Euro-Hafen Emsland-Mitte (in Germany) are analysed. For some of these entrance studies also morphological aspects were studied. The relevant conclusions from these studies, with respect to nautical safety and minimising siltation, are presented in the next sections. In appendix A, for each study the different required entrance widths that were found with the conducted simulation studies are shown. A graphical overview, of the relation between the flow velocity and required entrance width, based on these results is included in the conclusion of this chapter, see paragraph 2.5.

In the analysed entrance studies, the nautical evaluations were performed by using fast-time or real-time simulation models. For an explanation of these models, see paragraph 2.4. The used ship types in these simulations studies are presented in table 2-1. The dimensions of these ship types are included in the table (L_{oa} = length overall, L_{bp} = length between perpendiculars, B = beam and T = draught amidships).

Table 2-1: Overview of ship types used in the analysed port entrance studies.

Port entrance study	CEMT class	Ship type	L_{oa} (m)	L_{bp} (m)	B (m)	T (m)
Haaften	Va	loaded motor ship	108.34	104.76	11.40	3.79
	Va	unloaded motor ship	108.34	104.76	11.40	1.42
	Vb	loaded pushed convoy, two barges long	191.0	190.0	11.40	3.5
	Vb	unloaded pushed convoy, two barges long	172.0	167.0	11.40	0.55
	VIa	container ship	135.0	129.8	16.9	2.35
Lobith	Va	loaded container ship	-	106.0	11.35	1.40
	Va	loaded motor ship	-	104.16	11.60	3.79
	Va	unloaded pushed convoy, one barge	-	96.0	11.40	1.8
	VIa	container ship	129.8	-	16.9	2.35
	VIa	loaded container ship	-	129.8	16.9	2.35
	Vb	unloaded pushed convoy, two barges	-	191.0	11.40	0.61
	VIb	unloaded pushed convoy, four barges		191.0	22.80	0.61
Waalhaven	Va	loaded motor ship*	108.3	104.2	11.4	3.8
	IV	loaded motor ship**	80.0	-	9.5	2.5
	Va	loaded motor ship**	96.0	-	11.4	2.8
Euro-Hafen	Va	loaded motor ship	-	110	11.40	2.70
	Va	unloaded motor ship	-	110	11.40	0.80

*Study performed by Ten Hove (2007). **Study performed by Lee (2014).

2.2.1 Haaften

In 2002 several accidents happened with a ship grounded around the port of Haaften (Raad voor de Transportveiligheid, 2003). In 2009 the entrance of the port was studied in order to improve the situation (Van Heel & Verheij, 2011). The ship manoeuvres were studied with a real-time simulator. Since most of the groundings occurred by night, the real-time simulations were also performed by night. A schematisation of the original port layout is shown in figure 2-2 (left figure). The funnel shaped entrance has a width of 230 meters along the waterway and a width of 95 meters at the basin side. The entrance length is circa 200 meters.

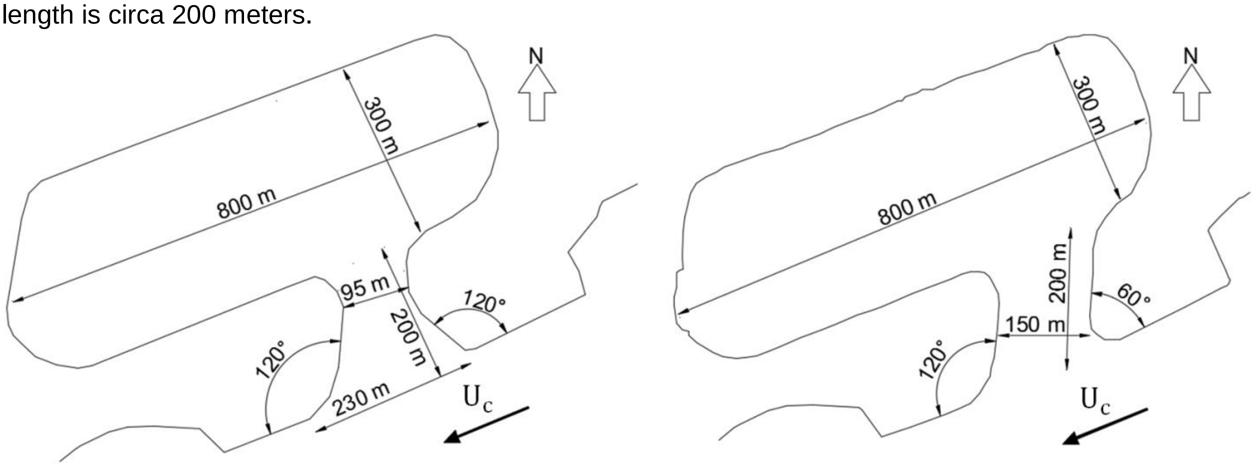


Figure 2-2: Schematisations of the original layout (left) and modified layout (right) of overnight port of Haaften. Figure based on report of Heel & Verheij (2011).

The study showed that the largest flow velocities in the waterway caused the most difficult manoeuvring situations. These large velocities occurred simultaneously with a water depth of 11 meters around the port entrance. For this situation the entrance dams were flooded, because of the large discharge of the river. The water level above the entrance dams was circa 0.5 meters. The influence of the wind was included in the simulation study; different speeds (between 8.0 and 11.7 m/s) and directions (East, South and West) were used. It was assumed that regarding the location of the entrance, these directions caused the most decisive wind conditions.

For the CEMT class VIa container ship, the study found that the entrance was not safe enough, when taking into account a current of 1.75 m/s. It appeared that when changing the layout to a rectangular entrance with a width of 150 meters, a much safer situation was provided. This rectangular layout is shown in figure 2-2 (right figure). The angle between the entrance and the waterway at the downstream corner is approximately 120 degrees.

The skippers advised during the evaluation that an entrance with banks parallel to each other provided a better orientation. This was an important aspect for the skippers in order to manoeuvre safely and efficiently through the port entrance. In addition, it was mentioned by the skippers that for the arrivals in upstream direction manoeuvring with a loaded Va ship was more difficult than with an unloaded Va ship, taking into account a flow condition of 1.75 m/s.

Furthermore, the study revealed that for the original layout the arrivals, when sailing downstream, were easier than when sailing in upstream direction. The arrival scenarios sailing upstream with a westerly wind were experienced as most problematic. Mainly the manoeuvres with a container ship were difficult due to the large influence of the westerly wind. The wind was pushing the ship too close to the upstream bank of the port entrance.

In several arrival runs when sailing upstream, the skippers had to cross the waterway and trough going traffic. This caused a difficult situation to manoeuvre safely into the port.

For the pushed convoy consisting of two barges in long formation, the manoeuvres were significantly more difficult than with the other ship types. When sailing upstream into the port, forward manoeuvres through the port entrance were possible. In contrary, when sailing downstream this was not possible. For these arrivals, backward manoeuvres were more appropriate to sail safely through the port entrance. For a backward manoeuvre the ship stops downstream of the entrance and then approaches the port with the stern of the ship first. The current along the entrance caused a moment opposite to the desired turning moment, which makes these backward manoeuvres difficult to perform. This opposite moment when sailing in a flow gradient is explained in more detail in appendix B. Since the backward manoeuvres were difficult to perform, these manoeuvres required more space at the entrance and a large amount of the steering capacity of a ship. For the manoeuvres with the pushed convoys a wider entrance than 150 meters was recommended.

As a result of the conducted departure scenarios, it was found that the wide entrance mouth was more favourable than the small entrance mouth. In a wider mouth more space was available to turn the ship in the desired sailing direction.

Based on the conducted real-time simulations, it was advised to widen the entrance at the basin side from 95 meters to 150 meters. The entrance width at the waterways side of 230 meters was maintained to provide manoeuvring space in the entrance for the departure scenarios.

Siltation

Besides the nautical safety, also the siltation around the port was studied. In order to calculate the siltation around the port entrance, the SILTHAR model was used. Four different layouts were calculated. The original situation, a rectangular entrance of 150 meters and 200 meters width and funnel shaped entrance with a width of 150 meters at the basin and 200 meters at the river. It was concluded that:

- The annual siltation of the original situation was 1302 m^3. For the rectangular entrance of 150 meters, the siltation was 9% smaller. For the rectangular entrance of 200 meters, the siltation was increased with 22%. For the funnel shaped entrance variant 200/150 meters, the siltation was 7% larger.
- For the funnel shaped entrance layout less siltation occurred compared to a rectangular layout, when taking into account similar entrance widths at the river.

2.2.2 Lobith

In order to investigate the possibilities for a new port of Lobith, MARIN and WL|Delft Hydraulics performed a study to optimise the port entrance (De Jong et al., 2002a; De Jong et al., 2002b; De Jong et al., 2002c;). The study was conducted by using fast-time simulations, real-time simulations and evaluations based on the opinion of a group of inland shipping professionals.

Two different layouts were studied. These are displayed in figure 2-3. The entrance widths are for both layouts 135 meters. The entrance length is approximately 20 meters. The width of the waterway is about 340 meters with a minimum fairway of 170 meters. The main difference between the two entrances is the bend in the downstream dam. In addition, the upstream entrance dams for the layout with bend has a vertical sheet pile at the basin side and in the entrance. At the river side the upstream entrance dam contains a slope. The study revealed that from nautical point of view the vertical sheet pile was desired.

The hydraulic conditions taken into account were: a water depth of 10 meters for a flow velocity of 1.71 m/s and a water depth of 12 meters for a velocity of 1.94 m/s. For these currents, the entrance dams were flooded. The water depth above the entrance dams was respectively circa 4 and 5 meters. Different wind speeds (between 6.0 and 12.0 m/s) and different wind directions (North West and East) were included in the simulations. It was assumed that regarding the location of the entrance, these directions caused the most decisive wind conditions.

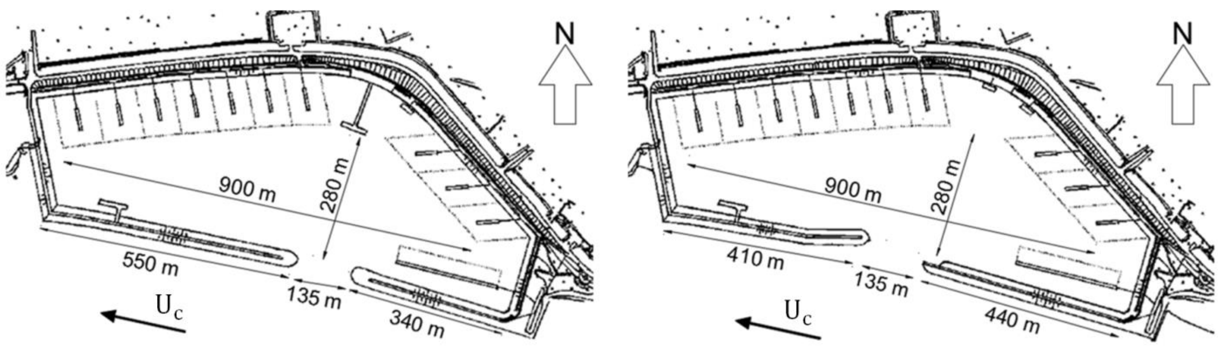


Figure 2-3: Overview of two port entrance layouts studied for the new port of Lobith (De Jong et al., 2002b). Left: layout with parallel entrance banks. Right: layout with bend in the downstream dam.

First, a fast-time simulation study was performed for a flow velocity of 1.94 m/s for the layout without bend. The loaded class Va ship, container class VIa ship and container class Va ship were included in these simulations. It was shown that a port entrance width of 135 meters was too small for arrival scenarios sailing downstream with the loaded Va and container VIa. Arrival scenarios sailing upstream were possible. Moreover, it was mentioned that a flow velocity of 1.71 m/s was more realistic than a flow velocity of 1.94 m/s.

Based on the real-time study, it was concluded that for all departure and arrival scenarios both layouts were safe, taking into account the loaded Va ship, container VIa, container Va ship and pushed convoy with two barges in long formation. However, it was advised for the arrivals sailing downstream to use a backward manoeuvre into the port instead of a forward manoeuvre for the container VIa ship and larger ships, in case of flow velocities of 1.71 m/s or larger. It was mentioned that a better controllability exists for the backward manoeuvres, when this type of manoeuvre was conducted with a low speed. However, an entrance width in line with the overall length of the ship was desired for these manoeuvres, because the backward manoeuvres required a significant amount of space in the entrance. The manoeuvres with the container VIa ship and the pushed convoy with two barges in long formation were most difficult.

With the bend in the downstream dam, a slightly better situation was created for the arrival scenarios sailing upstream. For the arrivals sailing downstream, this adjustment was less favourable and required a slightly larger entrance width compared to the layout without the bend. In addition, the group of professionals judged that the asymmetrical layout had a negative effect on the orientation of the skippers.

The layout without the bend has an asymmetrical basin, which influenced the manoeuvres through the port entrance. The east side of the basin is significantly smaller than the west side for the layout without the bend. This required a short stopping distance for arrivals sailing upstream. It was mentioned, that this asymmetrical basin was in line with the asymmetrical ship speeds when sailing up- and downstream. A ship sailing upstream used a significant smaller ground speed when manoeuvring into the port. As a consequence, a smaller stopping length was required. In the fast-time simulation study two different forward manoeuvres were conducted when sailing downstream into the port basin. These are illustrated in figure 2-4. When manoeuvring through the entrance with the bow in the direction of the west side of the basin, a swept path width of 104 meters was measured. For the manoeuvre with the heading of the ship parallel to the entrance banks, a swept path of 130 meters was found. The swept path is the envelope of the travelled path by the sailing ship.

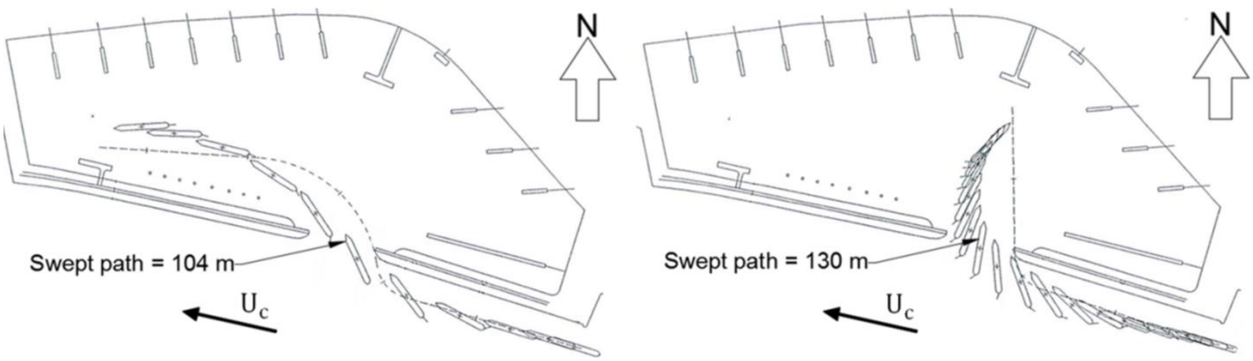


Figure 2-4: Two arrival scenarios for sailing downstream with a loaded Va ship for a flow velocity of 1.94 m/s. Left: a sideways manoeuvre through the entrance. Right: a manoeuvre with a heading parallel to the entrance banks. Figures adjusted from De Jong et al. (2002c).

Siltation

Besides the nautical safety, also the siltation around the port was studied. In order to calculate the siltation, the SILTHAR model was used. It was concluded that:

- For an entrance width of 135 meters, the annual siltation for the layout without bend was 19,500 m^3 and for the layout with bend 16,000 m^3. The accuracy of these calculations was limited. An uncertainty range of 30% should be taken into account.
- For an entrance width of 175 meters, the annual siltation will increase with approximately 15%. This was caused by the larger available exchange surface.
- The bend in the downstream dam reduced the flow velocities of the eddy in the port. As a consequence, the horizontal water exchange was lower. This resulted in a reduction of the siltation. The water exchange between basin and river is explained in more detail in section 2.3.1.
- With respect to minimising the siltation it was not desired to have a vertical sheet pile at the river side of the dam. This increased the siltation considerably.

2.2.3 Waalhaven

The Waalhaven is an inland port along the Waal with a funnel shaped entrance. The width at the basin side is approximately 40 meters, at the waterway side this is about 100 meters. Ten Hove (2007) analysed the manoeuvres in and out of the port for a loaded Va ship. A wind velocity of 11.3 m/s and directions of West and North West were included in the study. Lee (2014) did this analysis for the loaded IV and Va ships, but only studied the manoeuvres into the port. A wind velocity of 8.0 m/s and a South East direction was included. The entrance was schematised to a rectangular entrance with a width of 40 meters. By contrast, Ten Hove (2007) used the funnel shaped entrance in line with the real situation. The entrance layouts of both studies are shown in figure 2-5. For both studies fast-time simulations were used. Furthermore, keel clearances of about 30 percent of the draught of the ship were used in both studies.

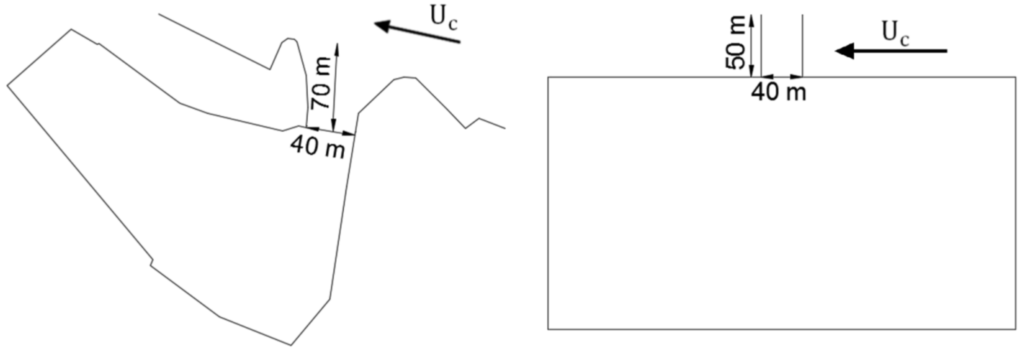


Figure 2-5: Schematisations of the Waalhaven for ship manoeuvring studies. Left: schematisation used by Ten Hove (2007). Right: schematisation used by Lee (2014).

Ten Hove (2007) concluded that the arrivals sailing upstream were possible for flow velocities of 1.2 and 1.7 m/s. However, the safety of both manoeuvres was assessed as critical, because the distance between the ship and the entrance bank was small. The nautical safety for the arrivals sailing downstream was only sufficient for the flow velocity of 1.2 m/s. Furthermore, a stopping length of 50 meters in the port basin was sufficient. The arrivals were more difficult than the departures. The asymmetrical shape of the basin made the arrivals more difficult; the stern of the ship could not deflect to port side when passing the entrance.

Lee (2014) concluded that for flow velocities larger than 1.0 m/s the entrance was too small for the manoeuvres into the port. In this study was concluded that for currents between 0.7 and 1.0 m/s a minimum entrance width of 4.9 times the beam of a ship was required.

The differences in the conclusions of both studies were caused by the different set-ups of the studies. The entrance schematisation of Lee (2014) is less favourable compared to the real situation used by Ten Hove (2007); the entrance mouth of the real situation is wider.

In addition, Lee (2014) showed in his research that a linear relation holds between the flow velocity along the port entrance and the required entrance width. For an increase in flow velocity, a larger entrance width was required. Lee showed that for currents larger than 0.5 m/s an entrance width larger than 4B was required. For flow velocities of 0.5 m/s the required entrance width was in agreement with the 4B rule provided by WG2011, see paragraph 2.1.

2.2.4 Euro-Hafen Emsland-Mitte

In 2006 an optimisation study was performed for the port entrance of the Euro-Hafen Emsland-Mitte (Stolker, 2006; Sloff et al., 2006). The objective of this study was to provide a solution for the siltation problems around the entrance. The old layout, a funnel shaped entrance, was replaced by so called Thijsse Egg. This is an elliptical basin, which is located between the entrance to the port and the entrance at the river. The old and new layouts are shown in figure 2-6. The length of the elliptical basin is approximately 140 meters, the width is about 200 meters, the entrance width along the river is 145 meters and the entrance to the port is 60 meters wide. For the old layout the mouth of the funnel shaped entrance is approximately 300 meters. The width of the waterway is 65 meters.

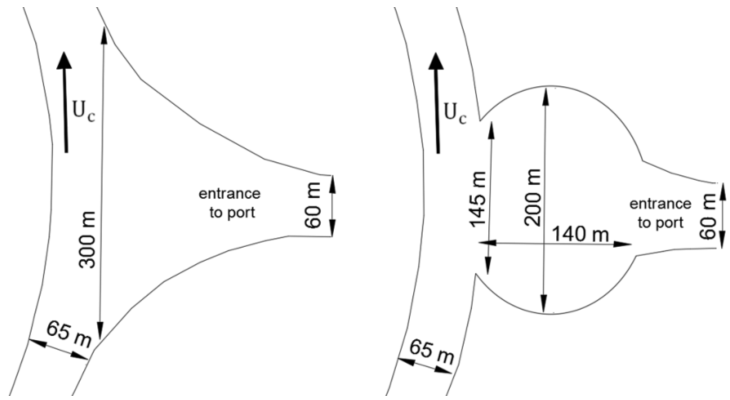


Figure 2-6: Schematisations of the Euro-Hafen. Left: old layout to the Euro-Hafen. Right: New Thijsse Egg layout. The schematisations are based on report of Sloff et al. (2006).

Besides a morphological study on the siltation reduction of the new layout, also the nautical safety was studied. A fast-time simulation study was performed for the new layout for an unloaded and loaded CEMT class Va ship. Flow velocities of 0.5 and 1.5 m/s were taken into account. Wind speeds of 7.0 m/s (South West direction) and 9.0 m/s (North East direction) were included. It was assumed that regarding the location of the entrance, these directions cause the most decisive wind conditions.

From the simulations followed that the limited width of the waterway was an obstruction. The ships must turn 90 degrees in order to manoeuvre safely into the elliptical basin. For this manoeuvre a certain space on the waterway is required. The entrance to the port basin was wide enough to ensure safe navigation. For the manoeuvres into the basin when sailing upstream, it appeared that larger flow velocities enabled more favourable situations; the positioning of the ships was improved by the current.

It was concluded that the entrance along the river should be enlarged to 163 meters and the entrance to the port should be widened with 15 meters. The width of the Thijsse Egg should be widened to 230 meters instead of 200 meters. From a nautical point of view these adjustments enable safe navigation for the ships when approaching the port.

Siltation

It was calculated that after two to three years, the siltation in the waterway in front of the entrance was approximately 1 meter smaller for the new proposed layout compared to the old situation. In the entrance, the reduction was circa 2 meters. The explanation for this significant improvement is given in section 2.3.2.

2.3 Siltation of inland ports

Many ports experience siltation. In order to minimise the maintenance dredging costs the siltation rate should be as low as possible. Different control measures can be applied in order to reduce the siltation rate in harbours. The local sediment regime determines which sediment mitigation approach is appropriate. Siltation is governed by a number of basic processes (PIANC, 2008). These processes are presented here in order to evaluate the influence of the geometry of an inland port entrance. Choosing a proper geometry of the port entrance and basin can have a major influence on the siltation rate.

River harbours could be situated in a tidal or non-tidal area. As is mentioned by PIANC (2008), in tidal areas the harbours are exposed to salinity-driven density currents and tidal filling. These two processes contribute to the increase of siltation. Previous research on harbours in coastal areas in Germany in various environmental conditions shows that harbour siltation is much larger for salt or brackish water conditions compared to fresh water conditions (Von Nasner, 1992). This research focuses on the harbours along a waterway in a non-tidal area; the generic geometry choices for a river harbour discussed in this section can therefore differ from those for a river harbour in a tidal area.

First, in section 2.3.1 the general siltation processes for a river harbour are presented. Section 2.3.2 discusses the geometry changes of the entrance that can be applied to decrease the siltation rate of a harbour. Besides the geometry adjustments, other control measures are available to influence the siltation of a harbour. However, this research is limited to the geometry of an inland port entrance.

2.3.1 Siltation processes

For a river harbour, the net sediment transport through the entrance into the basin is related to the water motion in the river and the harbour. Two transport mechanisms can be distinguished (Van Schijndel & Kranenburg, 1998; PIANC, 2008):

1. A net flow into the harbour caused by a rise or fall of water level.
2. An exchange of water between the harbour and the river. This is caused by horizontal entrainment.

According to Winterwerp (2005) the second mechanism is the main water exchange mechanism for non-tidal rivers. This mechanism is causing horizontal eddies in the harbour. According to Van Rijn (2016), the major cause of siltation in harbours along a waterway, is the water and sediment exchange due to these horizontal eddies. These eddies are generated in the entrance of a basin. By suppressing the generation of eddies and dead water zones in the harbour, the situation can be improved.

This exchange between the water in the harbour basin and the river occurs in any harbour along flowing waters (PIANC, 2008). This process is shown in figure 2-7. The river flow separates at the upstream entrance corner and forms a turbulent mixing layer in the entrance. Due to the horizontal entrainment and the blocking in the stagnation zone, one or more eddies are created in the entrance or basin of a port. The magnitude of eddies can increase as a consequence of the increased velocity difference in the mixing layer (Barneveld et al., 2007). The dividing streamline is connecting the flow separation point with the stagnation zone.

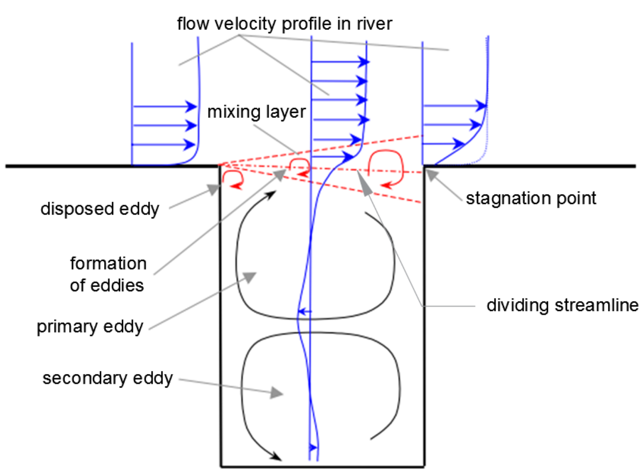


Figure 2-7: Sketch of exchange flow around entrance by horizontal entrainment and the forming of eddies. Figure adjusted from Barneveld et al. (2007).

The basin geometry is also influencing the siltation rate. More than one eddy occurs when the length/width ratio is larger than approximately two. The residence time of the water in the basin is related to the amount of eddies in the basin. Hence, reducing the amount of eddies will decrease the residence time. A smaller residence time will reduce the trapping efficiency (Van Rijn, 2016).

The siltation rate is a function of the trapping efficiency (p), the water exchange rate (Q_r) and the sediment concentration in the river water (c_a) (PIANC, 2008). As mentioned before the horizontal entrainment is the governing process for the rate of water exchange for a river harbour. Therefore, the exchange flow from horizontal entrainment (Q_e) is substituted for the exchange rate. The gives the next relation:

$$\text{Siltation rate} = pQ_e c_a$$

With the following formulas to determine Q_e and p (PIANC, 2008):

$$Q_e = f_e A U_c$$

$$p = 1 - \exp\left\{-\frac{W_s}{h_b} \cdot \left(1 - \frac{u_b^2}{u_c^2}\right)_{\text{basin}} \cdot T_h\right\}, \text{ with: } T_h = V/Q_h$$

Where:

p	= trapping efficiency (-)	W_s	= sediment settling velocity (m/s)
Q_r	= water exchange rate between harbour basin and waterway (m^3/s)	h_b	= basin water depth (m)
		u_b	= average basin velocity (m/s)
c_a	= sediment concentration in the river water (kg/m^3)	u_c	= critical velocity for sedimentation (m/s)
f_e	= coefficient related to the configuration of the harbour entrance and the local flow patterns (-)	T_h	= horizontal residence time in the harbour (s)
		V	= water volume in harbour basin (m^3)
A	= cross-sectional area of the harbour mouth (m^2)	Q_h	= discharge through the entrance (m^3/s)
U_c	= flow velocity in the waterway (m/s)		

2.3.2 Geometry improvements of entrance

The trapping efficiency can only be reduced significantly when $u_b > u_c$. However, generally the ratio u_b/u_c is significantly smaller than 1. Then the trapping efficiency is mainly influenced by the ratio between the horizontal residence time and the vertical residence time (h/W_s). A reduction in p requires a reduction in T_h and thus an increase of Q_h or a decrease of V. However, a larger Q_h provides a larger siltation rate. Besides, a smaller V is not always possible with respect to the minimum required space for safe navigation. Another possibility is larger water depth (h), but this results in a larger V. Since all the parameters are related to each other, it is difficult to reduce the trapping efficiency (PIANC, 2008).

The horizontal entrainment Q_e can be reduced by decreasing the cross-sectional area of the harbour mouth; a decrease in A results in a smaller Q_h. However, the same applies as for the basin dimensions; the cross-sectional area should be large enough to ensure safe navigation. Another option is changing the geometry of the port entrance. As is summarised by Van Rijn (2016), laboratory studies performed by Jenkins (1981) and Booij (1986) showed that the choice of entrance geometry is influencing the water exchange between river and port:

- A rectangular shape of the cross-sectional area reduces the water exchange considerably compared to a trapezoidal shape. Note that the available width on the bottom should be similar for both cross sections. This shape difference is very effective for a relatively small entrance width (Jenkins, 1981).
- The angle of the downstream corner is influencing the coefficient f_e. An angle smaller than 90 degrees results in larger values than an angle larger than 90 degrees. For an angle of 135° a value of 0.02 was found, 0.03 for 90 degrees and for 45 degrees a value of 0.05. (Booij, 1986). These different angles and values for f_e are illustrated in figure 2-8. An angle of 135 degrees reduces the horizontal water exchange with a factor of 1.5 and 2.5 compared to angles of respectively 90 and 45 degrees.

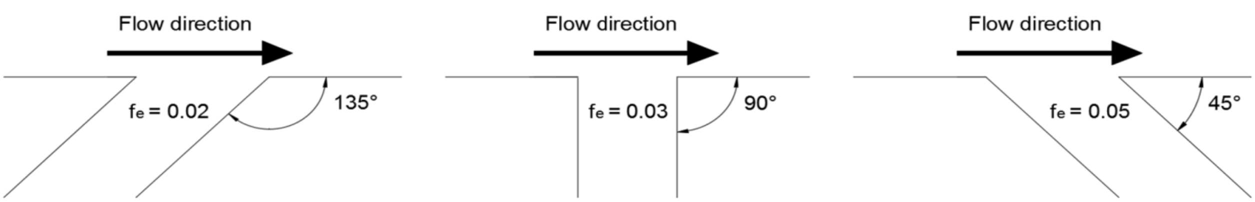


Figure 2-8: Entrance geometries and associated horizontal exchange coefficients f_e, based on figure of Van Rijn (2016).

Another entrance geometry that can contribute to a lower siltation rate is the Thijsse Egg, see also section 2.2.4. In the optimisation study of the Euro-Hafen Emsland-Mitte (Sloff et al., 2006), the funnel shaped and wide entrance mouth was replaced by a Thijsse Egg layout. This adjustment resulted in a significantly lower siltation rate around the entrance.

The eddy in the ellipsoidal basin is created by the main flow at the entrance mouth. In an ideal situation this keeps the main flow stream in its original shape. Normally, the widening in the river caused by the port entrance causes a reduction of the flow velocities in the river around the entrance. In figure 2-9 the differences in flow velocities around the entrance are shown for the Euro-Hafen. For the Thijsse Egg layout the flow velocities in the river around the entrance mouth are considerably larger. A deceleration in flow velocities increases the siltation rate. Hence, the siltation rate for the Thijsse Egg is considerably lower.

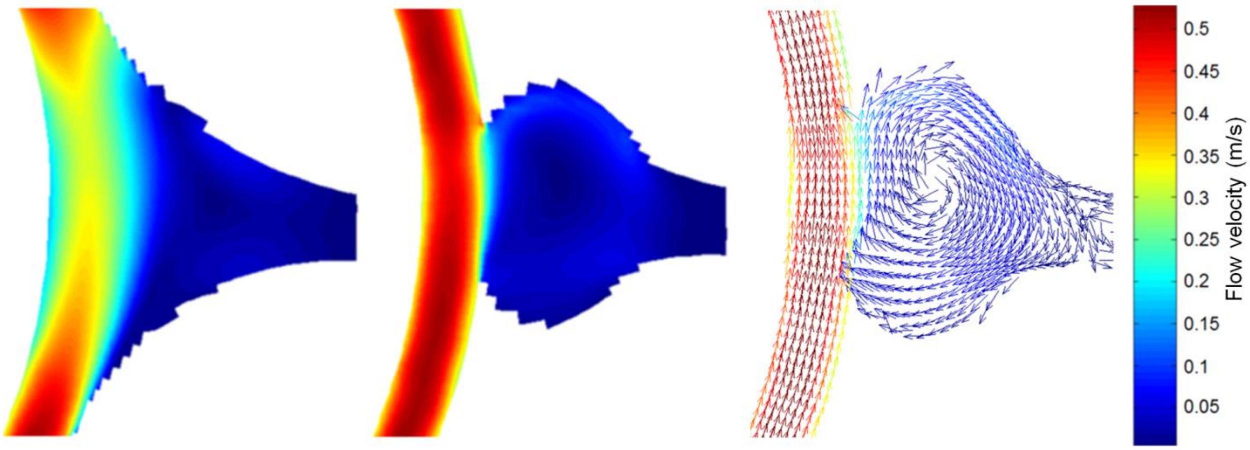


Figure 2-9: Flow velocities around funnel shaped entrance (left) and for the Thijsse Egg geometry (middle). In the right figure a vector plot for the Thijsse Egg layout is shown (Sloff et al., 2006).

One large eddy can only be present in the elliptical basin when substantial hydraulic boundary conditions are applied (Sloff et al., 2006). This principle is explained by Jansen et al. (1979) for a groyne field. In order to get one strong eddy the following should hold:

$$W_e < C^2 h / 2g$$

Where:

W_e = Entrance width of basin (m)
C = Chézy coefficient ($m^{1/2}/s$)
h = water depth (m)
g = acceleration due to gravity (m/s^2)

To satisfy this criteria, the water level in the stagnation point (point B) should be larger than the water level at point A, see figure 2-10. Therefore, the energy loss between A and B has to be smaller than the velocity head.

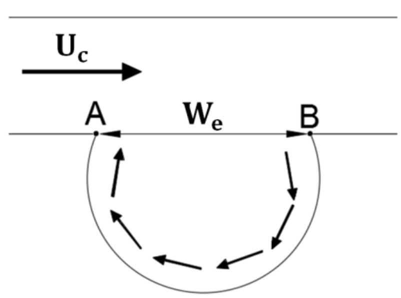


Figure 2-10: Schematisation of eddy in ellipsoidal basin. The depth average flow pattern is shown. Schematisation based on Sloff et al. (2006).

2.4 Ship manoeuvring simulation models

Ship navigation and manoeuvring simulation systems can be used to verify and optimise the horizontal design of a navigation channel or port basin. When optimising a design, simulation models are a cost-effective tool to verify the design in an effective and efficient manner. The simulation models can be subdivided into two types:

- Fast-time simulation models
- Real-time simulation models

Normally, for the real-time and fast-time simulation systems similar software, mathematical ship models and geographical databases are used. Besides, the analysis tools for evaluating the results are also similar. The main difference between these models is that fast-time simulation models use autopilot algorithms to control the ship and tugs, whereas real-time simulation models use an actual human operator to control the simulated ship and tugs. The information in this paragraph is based on the literature of PIANC et al. (2014) and AISM (2011).

2.4.1 Fast-time simulators

Fast-time simulation models are two dimensional tools and can be used as a first design tool for the dimensions of a waterway or port where one or more options are proposed. The models can give information about the possibility to steer along a desired reference track within the physical and environmental limits. The systems are operating with a speed up factor. Therefore, quick feedback is provided to the user. Furthermore, different scenarios can be assessed quickly. Fast-time simulations are also appropriate to make a first selection of relevant scenarios which require additional analysis using real-time simulations.

For the fast-time simulations, ship models are used that provide realistic behaviour of a ship. The fast-time systems do not have an actual human operator as it is not realistic to use a human operator when operating with a speed up factor. Instead of a real person steering, the systems operate through the use of a number of equations which represents the behaviour of the operator. The autopilot has perfect knowledge of environmental conditions to encounter, which makes it uncertain whether a human operator will be able to perform in the same manner. The lack of the human behaviour is the major disadvantage of these systems.

2.4.2 Real-time simulators

For a real-time simulator a human operator is used to steer the ship model. Basic and advanced simulators exist. For example, the desktop simulator is the most basic and low cost one, since the human operator is only manoeuvring using a birds-eye view of the situation. An advantage of these systems is that the desktop is portable and can easily be brought to the users. The full mission simulator is the most advanced and high cost simulator, since a full mission bridge simulator is equipped with projections of the outside view, actual steering controls and radar. A real bridge is made to provide a realistic experience to the operator. According to PIANC et al. (2014), the full mission simulator should be used to verify a final design. For initial designs and comparing different design options more basic simulators could be sufficient. Due to the high costs, the full mission simulator is not a desired system to use for comparing and optimising initial designs. Several other simulations systems are available which are less advanced as the full mission simulator and more advanced as the desktop simulator.

2.5 Conclusions

In this chapter several aspects regarding inland port entrances were discussed. The existing guidelines were presented. Several port entrance studies were analysed. These studies mainly provided insight into the design aspects of an inland port entrance regarding nautical safety, but also siltation aspects were included. Furthermore, research on the influence of the entrance geometry on the siltation rate was used to establish the most efficient entrance layout. Several findings described in this chapter regarding nautical safety and minimising siltation are contradictory. In addition, an overview of different ship manoeuvring simulation systems was given. The advantages and disadvantages of these systems were mentioned. First the conclusions with respect to the above described aspects are presented in this paragraph. Thereafter, based on the presented conclusions, the chosen starting points for the set-up of a ship manoeuvring simulation study are described. Furthermore, the conclusions of this paragraph are used to discuss (in chapter 6) the results of the conducted simulation study for this research.

Existing guidelines

Currently, only two design rules are available for the design of an inland port entrance. WG2011 states that a minimum entrance width is required of four times the beam of the design ship, for conditions with flow velocities up to 0.5 m/s. Besides, in the Netherlands, an entrance mouth width equal to the length of the design ship is often applied for ports along flowing waters (Ten Hove et al., 2015). This was also advised by PIANC et al. (2014) in order to avoid the possibility of a ship becoming stranded across the entrance in case of an incident. It should be noted that the PIANC guidelines are made for sea ports and not for inland ports.

Entrance design regarding nautical safety

As a result of the analyses of five entrance studies for four different ports, several peculiarities were found. The following was observed in the recently performed entrance studies:

- In general, the largest ships require the largest entrance widths. Moreover, it was mentioned by a group of skippers for the port of Haaften that for a current condition of 1.75 m/s, it is more difficult to manoeuvre with a loaded CEMT class Va ship than with an unloaded Va ship for arrivals sailing upstream. In addition, it appeared that the manoeuvres with pushed convoys are more difficult compared to other ship types. It was also found that when container ships experience a large influence of the wind, manoeuvring it safely into the port becomes more difficult.
- In two simulations studies, backward manoeuvres into the port were included. These manoeuvres replace the forward manoeuvres when sailing downstream. It was found that the backward manoeuvres are a good alternative when forward manoeuvres are not sufficiently safe. The backward manoeuvres can be better controlled, because this type of manoeuvre is conducted with a low speed.
- It was shown that crossing other traffic when approaching the port entrance can result in an unsafe situation.
- A narrow waterway influences the ship manoeuvres. As a consequence, a larger entrance width is required to provide nautical safety.
- The shape of the port basin can influence the ship manoeuvres through the port entrance. When the available stopping length is too small, this has a negative effect on the manoeuvre through the entrance. Furthermore, for large flow velocities and sailing in downstream direction, it appeared that a sideway manoeuvre into the port can be more efficient than a manoeuvre with a heading parallel to the entrance banks.
- In most of the analysed studies, departure scenarios were also simulated. These manoeuvres were mainly assessed as less difficult than the arrival scenarios.

With respect to the entrance layout, several conflicting aspects were found in the entrance studies:

- For the skippers an entrance with banks parallel to each other is preferred. Parallel banks contribute to a better orientation of the skippers with respect to the port entrance and the waterway axis.
- For the departure manoeuvres it was mentioned that a funnel shaped entrance is desired, because for a wider mouth more space is available to turn the ship in the desired sailing direction.
- With a bend in the downstream entrance dam, see figure 2-3, a more favourable situation is created for arrivals when sailing upstream. For sailing downstream this is less desired.

An overview of the results of the conducted fast-time and real-time simulations are shown in figure 2-11. The chosen values based on the different simulations studies are presented and explained in appendix A. The relations between the flow velocities and required entrance widths are plotted. The required entrance widths are divided by respectively the beam and the overall length of the design ship. Only the results of the arrivals are used in this study, because it was found in the analysed entrance studies that in general the departure scenarios were less difficult to perform. Hence, it is assumed that the arrivals represent the decisive situation. The existing design rules are added to figure 2-11.

In addition, the results for the arrivals sailing upstream (squares) and downstream (triangles) were split when these results were explicitly mentioned in the entrance studies. If one result is given for both up- and downstream, then this result is indicated with a circle. The other design parameters are not included in this figure. Therefore, the visible differences are not purely based on the relation between flow velocity and required entrance width. However, several peculiarities can be observed figure 2-11:

- When the flow velocity increases, the required entrance width increases. Moreover the 4B rule of WG2011 seems in agreement with the data points.
- The arrivals when sailing in downstream direction require a larger entrance width compared to sailing in upstream direction. These differences increase when the flow velocity increases. Only for the entrance of Haaften, it was shown that the arrivals sailing upstream were sometimes more difficult due to the westerly wind. This is not indicated in the figure, because no clear differences in required entrance width, regarding sailing up- or downstream, were given in this study.
- The Thijsse Egg layout (Ems-Hafen) requires a significant larger entrance width than used for the rectangular and funnel shaped entrance layouts. However, it should be mentioned that this Thijsse Egg was positioned along a narrow waterway. So, the large required entrance width is not necessarily caused by the Thijsse Egg layout. Therefore, another Thijsse Egg layout was added to the figure (indicated with the plus marker). This is a Thijsse Egg layout for the connection of the Waal and Amsterdam-Rijnkanaal in the Netherlands. For this situation a larger flow velocity was taken into account and the required width is smaller. So, when a Thijsse Egg is located along a wide waterway, such as the Waal, the entrance width is smaller. However, based on this figure it seems that a Thijsse Egg layout requires a larger entrance width than a rectangular or funnel shaped layout.
- The 1L rule from PIANC et al. (2014) is an overestimation of the situation for the flow velocities smaller than 1.5 m/s. For the larger velocities this rule seems more appropriate; a part of the data points are above the line and a part of the data points are below the line.
- A similar relation can be observed between the flow velocity and the required entrance widths divided by the beam of the ship and divided by the overall length of the ship.

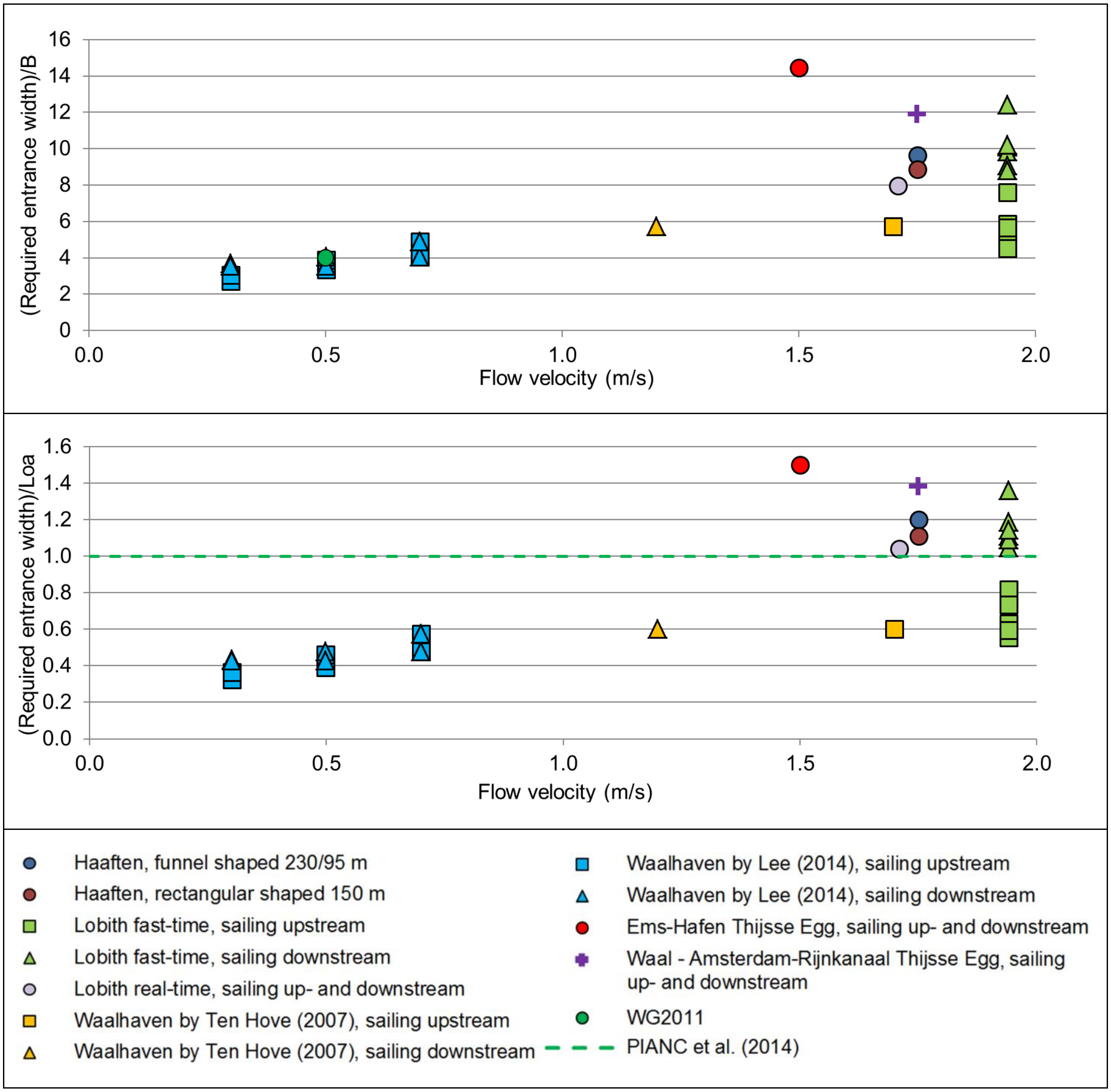


Figure 2-11: Overview of results of previous entrance studies. The required entrance width is plotted against the flow velocity.

Entrance design regarding minimising siltation

As described in literature, the siltation in a river harbour is related to the trapping efficiency of the basin, water exchange rate between the river and harbour and the sediment concentration in the river water. An increase in one or more of these three aspects results in a larger siltation rate. By adjusting the geometry of the port entrance and basin, the siltation can be influenced.

Since all parameters that are related to the trapping efficiency are also related to each other, it is difficult to reduce the trapping efficiency. Therefore, focussing on reducing the exchange rate is easier. The horizontal entrainment is the most important exchange rate which is influencing the siltation of river harbours. Horizontal entrainment can be reduced by:

- Decreasing the cross-sectional area of the port entrance.
- A rectangular shape of the cross-sectional area reduces the water exchange considerably compared to a trapezoidal shape (Jenkins, 1981). Note that the available width on the bottom should be similar for both cross sections. This shape difference is very effective for a relatively small entrance width.
- Changing the entrance orientation with respect to the river axis. An angle of 135 degrees at the downstream corner of the entrance reduces the water exchange with factor 1.5 and 2.5 compared to angles of respectively 90 and 45 degrees (Booij, 1986), see figure 2-8.

Another geometry adjustment to reduce the siltation in a port significant is the Thijsse Egg layout. This type of entrance limit the flow velocity reduction in front of the port entrance, see figure 2-9. Since a deceleration in flow velocities increases the siltation rate, the siltation rate for the Thijsse Egg layout can be a significant improvement compared to other layouts.

In addition, as a result of the analysed entrance studies, it was concluded that for a funnel shaped entrance less siltation occurs compared to a rectangular layout with a similar entrance width at the river. A layout with bend in the downstream dam, see figure 2-3, reduces the siltation compared to a situation with entrance banks parallel to each other. Moreover, a vertical sheet pile at the river side of an entrance dam is not desired.

Entrance design regarding nautical safety versus minimising siltation

The findings of previous entrance studies were analysed with respect to nautical safety and minimising siltation. Moreover, the influence of the entrance geometry on the siltation was discussed in this chapter based on previous research. In general, a smaller entrance cross section is more desired with respect to minimising siltation, but less desired with respect to provide nautical safety. In this chapter several other conflicting aspects were found for optimising an entrance and taking into account nautical safety and minimising siltation:

- In general, the arrivals when sailing downstream are more difficult than when sailing upstream. To provide an easier nautical situation when sailing downstream, an entrance angle smaller than 90 degrees seems more favourable. However, an angle smaller than 90 degrees contributes to a larger siltation rate.
- The orientation of the skippers with respect to the port entrance and waterway axis is an important aspect to provide nautical safety. From this point of view, a bend in the downstream dam (see figure 2-3) is not desired for arrivals sailing downstream. Furthermore, for arrivals funnel shaped entrances (figure 2-2) are not favourable compared to rectangular layouts. With respect to minimising siltation, a funnel shaped entrance reduces the siltation rate compared to a rectangular entrance, when the widths of the mouths are similar for both layouts. Moreover, when the downstream entrance dam is turned into the basin, the siltation is reduced. In addition, a downstream bend in the entrance dams is also more favourable when sailing upstream into the port entrance.

Ship manoeuvring simulation systems

Ship navigation and manoeuvring simulation systems can be used to verify and optimise the horizontal design of a navigation channel or port basin. Fast-time models operate with a speed-up factor and therefore provide quick feedback to the user. Furthermore, different scenarios can be assessed quickly. The major disadvantage of the fast-time systems is that an automatic pilot is used to steer the ship model.

As a consequence the human behaviour is not included in these simulations. Therefore, it is uncertain for a fast-time simulation whether the performance of a human operator is similar. The real-time simulators are steered by a human operator. Hence, these simulators provide more realistic results. However, these systems are more advanced and more expensive.

Starting points for ship manoeuvring simulation study

For this research, a considerable amount of manoeuvring simulations is required in order to study many different scenarios. These simulations should give an insight into the most efficient entrance layout for an inland port. Furthermore, the manoeuvring study should reveal the relevance of the different design parameters. As described in this chapter, fast-time simulation systems are suitable for comparing different scenarios, providing quick feedback and enabling a quick assessment of the simulations. Within this research many different scenarios should be compared. Therefore, fast-time simulation systems are selected as the most appropriate tool for the ship manoeuvring simulation study. Based on the conclusion in this paragraph, the following starting points for the simulation study are used:

- The largest ships require generally the largest widths. Besides the size of the ship, the ship type is also an important aspect. The pushed convoys are beyond the scope of this research. The design ship used for the simulation study can be a loaded ship, unloaded ship or container ship. The most decisive ship should be chosen for the simulation study. The most decisive ship will be determined with a simplified wind and current force calculation. This is further explained in section 3.3.1.
- Backward manoeuvres into the port for the arrivals sailing downstream can be used as replacement for forward manoeuvres in case these manoeuvres are too difficult for large flow velocities. Moreover, it was shown that sideway manoeuvres (see figure 2-4) can contribute to a more efficient manoeuvre through the entrance. Hence, these types of manoeuvre should be included in the simulation study in order to find the most efficient entrance.
- It was found that a narrow waterway influences the required entrance width. Hence, a narrow waterway layout should be included in the simulation study to analyse this effect.
- The shape and size of the basin can influence the required entrance width. As described in paragraph 1.3, the influence of the basin is beyond the scope of this research. Therefore, a sufficiently large basin should be used for the simulation study in order to avoid the influence of the basin on the simulation results.
- The previous entrance studies showed that the departures were less difficult than the arrivals. However, these simulations were conducted for wide waterways. Therefore, the departure manoeuvres in combination with a narrow waterway should be studied to investigate which type of manoeuvre is most decisive for smaller waterways.
- It was mentioned by skippers that an entrance width parallel entrance banks is most desired with respect to the orientation, taking into account arrivals sailing up- and downstream. Moreover, based on figure 2-11 the Thijsse Egg layout seems less efficient than the rectangular layout. Therefore, a rectangular shaped entrance is used in the simulation study.
- A rectangular cross-sectional area of the port entrance is more favourable with respect to minimising siltation than a trapezoidal cross section, taking into account a similar available entrance width on the bottom. Furthermore, it was mentioned in the study of Lobith that a vertical sheet pile in the entrance is desired from nautical point of view. Hence, a rectangular cross-sectional area of the port entrance is chosen for the simulation study.
- Regarding minimising siltation, angles larger than 90 degrees are desired. However, from nautical point of view the most efficient angle is unknown and should be determined. Besides, the main focus of this research is on the optimisation of the entrance width with respect to nautical safety. Therefore, scenarios with entrance angles smaller and larger than 90 degrees should be included in the simulation study.

3

Set-up of manoeuvring simulation study

This chapter explains the set-up of the ship manoeuvring simulation study. With this simulation study the different design parameters of an inland port, the smallest possible entrance width and the most efficient entrance layout are determined. As was concluded in chapter 2, a fast-time simulation system is most appropriate for this research. It is chosen to use the fast-time simulation program SHIPMA 7.4.2. SHIPMA is a joint development of MARIN's nautical centre MSCN and Deltares (MARIN & Deltares, 2015). A brief description of the used fast-time simulation program is given in paragraph 3.1. It should be noted that other fast-time programs are available. However, these programs are often combined with real-time simulators. For example, a simulator with a speed up factor and controlled by an actual human operator (MARIN, personal communication, 2017).

For a simulation study, it is import to use an efficient approach. This means that the different simulated scenarios should be chosen strategically; each simulation should provide as much new information as possible. The used approach for the simulation study is explained in paragraph 3.2.

In chapter 2, several findings from literature were described with respect to optimising an inland port entrance. This research focuses on the minimum required entrance width to provide nautical safety. Siltation aspects are also taken into consideration, but to a smaller extent. In order to find the minimum safe entrance width, scenarios that are undesired with respect to minimising siltation are also included in the simulation study. By using this approach an insight is provided in the different options with respect to finding the minimum nautical safe entrance width.

Paragraph 3.3 describes the input of the model. The used assessment method to determine the safety for each simulated scenario is described in paragraph 3.4.

3.1 SHIPMA simulation model

The explanation of the SHIPMA (**Ship Ma**noeuvring) simulation model in this paragraph is based on the user manual of SHIPMA 7.0 (MARIN & Deltares, 2015). SHIPMA is a fast-time manoeuvring model that is suitable for the initial design of a port or fairway. The model can be used for comparing different port designs. Furthermore, the effects of physical conditions on the manoeuvrability can be determined. The following aspects are taken into account by SHIPMA:

- Manoeuvring characteristics of ships
- Type of manoeuvre and desired track
- Rudder and engine actions
- Tug assistance
- Wind, waves and currents
- Under keel clearance effects when manoeuvring in shallow water
- Bank suction

SHIPMA calculates for every time step the position, course angle and the speed of the used mathematical ship model during a run. The behaviour of the ship model is influenced by different input parameters. In figure 3-1 the mathematical manoeuvring model is illustrated with a flow diagram. The wind, waves and tug forces are not included in the performed simulation study. The reasons for neglecting these parameters are explained in more detail in section 3.3.5. For the explanation of the SHIPMA simulation model only the used input parameters for this research are mentioned.

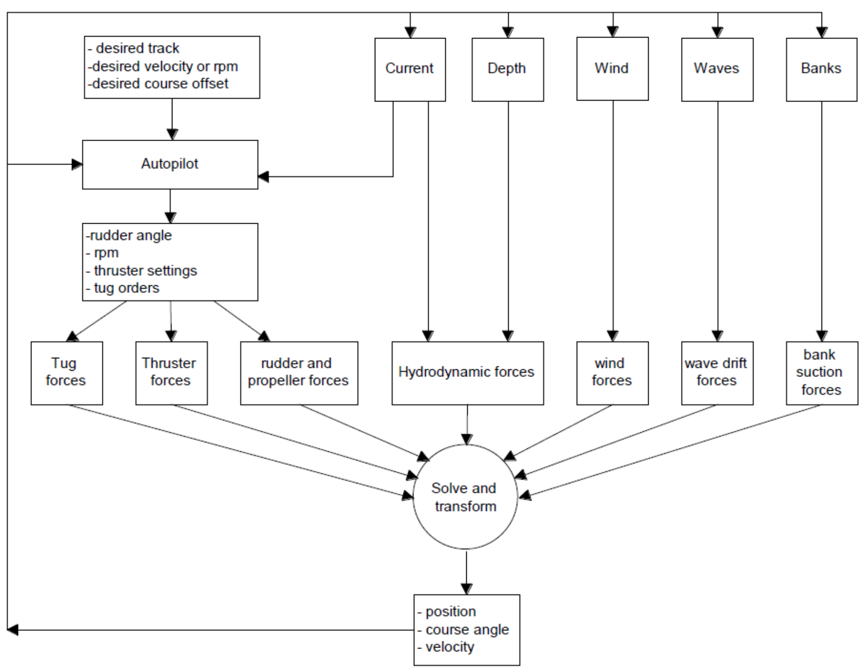


Figure 3-1: SHIPMA flowchart of mathematical manoeuvring model (MARIN & Deltares, 2015).

The current field and bottom profile are together responsible for the hydrodynamic forces on the hull of the ship. The bottom profile is important to derive the under keel clearance, whereas the current is important to derive the sailing speed through the water as well as over the ground. The two bank lines (one for starboard and one for port side) are used to determine the bank suction forces on the ship. The implementation of the bank suction is described in section 3.3.3.

The steering input consists of a track that is specified by the user. Along this track the desired propeller revolutions and course offsets are specified. The only task of the autopilot is to follow this track as good as possible. The settings of the autopilot are influencing the behaviour of the ship in order to follow the desired track. Three autopilot modes are available in SHIPMA: track-keeping, turning circle and zig-zag manoeuvre. For normal operation of SHIPMA simulations the track-keeping mode should be used. The other autopilot modes can be used to perform a turning circle or zig-zag test, these modes are used to verify the manoeuvring behaviour of the ship. These modes are not relevant for this simulation study. Hence, for this research only the track-keeping mode is used.

The input of the autopilot can be split into three parts: the manoeuvring devices, the anticipation length and the autopilot coefficients. For the manoeuvring devices, it can be specified what the allowed rudder angle, power burst, propeller revolutions and thruster force are. The anticipation length is the distance ahead of the ship, which is used by the autopilot to look ahead and to determine which actions should be taken. The autopilot coefficients are used to make the autopilot more or less sensitive to particular deviations. The autopilot can be installed in such a way that the desired track is followed as accurate as possible in combination with the external forces on the ship model. Finding the most appropriate fit for the autopilot settings is an iterative process. The user has to run each scenario multiple times and adjust the autopilot settings in order to get the best fit and thus the most efficient run.

The input for the desired track, propeller revolutions, course offsets and the settings of the autopilot results in a used rudder angle, power burst and thruster force. Note that the SHIPMA-user can only determine which manoeuvring devices are allowed and to which extent, the actual used devices are determined by the autopilot.

When all the input is given, SHIPMA will solve all the calculations and transform these to output for each time step. The steps in the flow diagram of figure 3-1 are repeated for every time step from start to end of a run. The run ends when the last time step is reached or when an implemented stop criterion is met. Different stop criteria can be chosen to end a run:

- Minimum forward speed
- Maximum distance travelled from starting point
- Maximum course deviation
- Minimum under keel clearance

Limitations

The SHIPMA model does not take the human factor into account. Besides, SHIPMA runs can be reproduced exactly. Therefore, a statistical analysis of the SHIPMA results cannot be made. Furthermore, the model is not suitable for detailed design. In addition, the model is not suitable for manoeuvres in which the interaction of two ships and skippers should be taken into account. Moreover, the influence of wind gusts on the ship cannot be simulated with SHIPMA.

To draw a full overview of the SHIPMA limitations; the SHIPMA model is also not suitable for training purposes and complicated mooring manoeuvres. However, these aspects are not relevant for this research.

3.2 Simulation study approach

In order to study the influence of different physical parameters for a port entrance design, several scenarios should be simulated. The approach used for performing the simulation study efficiently, is illustrated in figure 3-2. Each group of simulated scenarios should ensure that as much aspects as possible can be excluded for the next group of runs. Hence, when completing a group of simulations, the results are analysed before the next group of simulations is selected. With this approach the smallest entrance width possible should be determined. Within these different steps, the influences of the design parameters are analysed.

Most of the simulations are conducted for an entrance width that is larger than required. This is chosen to make scenarios easily comparable. For example, when comparing a scenario with an entrance width of 200 meters and an angle of 90 degrees, with an entrance width of 100 meters and an angle of 45 degrees. When comparing these two scenarios, it is difficult to establish whether the differences are induced by the different entrance width or angle.

This research is limited for flow velocities between 1.0 and 2.5 m/s. Hence, often only these two boundary values are used for the simulated scenarios. The flow velocities within this range are expected to give also a result between the output for 1.0 and 2.5 m/s.

Two main groups of simulated scenarios can be distinguished. In Group 1 the influence of the waterway width and different types of ship manoeuvres are simulated. Since, as described in chapter 2, the available waterway width is influencing the ship manoeuvres, these aspects are analysed simultaneously. A narrow waterway layout and a wide waterway layout are used. First different manoeuvres for the narrow waterway are simulated. Subsequently, manoeuvres for the wide waterway are simulated. On the wide waterway, different approach distances to the port entrance are simulated. For example, a skipper can decide to cross the entire waterway when approaching the entrance.

Based on the simulation results of Group 1, the decisive manoeuvres can be selected. Only these manoeuvres are used for the next group of simulations, namely Group 2. The other manoeuvres are neglected for Group 2.

In Group 2, first different angles between the entrance and waterway are simulated. In chapter 2 was mentioned that for large flow velocities backward manoeuvres can be used for arrivals sailing downstream when forward manoeuvres are not sufficiently safe and efficient. Therefore, these manoeuvres are included in the simulation study for further optimisation of the port entrance.

Subsequently, for the most efficient entrance orientation, the influence of different flow velocities, entrance lengths and widths can be determined. Also the effect of flooded entrance dams is simulated.

Finally, several simulations for a lock approach harbour are conducted. These approach harbours are positioned parallel to the waterway axis. Manoeuvres sideways through the entrance can be used for the manoeuvres into the lock approach harbours. Based on these simulated scenarios, the differences between these types of harbours can be compared with the simulation results of the other port entrances in this simulation study.

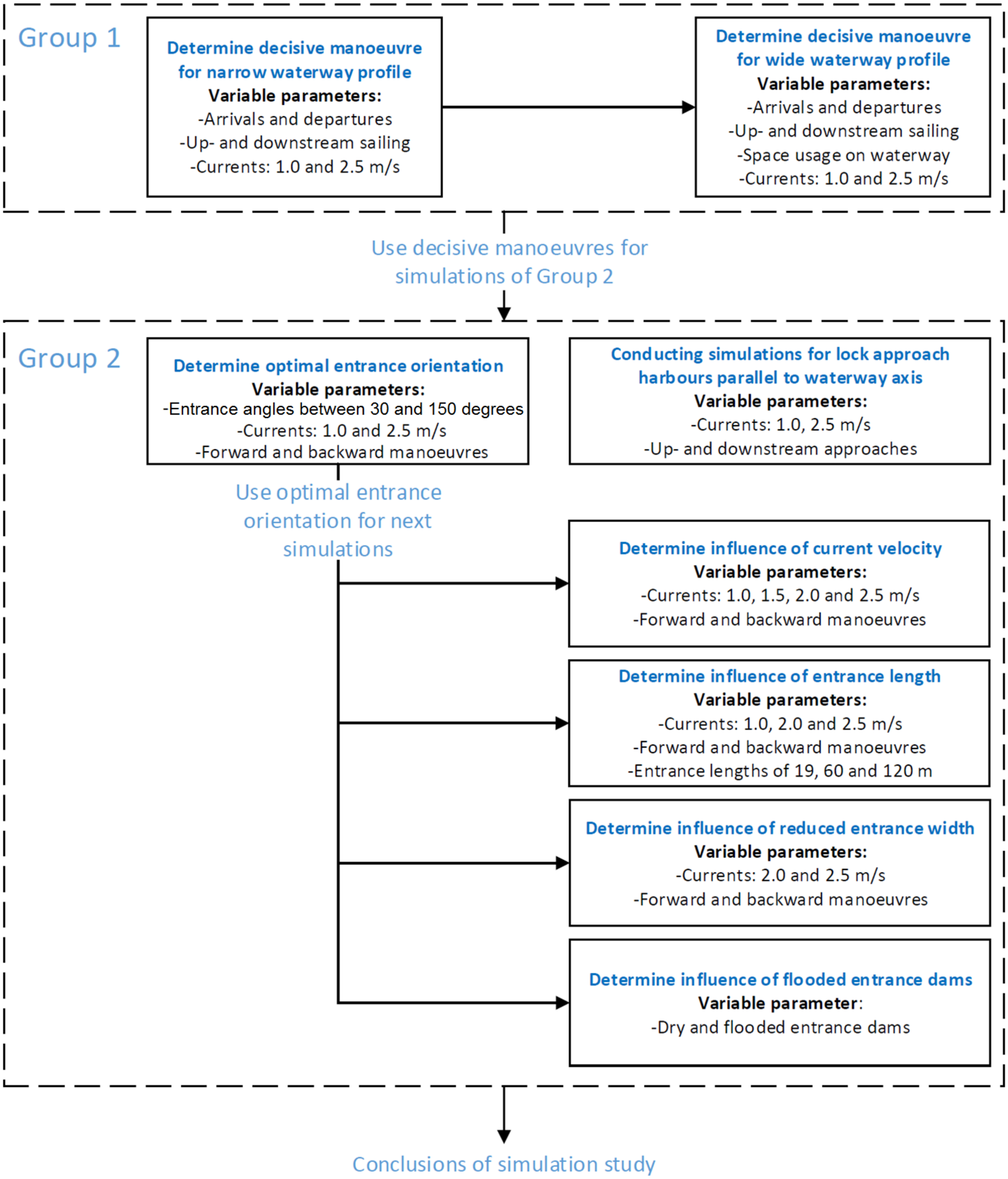


Figure 3-2: Overview of simulation study approach.

3.3 Model input

3.3.1 Mathematical ship model

As was discussed in chapter 2, the manoeuvres through a port entrance with the largest ships (CEMT class VI) and pushed convoys are generally most difficult and thus require the most manoeuvring space. As described in section 1.3, the CEMT class Va ships are the largest ships which are received frequently in the inland ports in the Netherlands (MARIN, personal communication, 2017). Therefore, it is chosen to use a ship from CEMT class Va for the simulation study. This makes the simulation results more applicable to the major part of the inland ports in the Netherlands. Due to this assumption, it is expected that the determined minimum entrance widths as a result of the conducted simulations are not wide enough for larger ships.

Loaded Va, unloaded Va and container ship

Different ship types can be used. Container ships, unloaded motor ships and loaded motor ships have a different behaviour in wind and currents. The wind and current forces on these ships were calculated with a static calculation for a non-moving ship. The calculations are shown in appendix C. It should be mentioned that these calculations are simplified and therefore give only an indication of the magnitudes of the current and wind forces on a sailing ship. The results are only used for a relative comparison of the current and wind forces.

The current forces for relative water velocities between 0.5 and 3.0 m/s were calculated. A minimum relative water velocity of 0.5 m/s was taken into account to avoid controllability problems of the ship. The relative water velocity around the ship's hull is the ground speed of the ship added to the flow velocity. A wind speed of 14 m/s was used, since this value will be exceeded in 0.2 to 3% of the time per year, depending on the location in the Netherlands (Wieringa & Rijkoort, 1983). This wind speed is normally given at a height of 10 meters with respect to a certain reference level on land. The height of the ships above the waterline is considerably lower. Therefore, the wind speed was corrected for the different ship types.

From the calculation results in appendix C can be concluded, that the loaded ship and the container ship are exposed to approximately the same total forces (current + wind) for a relative water velocity of 0.5 m/s. For larger relative water velocities the total forces on the loaded ship are significantly larger. The total forces on the unloaded ship are smaller compared to the other two ships. Therefore, only simulations with a loaded Va ship are conducted, because this ship is exposed to the largest forces (current + wind). An example of a loaded CEMT class Va tanker is shown in figure 3-3.

Figure 3-3: Example of loaded CEMT class Va ship (BVB, n.d.).

Chosen mathematical ship model

A mathematical ship model with exactly the same dimensions of the loaded Va ship is not available in the SHIPMA database. Therefore, a ship model with dimensions close to loaded Va is chosen. The main characteristics of the chosen mathematical ship model for the fully loaded Va ship are shown in table 3-1.

Table 3-1: Characteristics of the loaded Va ship model (MARIN, 2010).

Characteristic	Loaded Va ship
Length over all (m)	108.34
Length between perpendiculars (m)	104.76
Beam (m)	11.60
Draught (m)	3.79
Maximum rudder angle (deg)	45
Bow thruster (kN)	27.2

The mathematical ship model is made by MARIN by geometrical scaling of the model of a class IV ship. The length of the class IV ship is scaled to the length of a class Va ship. A correction is made in order to reduce the beam from 13.25 meter to 11.60 meters and therefore the mass is reduced by 14%. This correction has little influence on the hydrodynamic properties of the ship's hull. A correction for the draught has a large influence on the hydrodynamic characteristics and thus on the manoeuvrability of the ship. Therefore, it was decided to use the scaled model with a draught of 3.79 meters. This model gives a better representation of the behaviour of the Va ship with a draught of 3.5 meters compared to ship model with a corrected draught from 3.79 to 3.5 meters. The manoeuvring behaviour of the model of a class Va ship, with a draught of 3.79 and a keel clearance of 30% of the draught, is sufficient to reproduce the behaviour of a real ship (MARIN, personal communication, 2017).

Normally, a ship model contains two sets of coefficients, each for a specified depth/draught ratio (h/T). During a simulation, SHIPMA will interpolate the values of the coefficients within the h/T interval. Usually, the minimum value applied is 1.2 and the maximum value is 2.0 for inland shipping (MARIN, personal communication, 2017). The manoeuvring behaviour outside the specified ratios is not extrapolated. In that case, the nearest ratio will be selected (MARIN & Deltares, 2015). In case the h/T ratio is smaller than the minimum set of coefficients, then using a larger h/T ratio makes a significant difference on the manoeuvrability of the ship. For situations where the h/T ratio is larger than the maximum set of coefficients, then using the maximum h/T ratio results in a less significant effect.

With the chosen ship model for the simulations, only one set of hydrodynamic hull coefficients is available and thus one h/T ratio. The second set is not added due to geometrically scaling of the ship model. Consequently, a changing water depth during the simulations is not influencing the manoeuvring behaviour of the ship, because for every h/T ratio the same set of coefficients is selected by SHIPMA.

The mathematical ship model is equipped with a bow thruster. It appeared that 99% of the CEMT class Va ships is equipped with a bow thruster with an average power of 350 kW (MARIN, 2007). Hence, it is reasonable to assume that the bow thruster is available in the simulations. It should be mentioned that for increasing relative water velocities around the ship's hull, the efficiency of the bow thruster is decreasing. For large relative water velocities of circa 3.0 m/s, the maximum available force of the bow thruster is 0 kN. The relation between the available thruster force and the ship speed related to the water velocity is shown in figure 3-4.

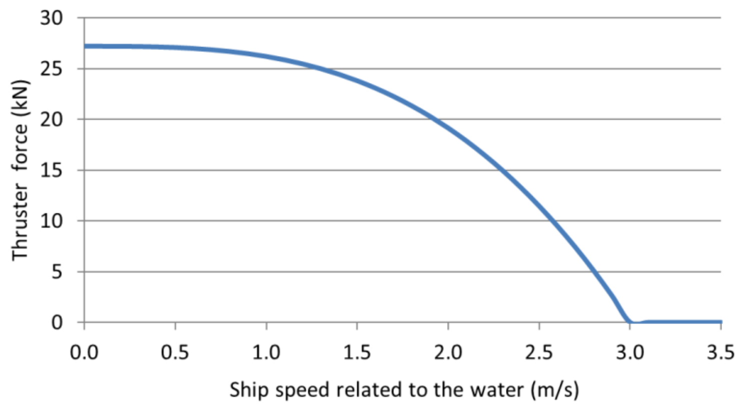


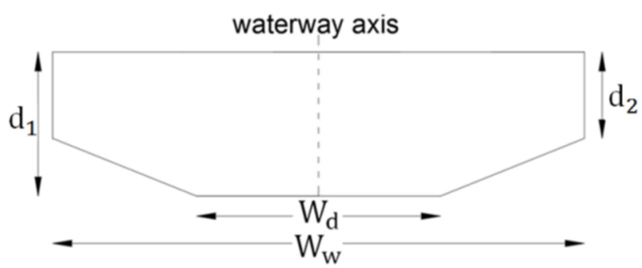
Figure 3-4: The maximum available thruster force for ship model (loaded Va) plotted as a function of the ship speed related to the water. Based on Ten Hove (2016).

3.3.2 Geometry of waterway, port entrance and port basin

Two different waterway layouts are included in the SHIPMA simulations: A narrow waterway profile of 48 meters wide and a wide profile with a width of 148 meters. The narrow profile is similar with the minimum required dimensions for a normal waterway profile for CEMT class Va. Since the influence of the wind is not included in the simulation study, the side wind increment, recommended by WG2011, is not added to the waterway profile. The influence of the wind is explained in more detail in section 3.3.5. The wide profile is in line with the minimum fairway dimensions of the larger waterways in the Netherlands, such as the Waal (MARIN, personal communication, 2017).

The cross-sectional view of a waterway and top view of the waterway, port entrance and port basin are shown in figure 3-5. The waterway width on the bottom of the waterway (W_d) and the width in the keel plane of a loaded ship (W_w), bottom levels (d_1 and d_2), the width of the port basin (W_b), the length of the port basin (L_b), the width of entrance (W_e), the length of the entrance (L_e), the width of the waterway (W_w) and the current direction (U_c) are indicated in this figure.

The port entrance is modelled as a rectangular cross section and both entrance banks are positioned parallel to each other. In chapter 2 was concluded that parallel entrance banks are most favourable for the orientation of the skippers. In addition, the rectangular cross-sectional entrance is more efficient with respect to limiting siltation around the entrance compared to a trapezoidal cross section. Therefore, a rectangular cross section for the entrance is chosen. The modelled banks at the entrance and basin are vertical. As a consequence of these steep banks, the bottom depth in the entrance and basin is equal to d_1. In appendix D the used bathymetry is further explained.



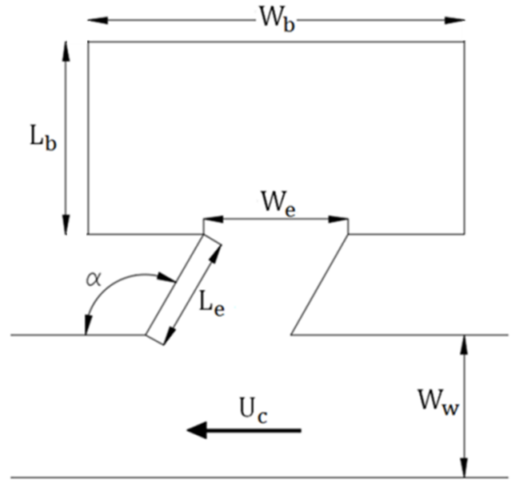


Figure 3-5: Cross-sectional view of waterway (left) and top view of waterway, port entrance and port basin layout (right).

For the wide waterway layout, the length, width and angle of the entrance are varied during the simulation study in order to study the influence of these parameters. In total 14 different layouts are used during the simulations study. The dimensions of the different layouts are given in table 3-2.

Table 3-2: Overview of characteristics of layouts used for SHIPMA simulations.

Layout nr.	Waterway type	W_w (m)	W_d (m)	W_e (m)	L_e (m)	α (deg)	W_b (m)	L_b (m)	d_1 (m)	d_2 (m)
1	Narrow	48	24	150	20	90	390	200	4.9	3.5
2	Wide	148	24	150	60	90	390	200	4.9	3.5
3	Wide	148	24	150	59	33	390	200	4.9	3.5
4	Wide	148	24	150	60	48	390	200	4.9	3.5
5	Wide	148	24	150	60	60	390	200	4.9	3.5
6	Wide	148	24	150	60	120	390	200	4.9	3.5
7	Wide	148	24	150	60	132	390	200	4.9	3.5
8	Wide	148	24	150	59	147	390	200	4.9	3.5
9	Wide	148	24	150	120	120	390	200	4.9	3.5
10	Wide	148	24	150	19	120	390	200	4.9	3.5
11	Wide	148	24	90	60	120	390	200	4.9	3.5
12*	Wide	148	24	200	8	90	610	200	4.9	3.5
13*	Wide	148	24	200	8	90	610	200	4.9	3.5
14**	Wide	148	24	150	60	120	390	200	4.9	3.5

*The difference between layouts 12 and 13 is the different orientations of the basins, see figure 3-7.

**The entrance dams of layout 14 are low, as a consequence the dams are flooded, see figure 3-8.

For layouts 12 and 13 the basins have different dimensions. These two layouts are schematisation for approach harbours before locks. To clarify this schematisation, the lock of Grave on the Maas in the Netherlands is shown in figure 3-6. This lock is located parallel to the waterway axis. The ships have to use the lock to pass the weir in the river. The sailing route is shown with the dashed blue line. To enter the lock, a ship has to manoeuvre into a lock approach harbour. The downstream and upstream approach harbours for such situations are schematised for the simulation study. In figure 3-7, these schematisations are shown.

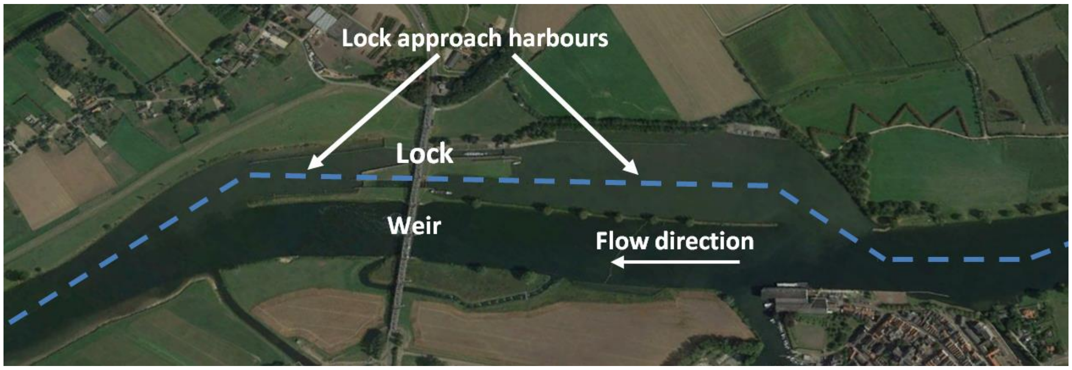


Figure 3-6: Example of lock with approach harbours positioned parallel to the waterway axis. The lock of Grave is shown. Source: Google Earth, retrieved on June 2nd, 2017.

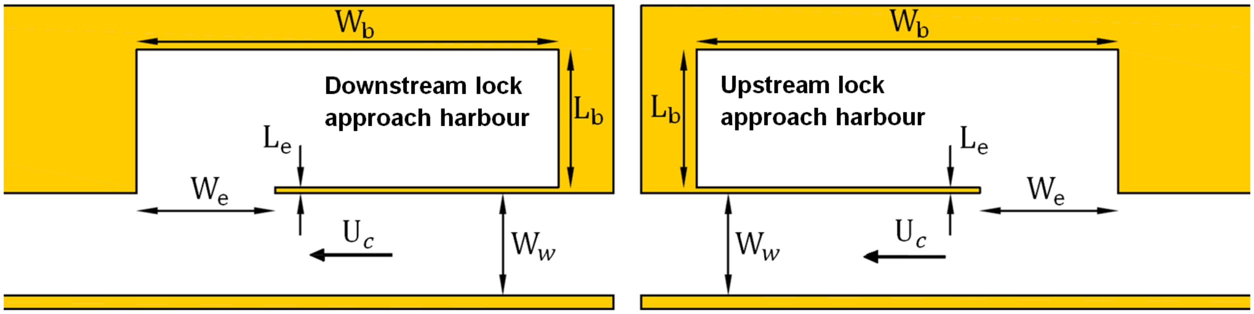


Figure 3-7: Top view of layouts of lock approach harbours. Left: layout nr. 12. Right: layout nr. 13.

Entrance layout number 14 consists of two entrance dams that are flooded. In chapter 2, the entrance studies to the port entrances of Haaften and Lobith were analysed. For larger river discharges, the entrance dams of these ports were flooded. The ratio between the water depth above the dams and in the entrance were respectively 1/22 and 2/5. These ratios are very different. According to S. Quartel from Rijkswaterstaat a large variety in the level of the entrance dams in the Netherlands exists (personal communication, April 20, 2017). For this study a situation is chosen with a ratio of circa 1/7; a water depth above the entrance dams of 1 meter and a depth of 6.9 meters in the entrance. The flooded entrance layout is illustrated in figure 3-8. This layout is used in combination with a flow velocity of 2.5 m/s.

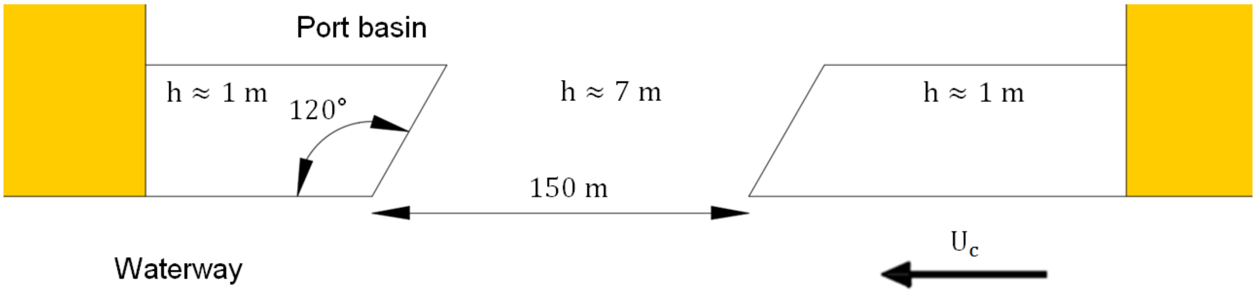


Figure 3-8: Schematisation of port entrance of layout number 14 (flooded entrance dams). The water depths (h) are indicated in the figure.

Basin layout

The main focus of the research is to investigate the most efficient entrance layout. The port basin can influence this layout. For example, a very small basin forces a ship to lower speed in or already before the entrance in order to stop safely within the basin. Another possible factor is the location of the basin with respect to the port entrance. The orientation of the basin can force a ship to steer directly in a certain direction. These two effects are not desired for this generic study, which focuses on the entrance layout.

To avoid the influence of the basin orientation, a rectangular basin is chosen with the entrance in the middle of the basin, see figure 3-5. A basin length of 200 meters is chosen to avoid the influence of the stopping manoeuvre in the basin. This chosen basin length is explained below.

According to the description made by MARIN of the mathematical ship model, the required stopping length is 243 meters for a ship speed of 4.17 m/s (MARIN, 2010). The ship speed when manoeuvring through the port is significantly lower. A ship speed of circa 1.0 m/s is desired (MARIN, personal communication, 2017). When using a power burst to make the rudder more effective, a sharper turn can be made in or out of the port. As a consequence of a power burst, the ship speed increases. The increase in speed depends on the duration of the power burst. For a ship speed of 2.0 m/s about 55 meters of stopping length is required. So, a distance of 55 meters plus the length of the ship (108 meters) is required in the port basin for a safe stopping manoeuvre. Generally, a stopping distance of 1.5 to 2.0 times the length of the ship is advised (MARIN, personal communication, 2017). This is in agreement with calculated value based on the ship model description. So, a basin length of 200 meters is in line with described required stopping distance.

Besides the relation between the basin layout and the nautical aspects, also the current patterns and the basin layouts are related to each other. The size and shape of the basin are influencing the current field in the basin. However, these changes in the current pattern in the basin are relatively small. Therefore, it is assumed that this aspect can be neglected in the nautical simulations. It should be mentioned that these relatively small pattern changes could have a considerable influence on the siltation in a port. This aspect is explained in paragraph 2.3.

Water depth

The chosen water depth is for most simulations equal to the chosen bottom depth (4.9 meters). Only for modelling the current fields of 2.5 m/s, a water depth of 6.9 meters was used and a larger discharge. For this larger water depth it was easier to get stable model results in combination with the chosen grid sizes, discharge, bottom conditions and time step. The modelling of the current fields is explained in more detail in section 3.3.4 and appendix D.

According to WG2011, for CEMT class Va the minimum water depth should be 4.9 meters for the waterway bottom width (W_d) and a depth of 3.5 meters for the waterway in the keel plane of the loaded ship (W_w). So, these water depths are equal to the chosen bottom depths d_1 and d_2, see figure 3-5 and table 3-2. It should be mentioned that d_2 should be equal to the draught of the class Va ship. However, the draught of the mathematical ship model is, due to the scaling of the ship model, larger than it normally is for CEMT class Va ships. It is chosen to use a value of 3.5 meters which is in line with the maximum draught according to WG2011 for CEMT class Va.

As described in section 3.3.1 the influence of different water depths cannot be studied with the mathematical ship model used for the simulations. The only h/T ratio used is 1.3; h = 4.93 m and T = 3.79 m. This ratio is smaller than the minimum advised ratio by WG2011 for a normal waterway profile, which is 1.4; h = 4.9 m and 3.5 m. The used h/T ratio is similar to the advised minimum ratio for a narrow waterway profile, which is 1.3; h = 4.6 m and T = 3.5 m.

The current drag force coefficients, which are used to calculate the current forces on a ship, are related to the h/T ratio. An increase in the current drag force coefficients causes an increase in the current forces on the ship. As is described by OCIMF (2010) the h/T ratio has the largest influence on the current drag coefficients (C_c), which is primarily induced by the blockage effect of the hull. This is illustrated in figure 3-9. A larger water volume has to pass around rather than under the hull when the h/T ratio is decreasing. Hence, a small h/T ratio will increase the current forces on the hull of the ship and this will reduce the manoeuvrability of a ship. In the Netherlands the largest flow velocities will generally occur for large river discharges. Normally, the water depth is also large for this kind of situations. This was also visible in the discussed entrance studies for the ports of Haaften and Lobith in paragraph 2.2. Therefore, it is expected that the h/T ratio of 1.3 is an underestimation of the manoeuvrability for many ports in the Netherlands, when taking into account large flow velocities. Hence, using an h/T ratio of 1.3 is conservative value for situations with large flow velocities.

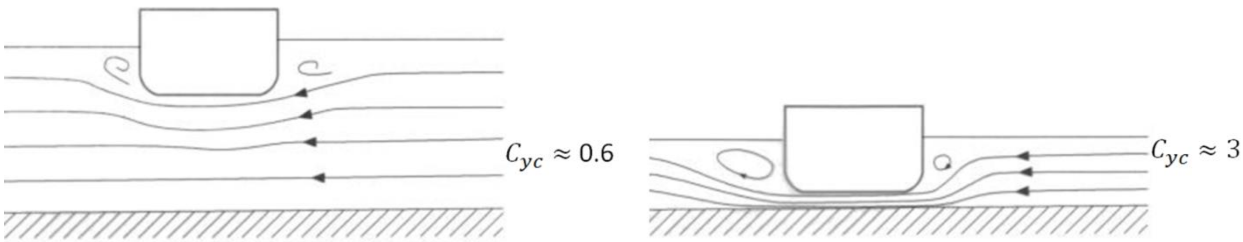


Figure 3-9: Relation between drag force coefficients and h/T ratio (Ten Hove D. , 2016).

3.3.3 Bank suction

The bank suction effect is influencing the manoeuvring behaviour of a ship when sailing eccentrically with respect to the waterway axis (Verheij, Stolker, & Groenveld, 2008). This aspect is included for every SHIPMA simulation. The bank suction effect is implemented in SHIPMA by adding two bank suction lines at the scenery for a particular simulation. One line is for the port side and the other line is for the starboard side of the ship. The lines should be defined at half the ship's draught in case of a standard bank slope with a steepness ratio of one to four or steeper (MARIN & Deltares, 2015). Since the bank slopes used for the simulations are vertical from a depth of 3.5 meters to the waterline, the bank suctions lines are implemented at the banks. This is illustrated in figure 3-10.

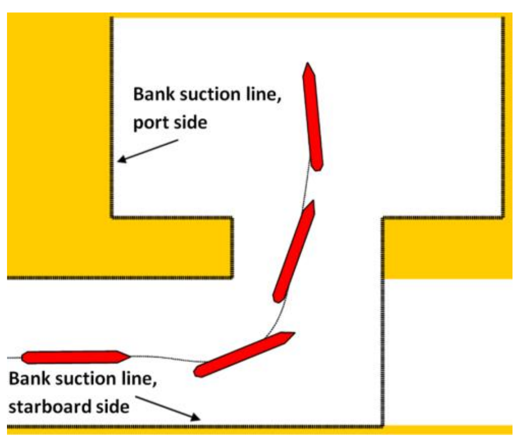


Figure 3-10: Example of bank suction lines for a SHIPMA simulation.

3.3.4 Current field

The current fields are modelled with Delft3D-FLOW 4.00.01. The grid size in the direction parallel to the waterway axis is 10 meters and perpendicular 4 meters. The used grid size in perpendicular direction is smaller than in longitudinal direction in order to model the current pattern more precisely in and around the port. With these grid sizes a smooth gradient is visible near the entrance. An example of a modelled current field of 1.0 m/s is shown in figure 3-11. For each current field the flow velocity was measured in the middle of the waterway and downstream of the entrance. This measuring point is indicated in figure 3-11. In appendix D, the used set-up for modelling the current fields is described. In this appendix also the model results are discussed and several current fields are shown.

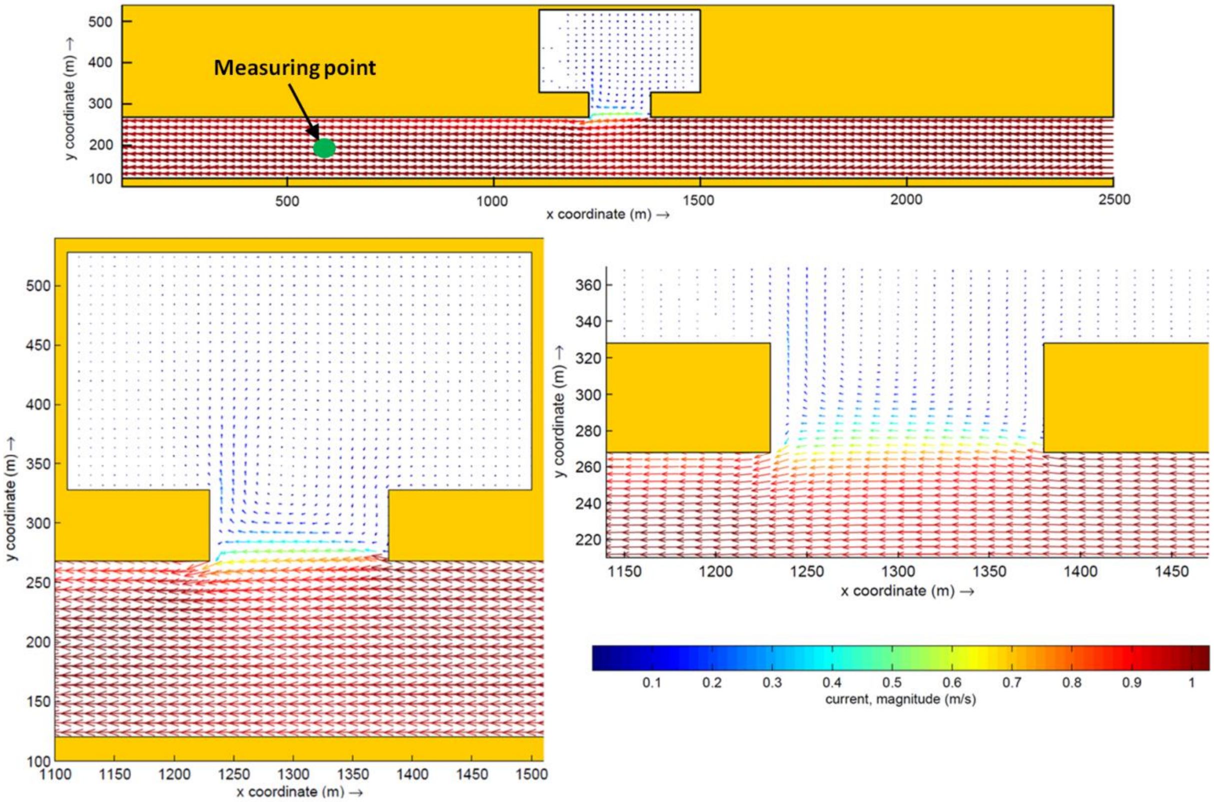


Figure 3-11: Example of depth average current field. Overview of entire field (top), close-up of port basin, entrance and waterway (bottom left) and close-up of port entrance (bottom right).

During a manoeuvre in or out of the port, the current forces in lateral direction of the ship will be large. The mathematical ship model consists of 20 points, equally divided over the length of the ship, which can detect external forces on the ship's hull (MARIN, personal communication, 2017). In figure 3-12 a situation is illustrated where the ship is in the flow gradient and is manoeuvring into the port. The flow changes perpendicular to the waterway axis are indicated by the blue box. The changes parallel to the waterway axis are indicated by the green box. The detection points of the ship are indicated on the ship.

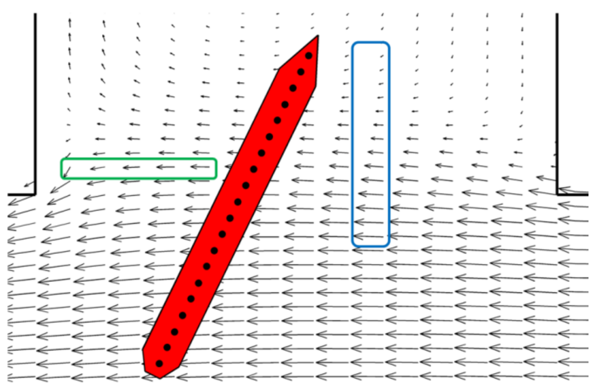


Figure 3-12: Example of mathematical ship model in flow gradient when entering a port entrance.

The total length of the ship is 108.34 meters which results in 5.4 meters between two detection points. The chosen grid size (of 4 meters) perpendicular to the waterway axis is smaller than 5.4 meters. Therefore, it is assumed that this grid size contributes to an accurate distribution of the current forces on the ship's hull. The changes in the current pattern and magnitude in the direction parallel to the waterway axis are much smaller than in perpendicular direction. Therefore, a larger grid size parallel to the waterway axis is sufficiently accurate. Hence, a grid size of 10 meters is chosen for this direction.

The current field is a two dimensional input field for SHIPMA, which means that a layered current field cannot be used in SHIPMA. Normally, the velocities around the bottom of a waterway are lower than close to the surface, which is illustrated in figure 3-13. For a small under keel clearance, the difference between the draught integrated current around the hull of the ship and the depth average current in the waterway are approximately similar. For large under keel clearances, these differences can be significantly larger. The bottom profile is affecting the velocity profile and consequently the flow velocity around the hull of the ship. The bottom characteristics can be different for every local situation. However, the influence of different bottom profiles is beyond the scope of this research. Therefore, the depth average current modelled with Delft3D is taken as the draught integrated current around the hull of the ship.

It should be mentioned that for strong layered currents, it is possible that the depth average velocity is zero for certain situations, but that the flow velocity in the top layer is significant. This is not an expected situation for inland waterways in the Netherlands. However, it should be taken into consideration that these situations are possible for certain locations in the world (MARIN, personal communication, 2017).

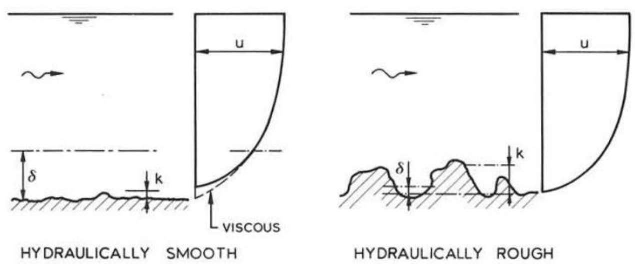


Figure 3-13: Schematisation of velocity profile for hydraulically smooth and rough bottom profiles. The flow velocity u, the bottom roughness k and the thickness of viscous sub layer δ are indicated (Jansen et al, 1979).

For every layout, described in section 3.3.2, a current field is modelled with Delft3D for a velocity of 1.0 m/s. For the larger flow velocities, the current fields are scaled by using the scale factor in the SHIPMA input file. The difference are small between modelling a current field of 2.5 m/s with Delft3D or a 1.0 m/s current field scaled to a 2.5 m/s current field. The largest magnitude differences between the fields occur in the port entrance, with a maximum of 0.3 m/s. These differences result in a 6% smaller swept path in the entrance for the scaled current field. For the required entrance width, the difference is 4%. The required entrance width, is the width of the swept path plus safety distance, this is explained in more detail in section 3.4.2. Since the differences between the scaled and modelled fields are small, it is decided to use the scale factor to speed up the preparation of the input for the different simulations. Only for the narrow waterway the current field of 2.5 m/s was modelled with Delft3D. The output of these runs can be slightly less favourable compared to the scaled fields of 2.5 m/s. This is only a minor difference, therefore this difference is neglected. Appendix D discusses the differences between the modelled and scaled current fields in more detail.

3.3.5 Neglected input

The SHIPMA model is also capable of including the influence of waves, tug forces and wind (MARIN & Deltares, 2015). At inland waterways wind waves are small in height and short of period, therefore the wave drift forces are small and insignificant for manoeuvring (MARIN, personal communication, 2017). It should be noted that for lakes the influence of the wind is more significant. However, this is beyond the scope of this research. Therefore, the influence of waves is not included in this research. Tug assistance is not common for inland shipping (MARIN, personal communication, 2017). Hence, tug assistance is not included in this research.

Wind

As mentioned before, the current and wind force calculations on a loaded Va ship are shown in appendix C. As described in section 3.3.1, the following current and wind conditions were used: relative water velocities between 0.5 and 3.0 m/s and a wind speed of 14 m/s, which was corrected for the average heights of the ships. A simplified calculation method was used. As a consequence, the calculation results should only be used for comparing the current and wind forces relatively to each other. Furthermore, it should be mentioned that when manoeuvring in or out of a port, a moment is required to make a turning manoeuvre. This yaw rotation is not included in the simplified current and wind calculation in appendix C. The calculations in appendix C give only an indication of the current and wind forces in longitudinal and lateral direction of the ship. In figure 3-14 the ratio between the calculated current forces and the wind forces ($\mathrm{F_c/F_w}$) is shown. The ratios in longitudinal direction ($\mathrm{F_{xc}/F_{xw}}$) and lateral direction ($\mathrm{F_{yc}/F_{yw}}$) are indicated.

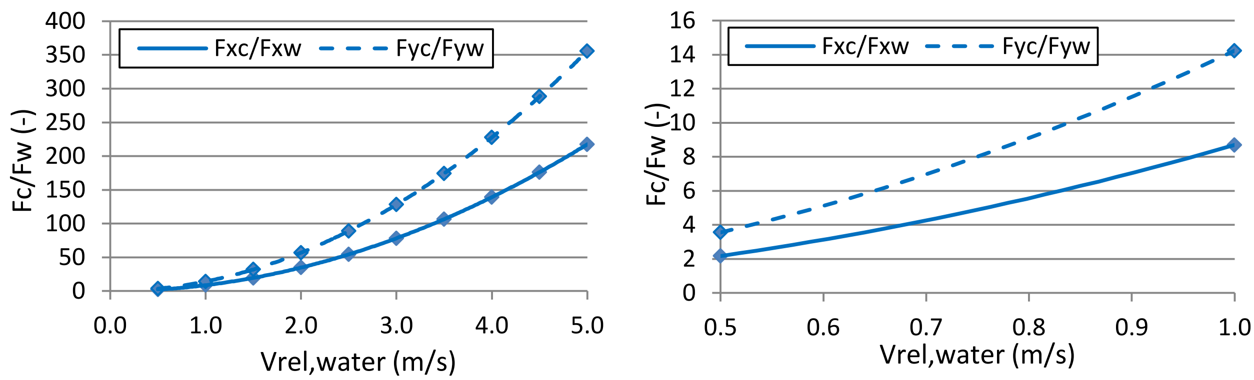


Figure 3-14: Ratio between calculated current and wind forces on loaded Va ship, for relative water velocities between 0.5 and 5.0 m/s (left). A close-up (right) is given between velocities of 0.5 and 1.0 m/s.

The current and wind force calculations for the loaded Va ship revealed that:

- The wind forces are about 50% in longitudinal direction and 25% in lateral direction of the current forces for a relative water velocity of 0.5 m/s.
- The wind forces are about 10% in longitudinal direction and 7% in lateral direction of the current forces for a relative water velocity of 1.0 m/s.
- The wind forces are less than 1% of the current forces in lateral direction for a relative water velocity of 3.0 m/s or larger. In longitudinal direction this percentage occurs for relative water velocities larger than 3.5 m/s.

The calculation results showed that only for small relative water velocities, the influence of the wind is noticeable compared to the current forces. When sailing on the waterway and parallel to the waterway axis, only the longitudinal forces are important. By contrast, when manoeuvring into or out of the port entrance, the ship is positioned more perpendicular to the current, see figure 3-12. So, when sailing in or out of the port, also the lateral forces on the ship's hull are important.

When sailing in upstream direction, the relative water velocity around the ship is always larger than 1 m/s, because flow velocities between 1.0 and 2.5 m/s are taken into account in this research. When sailing downstream, the relative velocities are smaller compared to sailing upstream. However, around the port entrance the ship is sailing (partly) perpendicular to the current. So, still a considerable relative water velocity around the ship's hull is expected. Besides, the ground speed of the ships must always be larger than the flow velocity when sailing in downstream direction to avoid controllability problems of the ship.

Therefore, it is assumed that for sailing in upstream and downstream direction the influence of the wind is negligible small compared to the influence of the current.

It should be mentioned that a wind gusts, when the duration of the gust is sufficiently long, can surprise a skipper and therefore can influence the ship behaviour. However, the influence of wind gusts cannot be implemented in SHIPMA. Furthermore, as described before, the human factor is not included in the SHIPMA model. The SHIPMA-user has perfect knowledge of a situation and can install the autopilot in such a way that it cannot be surprised.

3.3.6 Ship manoeuvres and automatic pilot

For every run the behaviour of the ship is influenced by a combination of the chosen, environmental conditions, manoeuvre and pilot settings. The ship manoeuvres are related to an implemented track which is followed by an autopilot that is steering the ship during the run. In case runs are set up with a similar approach to implement the manoeuvre and autopilot settings, the run output can be compared more properly.

For each run, it was attempted to use the most efficient manoeuvre through the port entrance. As was described in paragraph 2.2 the heading of the ship in the entrance is important with respect to the required entrance width. In figure 2-4, it was shown that manoeuvring sideways through the entrance can be more efficient than a heading parallel to the entrance banks. Therefore, for every run the different options are analysed and the most efficient manoeuvre was used. In figure 3-15, the possible manoeuvring directions through the entrance for an arrival manoeuvre are shown.

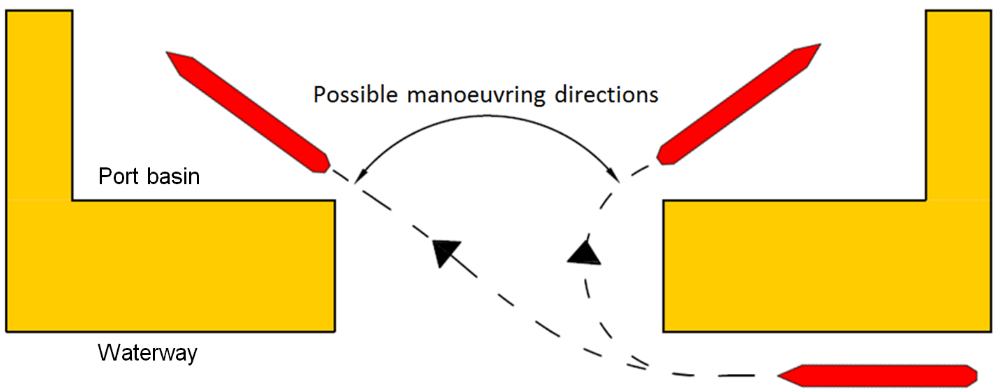


Figure 3-15: Example of possible manoeuvring directions when sailing into a port.

Manoeuvres

It is attempted for every run to set up the runs in such a manner that the runs can be easily compared with each other. The manoeuvres used in this research, illustrated in figure 3-16, can be split into four categories:

1. Arrival scenario, sailing upstream: Run starting on the waterway downstream of the port entrance and ending in the port basin.
2. Departure scenario, sailing downstream: Run starting in the port basin and ending downstream of the port entrance on the waterway.
3. Departure scenario, sailing upstream: Run starting in the port basin and ending upstream of the port entrance on the waterway.
4. Arrival scenario, sailing downstream: Run starting on the waterway upstream of the port entrance and ending in the port basin.

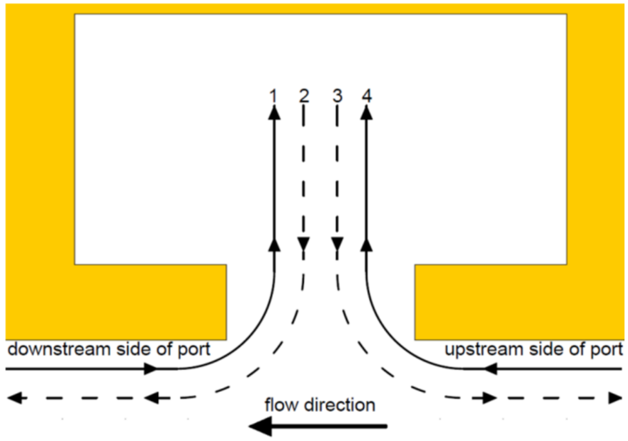


Figure 3-16: Schematisation of the four different forward manoeuvres.

For all manoeuvres applies that the objective for every run is to occupy as less space as possible in the entrance width. This is more important than the required space in the port basin and on the waterway. However, the space in the port basin and on the waterway has to be approximately the same for a group of runs in order to make a fair comparison between those runs. During the set-up of each run, it is attempted to satisfy the safety criteria, explained in section 3.4.1, as much as possible.

For categories 1 and 4 the following run characteristics hold:

- The run starts with a ground speed of 2 m/s on the waterway and ends with a ground speed of 0 m/s in the port basin. Just before the start of the turning manoeuvre into the port, it is attempted to reduce the ground speed to 1 m/s. During the manoeuvre the ground speed can increase because of power bursts (short periods of more propeller revolutions) to increase the steering capacity.
- When sailing in downstream direction (category 4), with a large current velocity, it is difficult to reduce the ground speed to 1 m/s just before the start of the turning manoeuvre. It is possible to reduce the speed. This can only be achieved by reversing the propeller astern. When the propeller is working astern, there is no flow over the rudder. For these manoeuvres, the ground speed is reduced before the start of the turning manoeuvre, but not always to 1 m/s.
- The stopping manoeuvre is started when the stern, or bow in case of backward manoeuvre, of the ship is in the basin. This is chosen in order to avoid that the stopping manoeuvre affects the results around the port entrance. The stern of a ship can deflect to port or starboard side during a stopping manoeuvre. When stopping, the propeller is working astern and the rudder is thus not effective. The deflection can be different for each ship and is therefore an undesired effect for this generic study. An aspect that influences the deflection of a ship is the rotation direction of the propeller (MARIN, personal communication, 2017).
- For most of the runs a lateral approach distance of circa 12 meters is used. Note that this is similar to one times the beam of the CEMT class Va ship. The lateral approach distance is illustrated in figure 3-17.

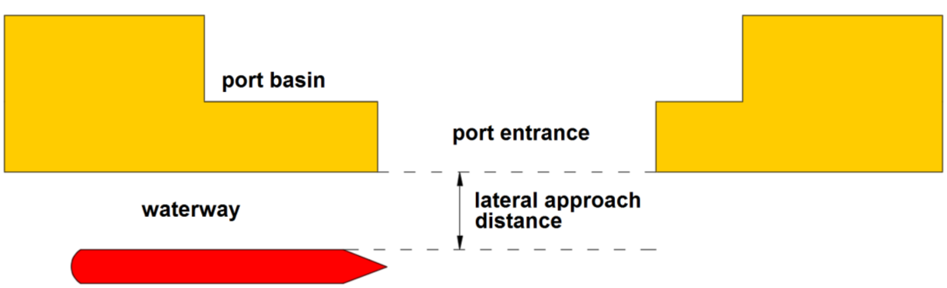


Figure 3-17: Schematisation of lateral approach distance of ship.

For categories 2 and 3 hold that the run starts with a ground speed of 0 m/s in the port basin. During the manoeuvre out of the port the speed is adapted to the required ground speed to cross the current gradient safely. On the waterway the ground speed can increase further. It is attempted to limit the space usage on the waterway and in the port entrance as much as possible.

Several runs are not set up in the manner as explained above, for these runs an explanation for the deviation is given when discussing the results of these runs.

Automatic pilot

The implemented track, the propeller revolutions and automatic pilot steering controls along this track are all changed step by step in order to find the most efficient situation for manoeuvring in or out of the port. These combinations can be different for each simulation. In order to create the most efficient run, this iterative process has to be repeated until no improvement of the run is possible. The most efficient run is often determined when the maximum allowed steering capacity is used. The allowed steering capacity is discussed in section 3.4.1.

In most of the runs, a track is implemented which cannot be followed precisely by the ship model. By adding a large anticipation length at the start of the turning manoeuvre, the ship is forced to steer with the maximum allowed capacity. With this approach it is easier to set up the most efficient manoeuvre than when following a track more precisely. An example of a run in which the track is not followed precisely is shown in figure 3-18. The anticipation length is the distance ahead of the ship, which is used by the autopilot to look ahead and to determine which actions should be taken. By taking a large anticipation length of the autopilot, the ship steers before the bend in the track. Just before the turning manoeuvre, the anticipation length is increased significantly. This point is indicated with a blue dot in figure 3-18. From this point, the autopilot is focussing on the look ahead point. As a consequence, the implemented track at the right side of the blue dots is not used by the autopilot. Therefore, it is not problematic that the implemented track is crossing the upstream entrance bank in figure 3-18. Although a part of the implemented track is not used by the autopilot, this part is still implemented for a run, because only continuous tracks can be implemented for a SHIPMA run.

It should be noted that it is possible to obtain similar results when implementing a track that can be followed precisely. However, it is more difficult for this strategy to find the most efficient autopilot settings for a run. As a consequence, the iterative process to find the best fit is more time consuming. Moreover, it is more likely that a slightly less efficient fit is found. As a consequence, a larger swept path is obtained when using this strategy. Therefore, it is chosen to use the strategy shown in figure 3-18 to obtain the most efficient runs.

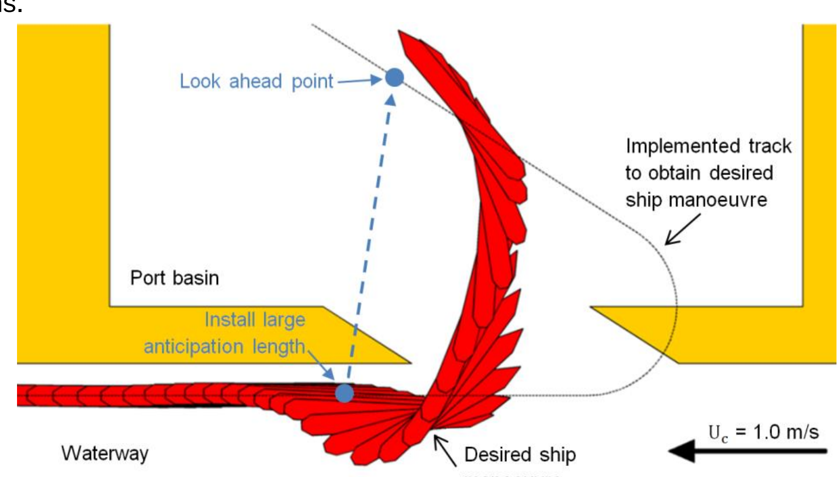


Figure 3-18: Example of run in which the ship model does not follow the desired track precisely.

3.4 Run assessment method

The objective of this research is to find the minimum entrance width. From the different simulated scenarios the required entrance width can be determined. Based on these obtained entrance widths, the influence of different design parameters can be studied. The usage of safety criteria makes it possible to compare the runs objectively with each other. The assessment of the runs consists of two parts. The first part is to determine the level of safety of a run. The second part consists of the assessment of the swept path and the required time for the turning manoeuvre of the ship on the waterway when sailing in or out of the port. In section 3.4.1 the safety criteria are explained. The methods for measuring the swept path and manoeuvring time of the ship are explained in section 3.4.2.

3.4.1 Safety criteria

A ship run should be safe from start to end of the run. For the assessment of the safety of the runs, two aspects are evaluated: the required manoeuvring space and the controllability of the ship. The safety criteria presented in this section are developed and in use by MARIN (MARIN, personal communication, 2017).

For the required manoeuvring space, the following criteria should be complied:

- On the waterway a ship should be at least 1B away from a water depth equal to the draught of the ship, with B the beam of the ship. This manoeuvring and navigating criterion is illustrated in figure 3-19.
- Around the port entrance and in the port basin, a distance of at least 0.5B is required, see figure 3-19.

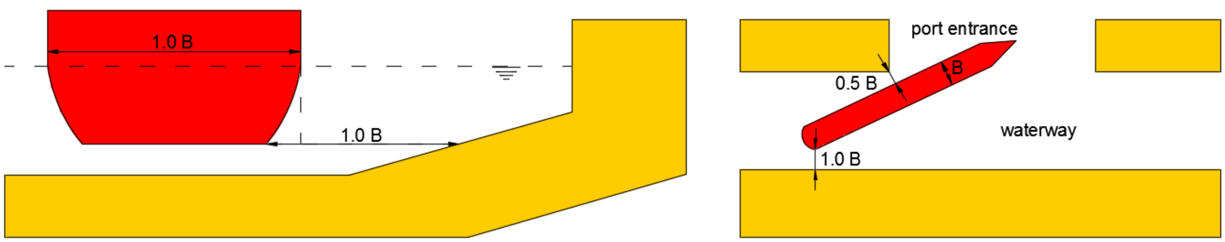


Figure 3-19: Schematisation of minimum required safety distances on waterway and around port entrance. Left: Cross-sectional view on waterway. Right: Top view of ship in waterway and port entrance.

The assessment of the controllability contains the following criteria:

- A maximum use of rudder angle of 20 degrees in combination with a full use of machine power. A larger rudder angle is allowed in combination with less machine power. A safety index is used to check whether a combination of rudder angle and machine power is permitted. The safety index shows the ratio between the product of the rudder angle and the steering power and the product of a rudder angle of 20 degrees and the steering power at full machine use. The steering power is proportionally with the propeller revolutions squared. Hence, the following formula can be used for calculating the safety index:

  $\text{Safety Index} = \frac{|\delta| \cdot n_p^2}{\delta_{crit} \cdot n_{crit}^2}$, with:

  δ Used rudder angle (deg)
  n_p Propeller revolutions (rev/minute)
  δ_{crit} Rudder angle criterion (20 degrees)
  n_{crit} Machine criterion (full power: 327 revolutions per minute for the used ship model)

  This relation shows that a rudder angle of 45 degrees (maximum rudder angle) is allowed in combination with 218 propeller revolutions per minute or less.

- A maximum use of 70% of the capacity of the bow thruster. The maximum bow thruster use should not be longer than 1 minute continuously. As described in section 3.3.1, the efficiency of the bow thruster is related to the relative water velocity around the hull of the ship. For larger velocities the efficiency of the bow thruster is small.
- During the stopping manoeuvre in the port basin, the yaw and transversal speed should be reduced as much as possible to avoid dangerous behaviour of the ship in the port basin. When the longitudinal speed of 0.0 m/s is reached, a rotational speed of 0.3 deg/s and a transversal speed of 0.3 m/s or less are allowed. For each arrival scenario is only checked whether the ship can stop safely in the port basin; mooring of the ships is not included in this research.

3.4.2 Swept path and manoeuvring time

The swept path and the manoeuvring time around the port entrance are measured and used for further analysis of the simulation results. The time required to complete a manoeuvre is important to evaluate a particular simulation. In principle, a manoeuvre that requires a small port entrance is more desirable than a manoeuvre that requires a larger entrance width. However, a manoeuvre that needs a lot of time on the waterway is undesirable. A slow manoeuvre is blocking the waterway for a long period. This can cause congestion of other traffic on the main waterway. A maximum time for the turning manoeuvre on the waterway of approximately 5 minutes, is taken as the maximum allowed for a sufficiently fast manoeuvre in or out of an inland port (MARIN, personal communication, 2017).

The evaluation of the swept path is split into two parts; the swept path around the port entrance and the swept path on the waterway. The swept path in the port entrance is important to determine the required entrance width. However, the used space on the waterway is also important to include when analysing the simulation results. For example, it is possible that for particular manoeuvre through the port entrance little space is used, but on the waterway a large area is occupied to make this manoeuvre. Then, still a lot of manoeuvring space is required. In order to make a fair comparison between runs, both aspects should be taken into consideration.

In figure 3-20 an example is shown of the used method for measuring the required entrance width for a simulated scenario. The required entrance width ($W_{e,req}$) in the entrance is measured by shifting the entrance banks (dashed blue lines) up to the plotted swept path (green). A safety distance of 0.5B is included to satisfy the manoeuvring space criterion around the entrance; the distance between solid and dashed blue lines. As a consequence, the measured required entrance width ($W_{e,req}$) is larger than the swept path width (W_{sp}).

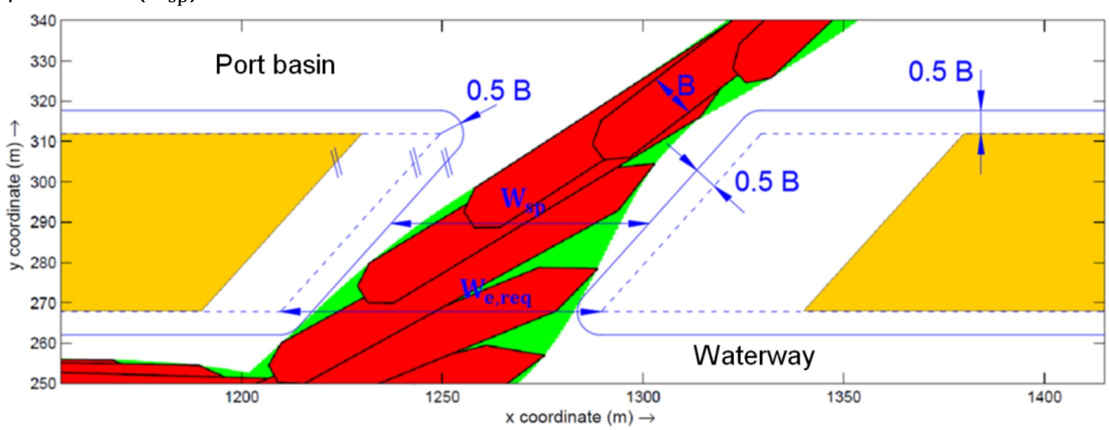


Figure 3-20: Example of the method used for measuring the required entrance width for a SHIPMA run. The ship snapshots are indicated in red and the swept path in green.

In figure 3-21 an example is shown of measuring the required waterway width for a manoeuvre. The maximum used width ($W_{w,used}$) and the maximum required width ($W_{w,req}$) are indicated in this figure. A safety distance of 1B is included to satisfy the manoeuvring space criterion on the waterway. Note that the used width is the width of the swept path and the distance between the ship and the bank at the entrance side of the waterway. To this distance is referred with lateral approach distance of the ship.

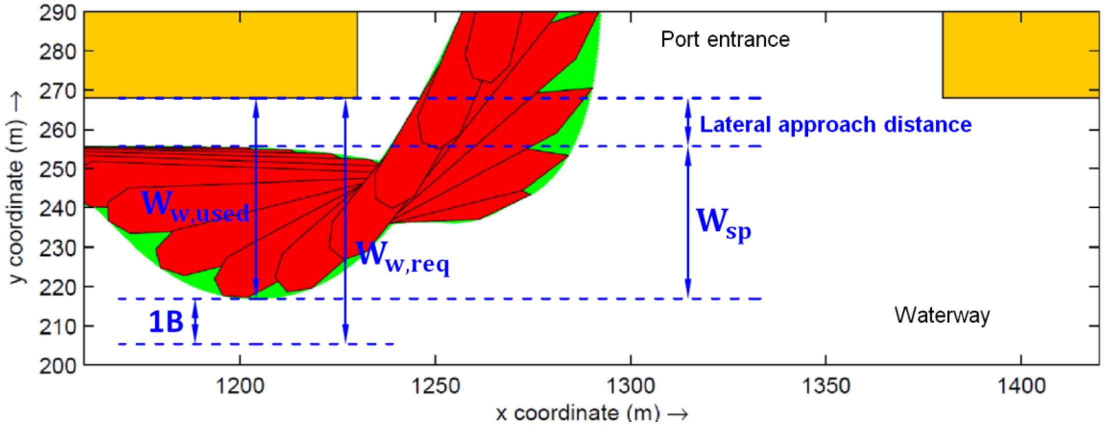


Figure 3-21: Example of measuring the required entrance width for a SHIPMA run. The ship snapshots are indicated in red and the swept path in green.

The widths of the swept paths are measured with AutoCAD 2016. The provided swept path results in this research are rounded to whole meters. The used measuring technique is accurate enough to provide these rounded values.

The manoeuvring time is defined as the time needed to complete the entire manoeuvre in the waterway. For manoeuvres into the port, the starting point is the moment when the ship starts turning and the end point is when the entire ship is out of the waterway, this is illustrated in figure 3-22. The starting point and the ending point of the manoeuvring time are indicated with a ship snapshot coloured blue. For manoeuvring out of the port, the starting point is the moment when the ship leaves the entrance. The end point is when the ship is sailing parallel to the waterway axis and on the starboard side of the waterway. Note that the manoeuvring time is different than the total run time; the turning manoeuvre is a part of the entire run.

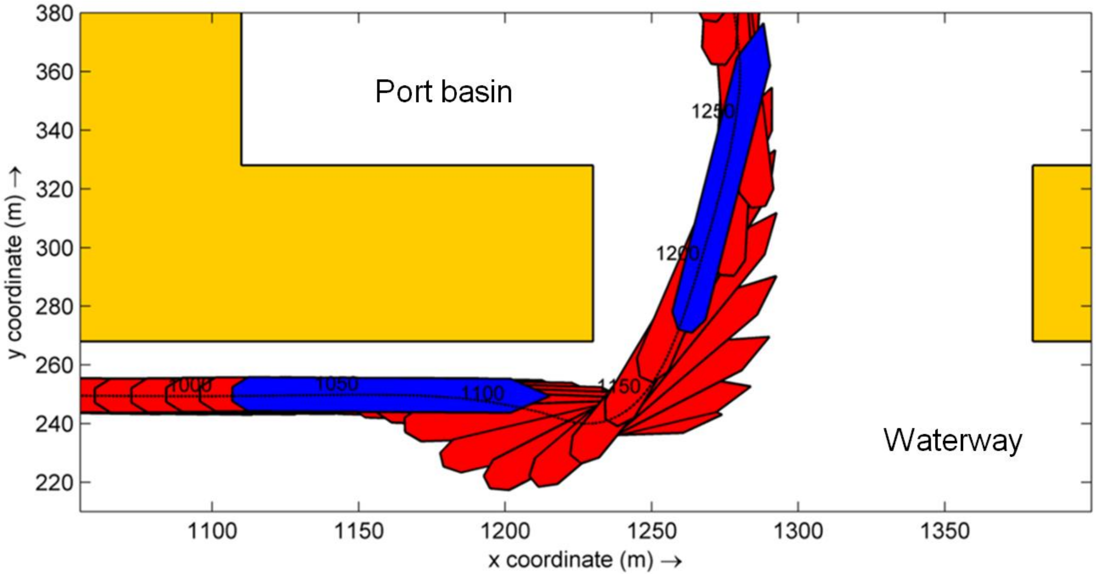


Figure 3-22: Example of distance over which the manoeuvring time is measured. The ship snapshots are indicated with red. The start and end of the measured manoeuvring time is indicated with the two blue ships.

4

Model results assessment

In this chapter, the conducted fast-time simulations are assessed with respect to the assessment criteria presented in paragraph 3.4. During the simulation study 66 different scenarios were simulated. As explained before the usage of safety criteria, presented in section 3.4.1, makes it possible to compare the runs objectively with each other. In addition, the runs are also assessed regarding the allowed manoeuvring time, described in section 3.4.2. Too slow manoeuvres are undesired, because these manoeuvres can cause congestion on the waterway.

In chapter 5, the run results are analysed in more detail with respect to the required entrance widths. The safety assessment results of chapter 4 are important to perform an objective analysis of the results in chapter 5.

In appendix F, an overview is given of the input and output of the runs. A more detailed presentation of the results is given by track and data plots of each run. These plots are shown in appendix G. The complete version of appendix G, with all the output plots, is available at: *http://researchdata.4tu.nl*. An example and explanation of these plots is given in paragraph 4.1. Paragraph 4.2 describes the assessments of the conducted runs.

Paragraph 4.3 presents an overview of the runs that were assessed as not sufficiently safe. When using these run results for the analyses in chapter 5, it should be taken into consideration that the acquired results of these runs are possibly not correct. This paragraph also describes several conclusions that follow directly from the run assessments.

4.1 Presentation of the results

The output of the SHIPMA runs are presented in track plots and data plots. In the track plots every 20 seconds a ships contour is plotted and the distance of the followed path is indicated every 100 meters. The non-water parts of the layouts are covered by a yellow contour. With the track plots can be assessed whether the used manoeuvring space is satisfying the criteria presented in section 3.4.1. Furthermore, the required entrance width and waterway width can be measured as described in section 3.4.2. With the data plots the controllability criteria can be assessed. The track and data plots for every run are presented in appendix G. Examples of these track and data plots are shown in figure 4-1, figure 4-2, figure 4-3 and figure 4-4. The following plots are provided for each run:

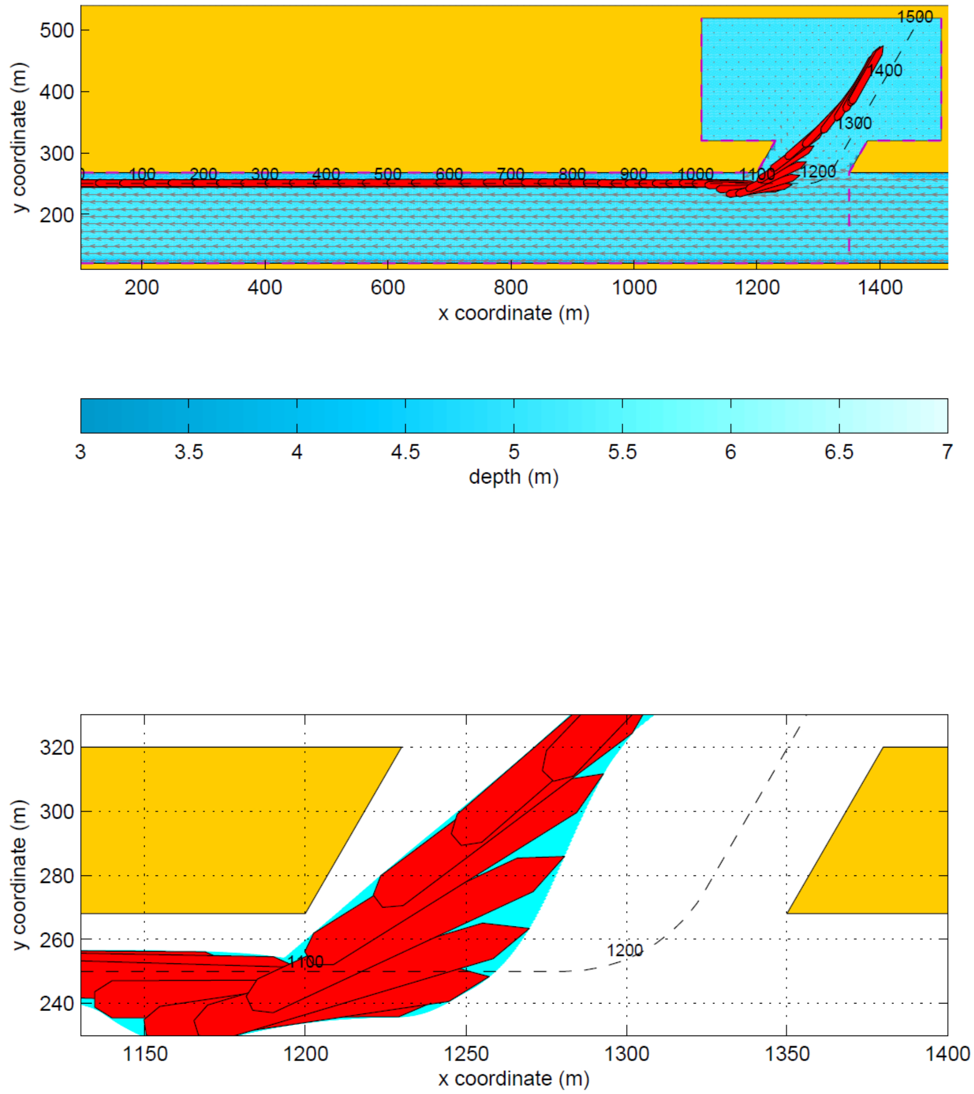
- Figure A1: Track plot overview of entire situation with the water depth, bank suction lines, current, implemented track and ship snapshots. Close-up of the port entrance with the swept path, implemented ship track and ship snapshots. The track plot overview gives an impression of the entire run. The close-up of the port entrance shows the required space around the entrance. With this plot the required entrance width can be determined.

- Figure A2: Track plot close-up of the port basin, entrance and the waterway in front of the port. In this plot the current, bank suction lines, implemented track and ship snapshots are included. This close-up gives an impression of the current pattern around the port entrance. Moreover, this plot can be used to measure the required waterway width.

- Figure B: Data plots with the propeller revolutions (rev/s), rudder angle (deg) and bow thruster force (kN) plotted as a function of the travelled distance (m). The bow thruster force (kN) plotted against the time (min) is also included. These plots can be used to check whether the controllability criteria for the use of machine power, rudder angle and bow thruster are satisfied.

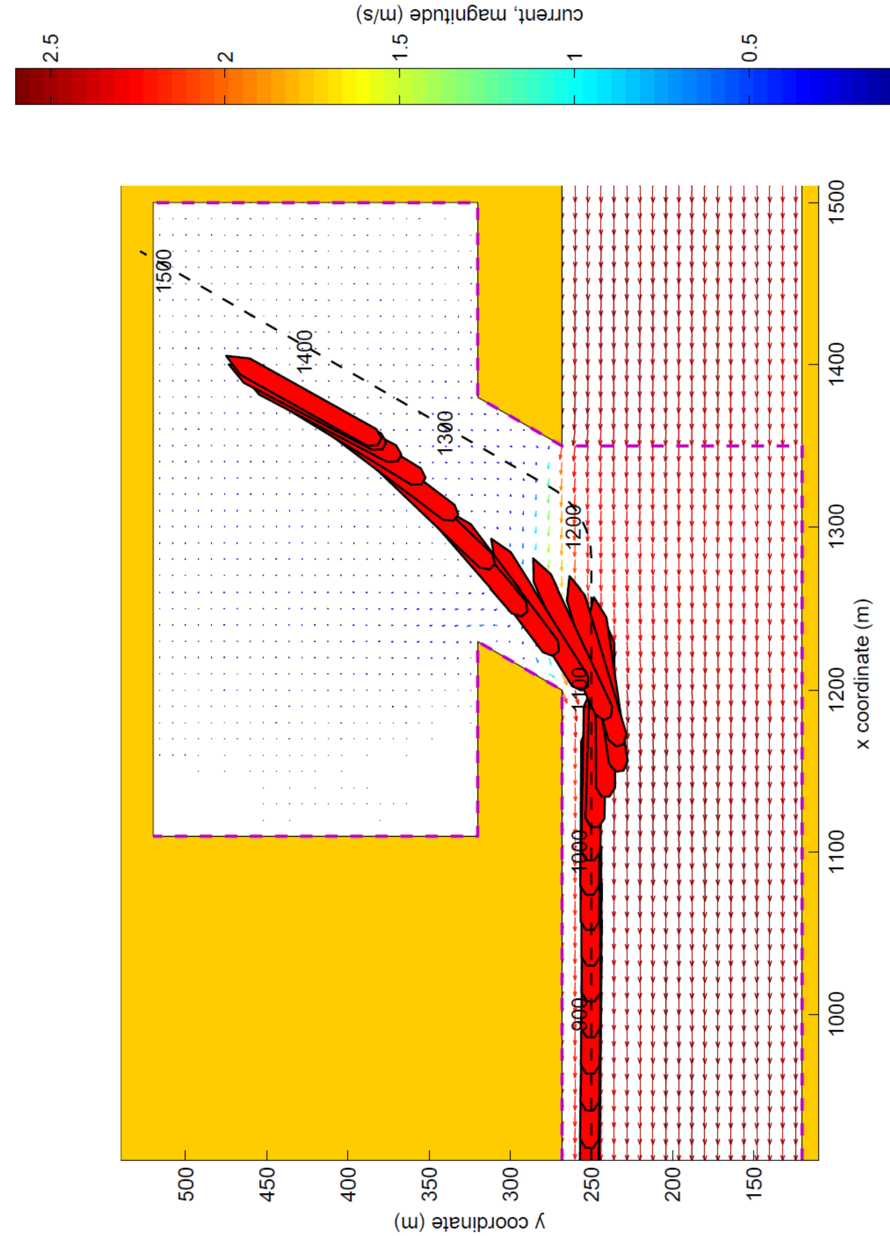
- Figure C: Data plots with the longitudinal ship speed (m/s), transverse ship speed (m/s) and the rate of turn (deg/s) plotted as a function of the travelled distance (m). The track distance plotted against the time (min) is also included. The first three plots give an impression of the speed of the ship during the run. These plots can be used to check whether the stopping criteria are met. The last plot can be used to determine the manoeuvring time of the ship.

In every figure the layout number is indicated. An overview of the different layouts used in the simulation study is given in table 3-2.



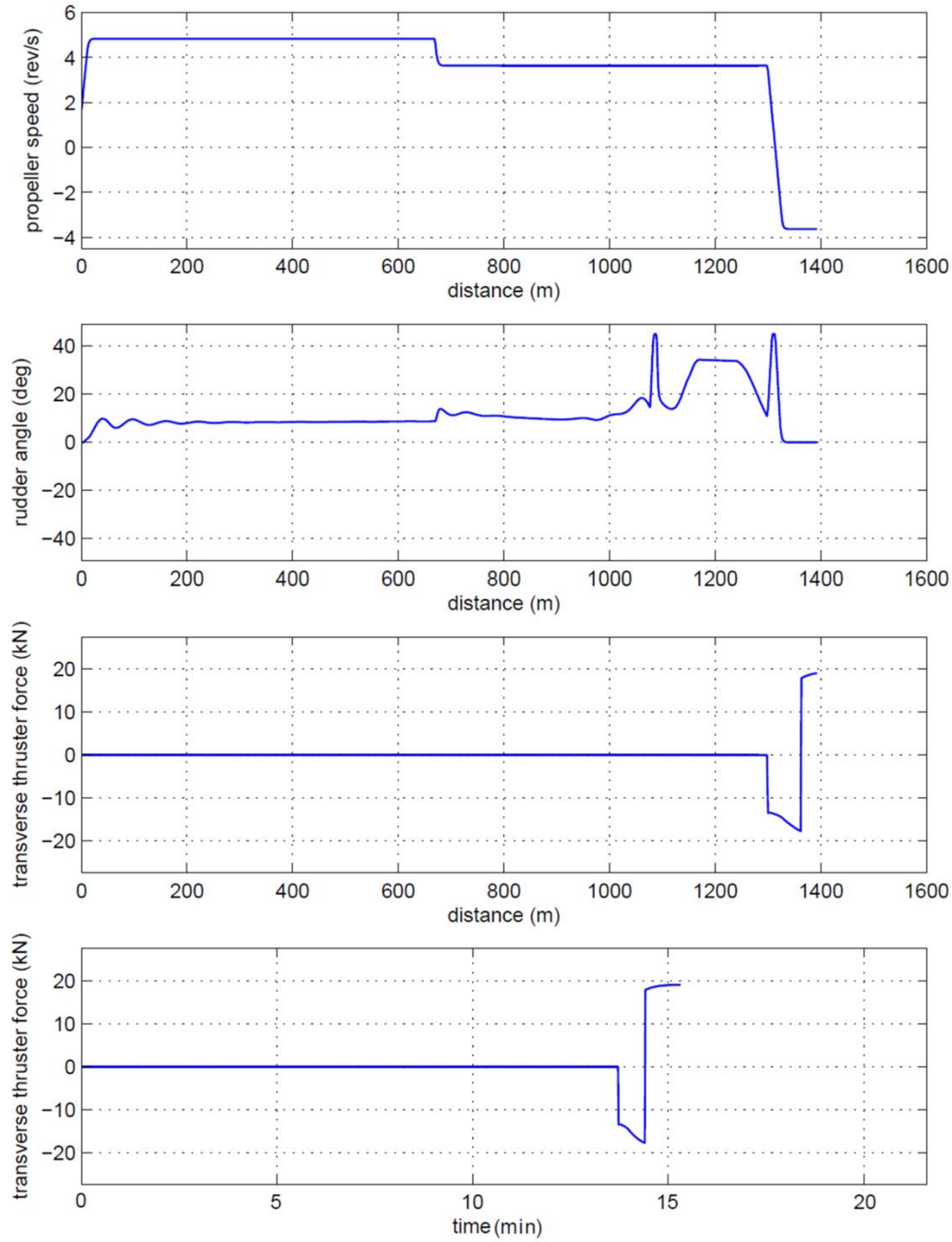
Overview plot: Implemented track (dashed black line), bank suction lines (dashed purple lines), ship snapshots, water depth and current. Close−up plot of port entrance: Implemented track (dashed black line) swept path (blue area) and ship snapshots.	Layout nr. 6	Current: 2.5 m/s
	SHIPMA 7.4.2	
Buckers, M.D. (2017). TU Delft MSc Thesis in cooperation with MARIN.	Run 37	Figure A1

Figure 4-1: Example of track plots figure A1.



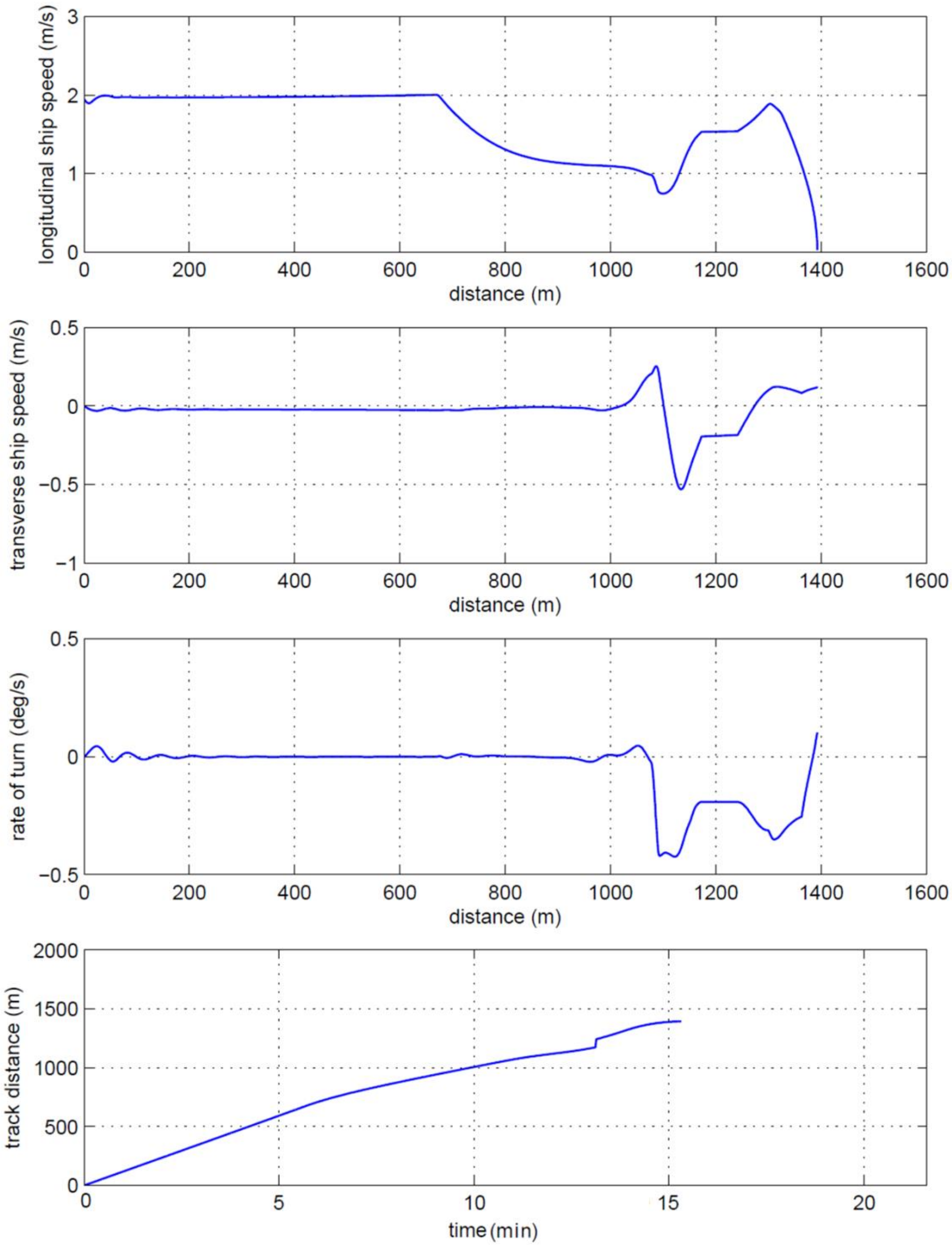
Close−up plot around port: Implemented track (dashed black line), bank suction lines (dashed purple lines), current and ship snapshots.	Layout nr. 6	Current: 2.5 m/s
	SHIPMA 7.4.2	
Buckers, M.D. (2017). TU Delft MSc Thesis in cooperation with MARIN.	Run 37	Figure A2

Figure 4-2: Example of track plot figure A2.



Data plots: Propeller speed, rudder angle, transverse thruster force plotted against the distance and transverse thruster force plotted against the time.	Layout nr. 6	Current: 2.5 m/s
	SHIPMA 7.4.2	
Buckers, M.D. (2017). TU Delft MSc Thesis in cooperation with MARIN.	Run 37	Figure B

Figure 4-3: Example of data plot figure B.



Data plots: Longitudinal ship speed, transverse ship speed, rate of turn plotted against the distance and the track distance plotted against the time.	Layout nr. 6	Current: 2.5 m/s
	SHIPMA 7.4.2	
Buckers, M.D. (2017). TU Delft MSc Thesis in cooperation with MARIN.	Run 37	Figure C

Figure 4-4: Example of data plot figure C.

4.2 Run results assessment

In the sections 4.2.1 to 4.2.10 the assessment of the SHIPMA runs are discussed. In every section a group of runs is discussed that contain similarities. For these groups the peculiar aspects of the results are expounded. The assessment of each run is presented in a tabular form. An example of such a run assessment table is shown in table 4-1. In columns 1 to 6 important input characteristics are shown to give an impression of the particular run. A complete overview of all the input values, which are characterising a run, is presented in appendix F. The track plots and data plot of each run are shown in appendix G. In columns A to E, the assessment of the different criteria is presented. Each column is explained in more detail below.

Table 4-1: Example of run assessment in tabular form.

1	2	3	4	5	6	A		B			C		D	E
Run nr.	Dir	Man	Uc (m/s)	Angle (deg)	Lateral approach distance (m)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
						Waterway	Port and entrance	Steering	Bow Thruster	Stopping	Time	Speed Peak (m/s)		
X	Up	In	1.0	90	18	+	+/-	+	+/-	-	2-3	1.2	100	+

1. The number of the run.
2. Sailing direction of the ship. ‘Up’ represents a ship that is sailing in upstream direction on the waterway. ‘Down’ indicates a situation where the ship is sailing in downstream direction.
3. Type of manoeuvre. ‘In’ represents a forward manoeuvre into the port. ‘Out’ indicates a forward manoeuvre out of the port. ‘Stop’ indicates a stopping manoeuvre on the waterway, in these runs the ship is sailing in downstream direction and is stopping just downstream of the port entrance. ‘Back In’ indicates a backward manoeuvre through the port entrance; this manoeuvre starts where the stopping manoeuvre ended.
4. The flow velocity (U_c) in the waterway.
5. The angle between the downstream corner of the port entrance and the waterway. See figure 1-2 for how the entrance angle is defined.
6. The lateral distance between the hull of the ship and the port entrance at the starting point of a manoeuvre. This lateral distance is illustrated in figure 3-17.

A. Assessment of manoeuvring space on the waterway, around the port basin and port entrance.
B. Assessment of the controllability. The steering criteria (safety index), use of bow thruster and the stopping manoeuvre are assessed in these columns.
C. Assessment of the required manoeuvring time for a manoeuvre, the time is given in a range of 1 minute. Also the longitudinal speed peak of the ship during the manoeuvre is indicated in order to give an impression of the ship speed during the manoeuvre.
D. Assessment of the required entrance width for a safe manoeuvre; the required entrance width equals the swept path plus the safety margins on both sides of the swept path, see figure 3-20.
E. In column E the total assessment of the run is shown.

If a criterion, presented in section 3.4 is met, it is assessed as sufficient. If it is not satisfied, this aspect is assessed as critical or insufficient. The used symbolism for the criteria is presented in table 4-2.

Table 4-2: Overview of used symbolism for the criteria.

Rating	Score	Manoeuvring space waterway
Sufficient	+	Distance to banks > 1B
Critical	+/-	Distance to banks < 1B, no grounding
Insufficient	-	Grounding at banks

Rating	Score	Manoeuvring space in port basin and around entrance
Sufficient	+	Distance to banks > 0.5B
Critical	+/-	Distance to banks < 0.5B, no grounding
Insufficient	-	Grounding at entrance banks

Rating	Score	Controllability, steering
Sufficient	+	Safety index smaller than or equal to 1
Insufficient	-	Safety index larger than 1

Rating	Score	Controllability, bow thruster
Sufficient	+	Maximum bow thruster force of 19 kN (70%), not longer than 1 minute continuously
Critical	+/-	Maximum bow thruster force of 19 kN slightly longer than 1 minute continuously
Insufficient	-	Bow thruster force larger than 19 kN. Or equal to 19 kN, but significantly longer than 1 minute continuously

Rating	Score	Controllability, stopping
Sufficient	+	Transverse speed < 0.3 m/s and rotational speed < 0.3
Critical	+/-	Transverse speed 0.3 – 0.5 m/s and/or rotational speed 0.3 -0.5 m/s
Insufficient	-	Transverse speed > 0.5 m/s and/or rotational speed > 0.5 m/s

Rating	Score	Manoeuvring time
Sufficient	+	Manoeuvring time < 5 minutes
Critical	+/-	Manoeuvring time 5 - 6 minutes
Insufficient	-	Manoeuvring time > 6 minutes

Rating	Score	Total run assessment
Sufficient	+	Safety of the run is assessed as sufficient
Critical	+/-	Safety of the run is assessed as critical
Insufficient	-	Safety of the run is assessed as insufficient

Rating	Score	Manoeuvring time
-	X	This aspect is not relevant for the particular run

When all the criteria are met, the total run is assessed as sufficient. In case not all the criteria are satisfied, it is possible that the total run is assessed as sufficient, critical or insufficient. In table 4-3 examples of the total run assessments are given for different combinations of assessed aspect. Only the combinations that occur in the sections 4.2.1 to 4.2.10 are shown in table 4-3 and a brief explanation is given why a total assessment is chosen. The assessments are discussed in more detail in sections 4.2.1 to 4.2.10. In general, it is chosen to assess a run with insufficient in case the manoeuvre is not sufficiently safe. Moreover, modifying these run to obtain a safer run will change the output significantly. In table 4-3 only the assessment for forward manoeuvre into and out of the port are shown. The assessments of the runs that consist of a backward manoeuvre into the port are explained in section 4.2.4.

Table 4-3: Overview of different total run assessments for forward manoeuvres into or out of the port.

	Manoeuvring space		Controllability			Manoeuvre	Total
	Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	
1	+	+	+	+	+	+	+
2	+	+	+	+/-	+	+	+
3	+	+	+	+	+	+/-	+
4	+/-	+	+	+	+	+	+/-
5	+	+/-	+	+	+	+	+/-
6	+/-	+/-	+	+	+	+	-
7	-	+	+	+	+	+	-
8	+	-	+	+	+	+	-
9	+	+	+	+	-	+	-
10	+	+	+	+	+	-	-

1 All the criteria are met and therefore the total assessment is sufficient.

2 For the forward manoeuvres into the port the bow thruster was only used during the stopping manoeuvre in the port basin. Using slightly less bow thruster capacity will only result in a slightly different swept path in the port basin. Therefore, a critical assessment for the bow thruster is actually not affecting the safety of a run, whereas a smaller use is also sufficient to stop safely. Furthermore, using less bow thruster during the stopping manoeuvre is not affecting the run output of the other parts of the run. This aspect is explained in more detail with an example in section 4.2.1.

3 A slightly larger manoeuvring time is not problematic when all the other criteria are met. The allowed manoeuvring time depends on the traffic intensity on the waterway. This can be different for each local situation. Hence, the used manoeuvring time criterion for this research is not a very accurate criterion. For this research a maximum manoeuvring time of 5 minutes was assumed (MARIN, personal communication, 2017). Moreover, a slightly larger manoeuvring time will not have a significant effect on the run results. Therefore, a run with a critical assessment for the manoeuvring time is still assessed as sufficiently safe.

4 When exceeding only the manoeuvring space criterion on the waterway without running aground at the waterway banks, then this run is assessed as critical. For these runs only a slightly larger waterway width (of several meters) is needed to satisfy the manoeuvring space criterion. This small adjustment will not have a significant influence on the output of a run. However, the run is close to running aground at one of the waterway banks. Therefore, this run is assessed as critical.

5 When exceeding only the manoeuvring space criterion in the entrance without running aground at the entrance banks, then this run is assessed as critical. For these runs only a slightly larger entrance width (of several meters) is needed to satisfy the manoeuvring space criterion. This small adjustment will not have a significant influence on the output of a run. However, the run is close to running aground at one of the entrance banks. Therefore, this run is assessed as critical.

6 In case both manoeuvring space criteria are assessed as critical (see point 4 and 5), the run is assessed as insufficient. If the waterway and entrance width are assessed as critical, this indicates that it is hard to perform a correct manoeuvre through the entrance in combination with the available waterway width. Therefore, these situations are assessed as insufficient.

7, 8 Running aground at a bank is assessed as insufficient. Groundings can damage the ships and banks and this is clearly undesired. As a consequence the total assessment is insufficient.

9 When the stopping criterion is assessed as insufficient, it indicates that there is no sufficient control of the ship in the port basin. This can result in dangerous situations. Hence, for these situations the run is assessed as insufficient.

10 In case the manoeuvring time is assessed as insufficient, then the manoeuvre causes too much hinder to through going traffic. This can result in dangerous situations or undesired congestion on the waterway. Hence, the total run assessment is insufficient when the manoeuvring time is assessed as insufficient. This aspect is explained in more detail with an example in section 4.2.2.

4.2.1 Assessment of runs 1-8

Runs 1 to 8 are conducted for the narrow waterway layout (48 meters wide) with an entrance width of 150 meters, a length of 20 meters and the angle of 90 degrees between the entrance and waterway. The lateral approach distance for every manoeuvre into the port equals approximately 12 meters. Note that this is equal to the beam of the (mathematical) ship (model). The variable input parameters used for these runs are the sailing direction, the type of manoeuvre and the flow velocity.

Table 4-4: Assessment of runs 1-8.

Run nr.	Dir	Man	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)		
1	Up	In	1.0	+/-	+	+	+/-	+	2-3	1.5	67	+/-
2	Up	In	2.5	+/-	+	+	+	+	1-2	1.4*	91	+/-
3	Down	In	1.0	+/-	+/-	+	+	+	2-3	2.2	140	-
4	Down	In	2.5	+/-	-	+	-	-	1-2	3.6	199	-
5	Up	Out	1.0	+	+	+	+	X	3-4	2.0**	84	+
6	Up	Out	2.5	+	+	+	+	X	3-4	1.0	101	+
7	Down	Out	1.0	+/-	+	+	+	X	4-5	2.0	76	+/-
8	Down	Out	2.5	+/-	+	+	+	X	2-3	3.0**	107	+/-

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

** The speed peak is at the end of the turning manoeuvre. After this end point the speed increases further.

The narrow waterway induces that in most of the runs the manoeuvring space on the waterway is insufficient to satisfy the space criterion of 1B. However, for most runs still several meters between the ship's hull and the banks are available. Although runs 1, 2, 7 and 8 are assessed as critical, they can be compared to other runs assessed as sufficient. However, it should be taken into consideration that these runs are not completely safe. By widening the waterway with several meters, this manoeuvring space criterion is satisfied.

Run 1 is using 70 percent of the bow thruster capacity slightly longer than 1 minute during the stopping manoeuvre in the port basin. In figure 4-5 the track plot of run 1 is shown, the ship snapshots are coloured red. This exceeding of the bow thruster criterion can be avoided by using slightly less bow thruster during the stopping manoeuvre. As a consequence, the position of the ship when using no bow thruster during the stopping manoeuvre is slightly different. This is illustrated in figure 4-5. For the ship snapshots coloured green, no bow thruster is used. The stopping manoeuvre without bow thruster is not problematic; the only difference is that the manoeuvre with use of the bow thruster is slightly closer to the implemented track.

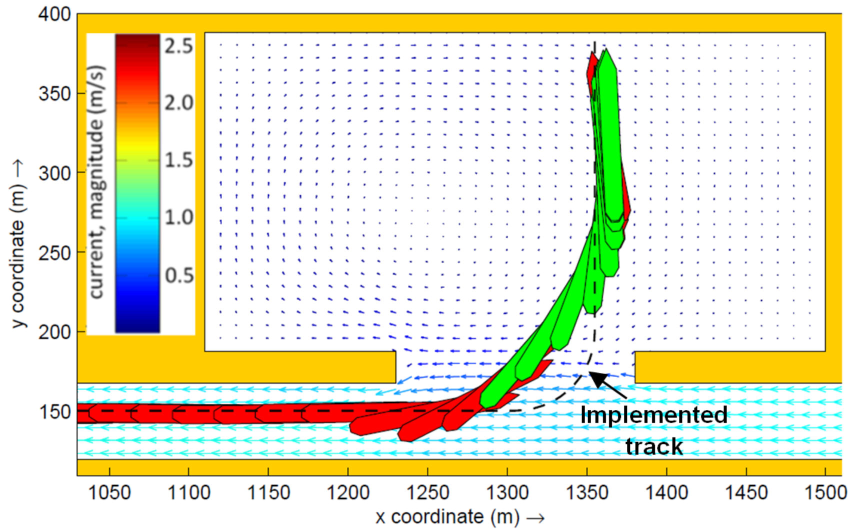


Figure 4-5: Track plot of run 1. Ship snapshots (red) of run 1 and ship snapshots (green) when using no bow thruster during the stopping manoeuvre are indicated.

Only for runs 3 and 4 the space around the entrance is not sufficient. These arrivals when sailing downstream required much space. The track plot close-ups around the entrance of run 3 and 4 are shown in figure 4-6. The ships are forced to the downstream entrance bank by the current. Due to the large ship speed a larger turning area is required. Run 3 requires a width of 147 meters in the entrance. This means that when the run is shifted, just enough space is available. However, it is difficult to perform such a run properly; a perfect timing is required in order to navigate safely through the entrance. During the simulation study it was impossible to execute run 4 safely. Besides the manoeuvring space criteria, also the bow thruster and stopping criteria are assessed as insufficient for run 4. These two runs show that for larger flow velocities than 1.0 m/s, an entrance width of 150 meters is too small for a forward manoeuvre sailing in downstream direction into the port basin in combination with this narrow waterway layout. A possible solution to improve these arrivals sailing downstream is a sidewards manoeuvre into the port. This is shown in section 4.2.9. In case the entrance length is small these sidewards manoeuvres can provide a more efficient result.

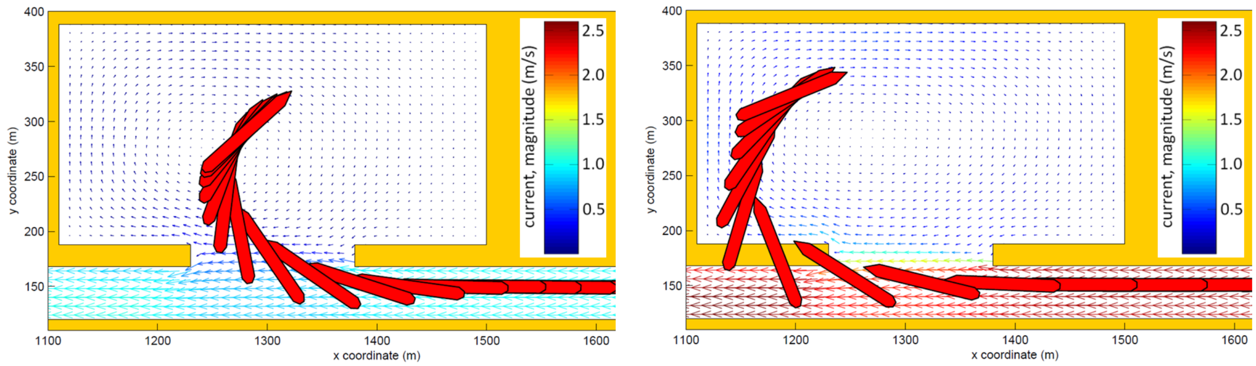


Figure 4-6: Track plot of run 3 (left figure) and run 4 (right figure).

The start speed for run 4 is circa 3.5 m/s. This larger speed was chosen in order to keep a relative speed with respect to the water of circa 1.0 m/s. However, for the other runs in downstream direction with a large flow velocity, a run start speed of 2.0 m/s was contained. It appeared that the different starting velocities do not affect the manoeuvres into the port. The travel time on the waterway is long enough to adjust a run in such a way that no differences, between a starting velocity of 2.0 or 3.5 m/s, are visible around the port entrance.

The simulation results show that a waterway width of 48 meters, in combination with an entrance width of 150 meters and length of 20 meters, is critical for providing safe navigation into the port and out of the port in downstream direction. Only manoeuvres out of the port in upstream direction are sufficiently safe.

4.2.2 Assessment of runs 9-21

The runs 9 to 21 are conducted for the wide waterway layout (148 meters wide) with an entrance width of 150 meters, a length of 60 meters and an angle of 90 degrees. Different lateral approach distances are used for the turning manoeuvres into the port. The other variable input parameters are the sailing direction, the type of manoeuvre and flow velocity.

Table 4-5: Assessment of runs 9-21.

Run nr.	Dir	Man	Uc (m/s)	Lateral approach distance (m)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
					Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)		
9	Up	In	1.0	121	+	+	+	+	+	4-5	2.0	47	+
10	Up	In	1.0	74	+	+	+	+	+	3-4	1.5	48	+
11	Up	In	1.0	12	+	+	+	+	+	5-6	1.3	60	+
12	Up	Out	1.0	X	+	+	+	+	X	4-5	3.2	50	+
13	Up	In	2.5	124	+	+	+	+	+	3-4	2.0*	86	+
14	Up	In	2.5	76	+	+	+	+	+	2-3	2.0*	83	+
15	Up	In	2.5	12	+	+	+	+	+	3-4	1.4	90	+
16	Up	Out	2.5	X	+	+	+	+	X	3-4	3.6	77	+
17	Down	In	1.0	122	+/-	+	+	+	+	6-7	2.2*	52	-
18	Down	In	1.0	74	+	+	+	+	+	2-3	2.4	65	+
19	Down	In	1.0	12	+	+	+	+	+	2-3	2.1	105	+
20	Down	In	2.5	97	+/-	+/-	+	+	+	4-5	3.2	157	-
21	Down	In	2.5	22	+	-	+	+	+	2-3	3.0	196	-

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

Most of the runs are satisfying all the safety criteria. Runs 9 to 12 are shown in figure 4-7. The manoeuvring time of run 11 is exceeded by only a few seconds. Therefore, this runs is assessed as sufficient.

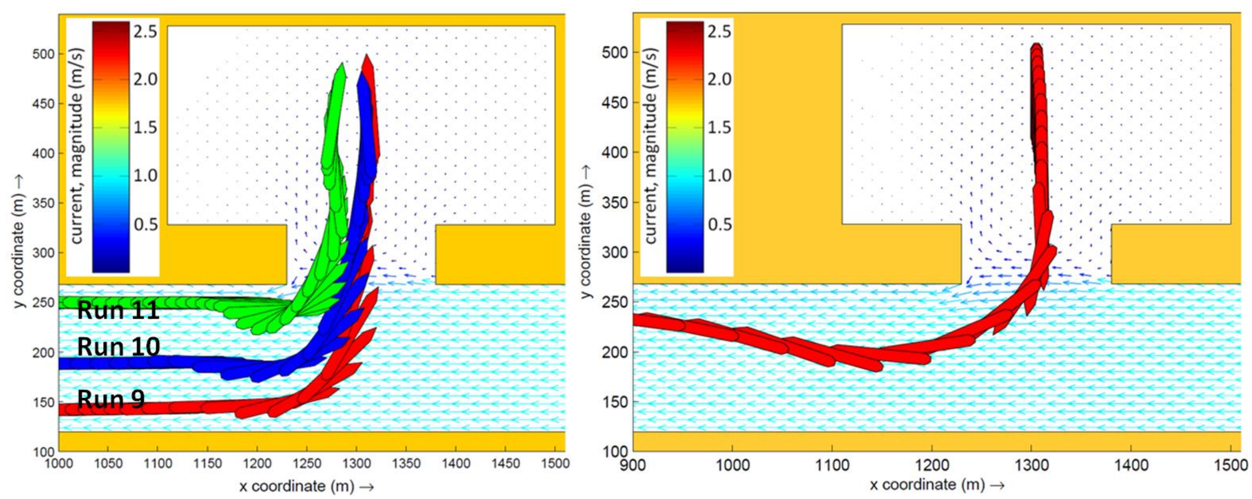


Figure 4-7: Track plots of arrival runs 9, 10 and 11 (left) and track plot of departure run 12 (right).

Although a large ship speed is used for the manoeuvre of run 17, the manoeuvring time exceeds the criterion of 5 minutes. This is because of the long distance needed in order to turn the ship in the desired direction, see figure 4-8. For this run the manoeuvring space criterion on the waterway is not met. The stern of the ship comes slightly too close, 0.8B instead of 1B, to the bank opposite to the port entrance. This can be solved by shifting the entire run 2 meters in the port entrance direction. This will result in a slightly larger required entrance width. However, the manoeuvre on the waterway requires too much space and time. Therefore, this manoeuvre is not desired.

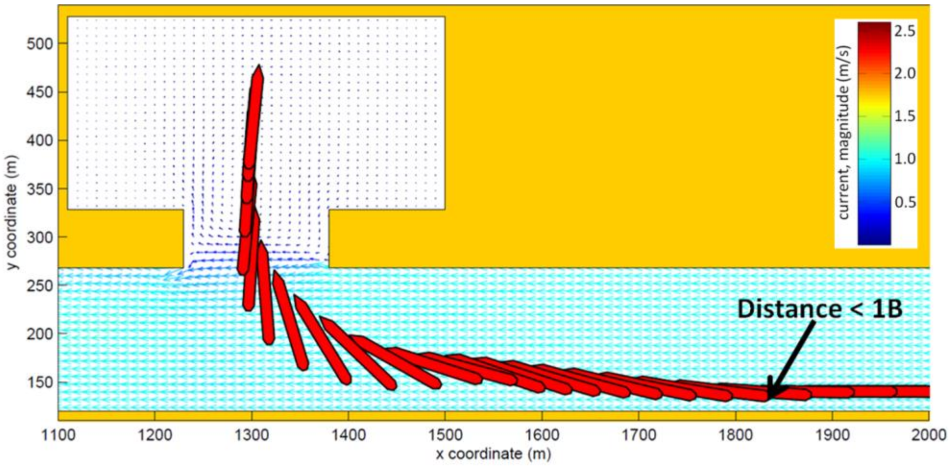


Figure 4-8: Track plot run 17.

The track plots of runs 20 and 21 are shown in figure 4-9. Run 20 requires slightly too much space on the waterway and around the entrance. In run 21 the ship runs aground at the downstream entrance bank. In addition, for this run the distance between the ship and the upstream entrance bank is too small. Runs 20 and 21 have a large speed peak, which is undesired. Moreover, the used manoeuvring area on the waterway for run 20 is significant and undesired. Due to these aspects, run 20 and 21 are assessed as insufficient.

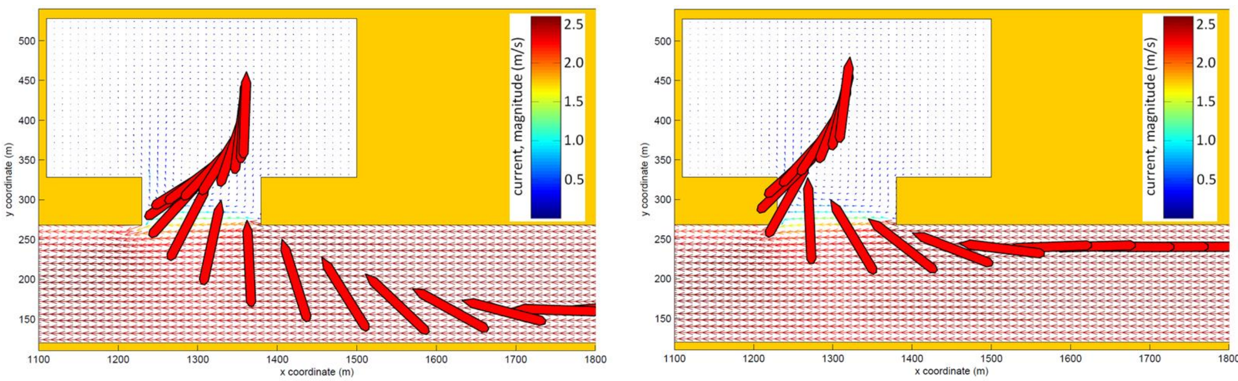


Figure 4-9: Track plots of run 20 (left) and run 21 (right).

The simulation results of runs 9 to 21 points to the fact that the arrivals when sailing downstream are more difficult compared to the arrivals sailing in upstream direction. This is in agreement with the conclusions from chapter 2. Furthermore, it can be concluded that arrivals when sailing downstream with a flow velocity of 2.5 m/s are not possible for an entrance width of 150 meters and a wide waterway.

4.2.3 Assessment of runs 22-39

The runs 22 to 39 are all runs in which a ship is manoeuvring into the port. The runs are conducted for the wide waterway layout with an entrance width of 150 meters and an entrance length of 60 meters. The lateral approach distance is for every run about 12 meters. The variable input parameters for these runs are the flow velocity, entrance angle and the sailing direction of the ship.

Table 4-6: Assessment of runs 22-39.

					Manoeuvring space		Controllability			Manoeuvre			
Run nr.	Dir	Man	Uc (m/s)	Angle (deg)	Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)	$W_{e,req}$ (m)	Total
22	Down	In	1.0	32.6	+	+	+	+	+	2-3	2.7	84	+
23	Down	In	1.0	47.7	+	+	+	+	+	2-3	2.6	74	+
24	Down	In	1.0	60.0	+	+	+	+	+	2-3	2.5	84	+
25	Down	In	1.0	120.0	+	+	+	+	+	2-3	2.2	137	+
26	Down	In	1.0	132.3	+	+	+	+	+	2-3	1.5	139	+
27	Down	In	1.0	147.4	+	+/-	+	+	+	2-3	1.5	151	+/-
28	Up	In	1.0	32.6	+	+	+	+	+	4-5	1.1	107	+
29	Up	In	1.0	47.7	+	+	+	+	+	4-5	1.2	96	+
30	Up	In	1.0	60.0	+	+	+	+	+	4-5	1.1	89	+
31	Up	In	1.0	120.0	+	+	+	+	+	3-4	2.1	54	+
32	Up	In	1.0	132.3	+	+	+	+	+	2-3	2.2	54	+
33	Up	In	1.0	147.4	+	+	+	+	+	2-3	2.3	62	+
34	Up	In	2.5	32.6	+	+	+	+	+	3-4	1.6*	138	+
35	Up	In	2.5	47.7	+	+	+	+	+	3-4	1.6*	129	+
36	Up	In	2.5	60.0	+	+	+	+	+	3-4	1.6*	118	+
37	Up	In	2.5	120.0	+	+	+	+/-	+	3-4	1.9	79	+
38	Up	In	2.5	132.3	+	+	+	+/-	+	3-4	2.0	80	+
39	Up	In	2.5	147.4	+	+	+	+/-	+	3-4	1.8	87	+

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

Only the bow thruster criterion for runs 37, 38 and 39 is critical. However, the bow thruster is only used during the stopping manoeuvres, thus changing the bow thruster settings will not affect the other parts of the run. Sufficient extra manoeuvring space is available in the basin. Therefore, it is possible to reduce the use of the bow thruster. For this reason, these runs are assessed as sufficient. In figure 4-10 the track plot of run 38 is shown.

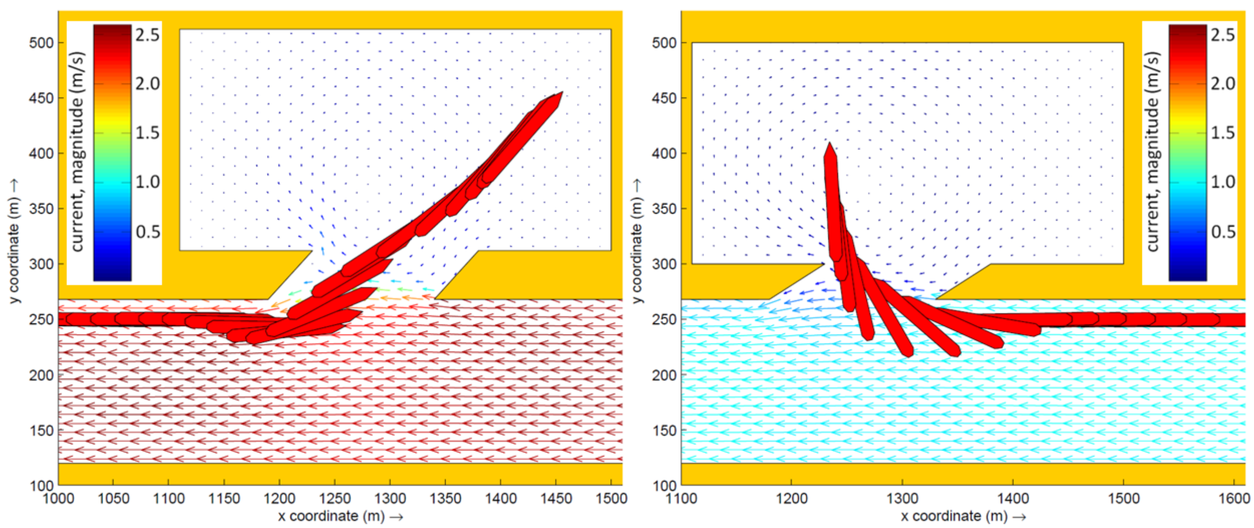


Figure 4-10: Track plots of run 38 (left) and run 27 (right).

For run 27, shown figure 4-10, in the entrance width is slightly too small in order to satisfy the manoeuvring space criterion. This does not make a large difference compared to a situation where the entrance is 1 meter larger. Although run 27 is assessed as critical, the run is suitable for comparisons with other runs.

It should be mentioned that the peak speeds for the runs 22, 23 and 24 are larger than 2.5 m/s. It is possible to conduct these simulations for these large speeds, because of the small angles. When using these run results, it should be taken into consideration that large ship speeds are used for these manoeuvres. It should be noted that a real skipper can prefer smaller ship speeds in certain situations. For example, when the visibility around the entrance is limited or the orientation of the ship with respect to the entrance and waterway axis is difficult.

4.2.4 Assessment of runs 40-48

Runs 40 to 48 are all runs in which the ship is manoeuvring backward into the port. The runs exist of two parts:

- Part a: Ship is sailing in downstream direction and stops downstream of the port entrance.
- Part b: Ship is sailing backward into the port. Hence, the backward manoeuvre is performed in upstream direction.

All the criteria are assessed separately for part a and b. The total assessment is given for the entire run (part a and b together). The lateral approach distance for the backward manoeuvres is 12 meters. The runs are all conducted for the wide waterway layout. The variable parameters for these runs are the flow velocity and the angle between the entrance and the waterway.

Table 4-7: Assessment of runs 40-48.

Run nr.	Dir	Man	Uc (m/s)	Angle (deg)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
					Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)		
40a	Down	Stop	1.0	90.0	+	X	+	+	+	2-3	1.6*	X	+
40b	Up	Back In	1.0	90.0	+	+	+	-	+	6-7	-0.9	88	
41a	Down	Stop	1.0	120.0	+	X	+	+	+	2-3	1.6*	X	+
41b	Up	Back In	1.0	120.0	+	+	+	-	+	5-6	-0.9	70	
42a	Down	Stop	1.0	132.3	+	X	+	+	+	2-3	1.6*	X	+
42b	Up	Back In	1.0	132.3	+	+	+	-	-	5-6	-0.9	71	
43a	Down	Stop	1.0	147.4	+	X	+	+	+	2-3	1.6*	X	+
43b	Up	Back In	1.0	147.4	+	+	+	+/-	-	6-7	-0.9	83	
44a	Down	Stop	2.0	90.0	+	X	+	+	+	1-2	2.3*	X	+
44b	Up	Back In	2.0	90.0	+	+	+	-	+	6-7	-0.9	97	
45a	Down	Stop	2.0	120.0	+	X	+	+	+	1-2	2.3*	X	+
45b	Up	Back In	2.0	120.0	+	+	+	-	+	5-6	-0.9	87	
46a	Down	Stop	2.0	132.3	+	X	+	+	+	1-2	2.3*	X	+
46b	Up	Back In	2.0	132.3	+	+	+	-	+	6-7	-0.9	88	
47a	Down	Stop	2.0	147.4	+	X	+	+	+	1-2	2.3*	X	+
47b	Up	Back In	2.0	147.4	+	+	+	-	+	6-7	-0.9	98	
48a	Down	Stop	1.5	120.0	+	X	+	+	+	1-2	1.9*	X	+
48b	Up	Back In	1.5	120.0	+	+	+	-	+	5-6	-1.0	78	

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

When adding the manoeuvring time of the a-part of the run to the time of the b-part of the run, all the runs are exceeding the criterion of 5 minutes. However, the used width on the waterway when sailing backward into the port is small. This is visible for both backward runs displayed in figure 4-11. As a consequence, the hinder of the trough going traffic on the waterway is small. Hence, exceeding the manoeuvring time criterion is less problematic compared to a manoeuvre in which a large waterway width is used.

Another peculiarity is that for almost every run the bow thruster criterion is assessed as insufficient, only for run 43b a critical assessment is given. During the simulations the use of bow thruster was not limited for these runs in order to give the ships enough steering capacity to turn into the port, because the bow thruster is the only steering tool when sailing backwards. For these manoeuvres the propeller revolutions are astern and therefore using the rudder has no effect. By allowing the ships to use 100% of the bow thruster capacity, no margin in the steering capacity is left. SHIPMA simulations for backward manoeuvres and a maximum use of the bow thruster capacity will still provide reliable results (MARIN, personal communication, 2017).

The stopping manoeuvre of run 42 and 43 is assessed as insufficient; this is because the rate of turn is larger than 0.5 deg/s. However, these two stopping manoeuvres are not unsafe. The large rotational velocity is due to the fact that the ships are turning in order to continue with forward navigation. In the simulation study the arrivals were stopped when the longitudinal ship speed equals 0.0 m/s in the basin. At this moment the ships were still turning, this is displayed for Run 42 in figure 4-11.

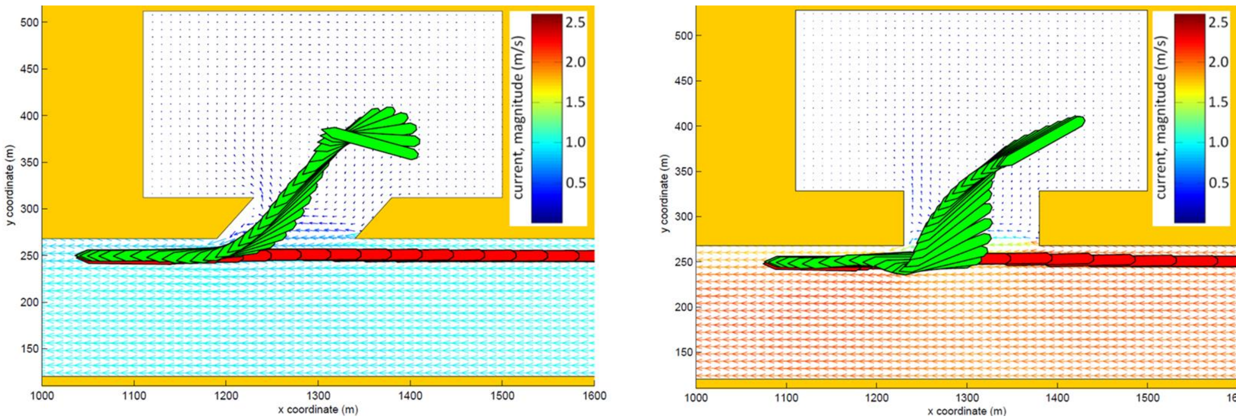


Figure 4-11: Track plots of run 42 (left) and run 44 (right). Part a (red) and b (green) of the runs are indicated.

All the backward runs are assessed as sufficient, because for these manoeuvres it is allowed to use 100% of the bow thruster capacity during a run. Furthermore, it is assumed that exceeding the manoeuvring time criterion is less problematic, because only a small waterway width is required for these manoeuvres.

The current along the entrance causes a moment opposite to the desired turning moment of the ship. This principle is explained in more detail in appendix B. Therefore, these backward manoeuvres are difficult. For flow velocities of 2.0 m/s, the ships have to manoeuvre almost sidewards through the entrance; this is shown in figure 4-11.

The maximum flow velocities, for which runs are conducted, are 2.0 m/s. It was not possible to conduct a backward manoeuvre for a flow velocity of 2.5 m/s. The relative water velocity is in this case at least 3.0 m/s, assuming a minimum ground speed of 0.5 m/s. As described in section 3.3.1, for relative water velocities larger than 3.0 m/s the available bow thruster force is 0 kN.

These backward manoeuvres can be compared to each other, because they are all set up in the same manner. The criteria are met, except for the use of bow thruster and manoeuvring time. However, this holds for every run. Furthermore, as described above, backward SHIPMA simulations with a maximum use of bow thruster capacity perform reliable results (MARIN, personal communication, 2017).

4.2.5 Assessment of runs 49-50

Run 49 and 50 are conducted for the wide waterway layout with a port entrance width of 150 meters, an entrance length of 60 meters and an angle of 120 degrees. In both runs the ships are sailing in upstream direction and make a manoeuvre into the port. The lateral approach distance is 12 meters. The only difference between these runs is the flow velocity. For both runs all the criteria are met. Run 49 and 50 are illustrated in figure 4-12.

Table 4-8: Assessment of runs 49-50.

Run nr.	Dir	Man	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)		
49	Up	In	1.5	+	+	+	+	+	3-4	2.0	63	+
50	Up	In	2.0	+	+	+	+	+	3-4	1.9	71	+

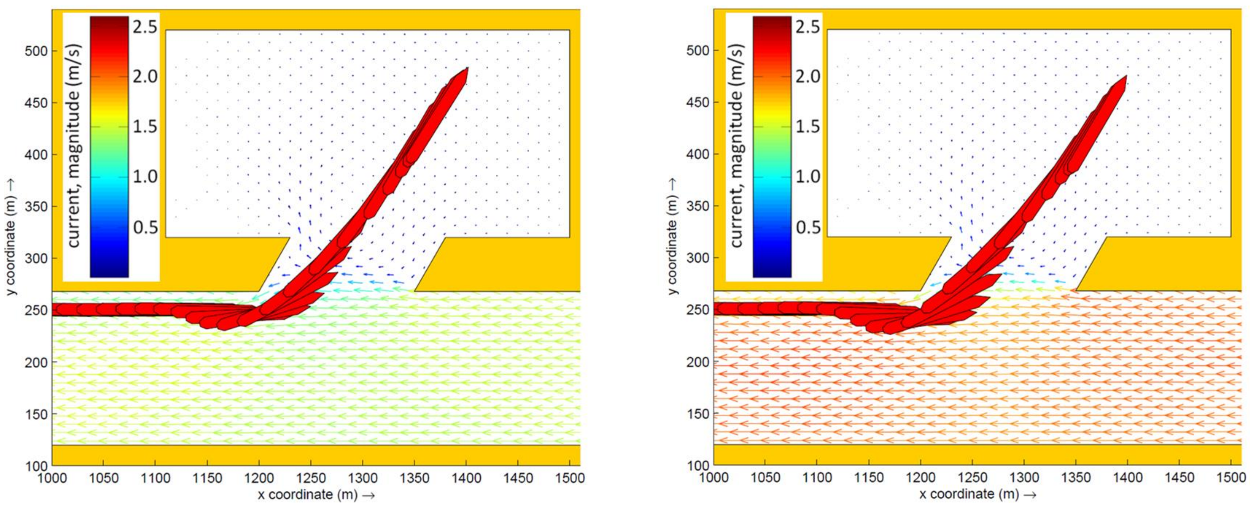


Figure 4-12: Track plots of run 49 (left) and run 50 (right).

4.2.6 Assessment of runs 51-54

The runs 51 to 54 are conducted for the wide waterway layout with a port entrance width of 150 meters, a length of 120 meters and an angle of 120 degrees. The lateral approach distance is 12 meters. Forward and backward manoeuvres are used. The backward runs are again split into an a-part and b-part. In addition, flow velocities of 1.0, 2.0 and 2.5 m/s are used.

Table 4-9: Assessment of runs 51-54.

Run nr.	Dir	Man	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)		
51	Up	In	1.0	+	+	+	+	+	3-4	1.4	54	+
52	Up	In	2.5	+	+	+	+	+	3-4	1.4	82	+
53a	Down	Stop	1.0	+	+	+	+	+	2-3	1.6*	X	+
53b	Up	Back In	1.0	+	+	+	-	+	5-6	-0.9	70	
54a	Down	Stop	2.0	+	+	+	+	+	1-2	2.3*	X	+
54b	Up	Back In	2.0	+	+	+	-	+	6-7	-0.9	94	

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

Run 51 and 52 satisfy all the criteria. Run 53 and 54 are again backward manoeuvres in which the manoeuvring time and the bow thruster use are exceeding the criteria. The same holds for these two runs as explained for the runs 40 up to 48 in section 4.2.4. The track plots of run 52 and 54 are visible in figure 4-13.

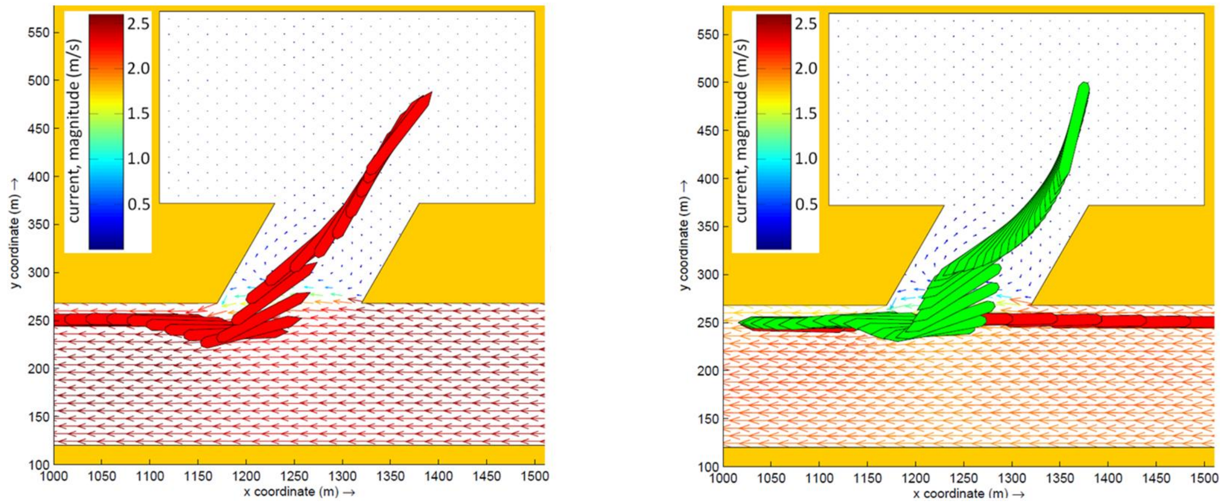


Figure 4-13: Track plots of run 52 (left) and run 54 (right). Part a (red) and b (green) of run 54 are displayed.

4.2.7 Assessment of runs 55-58

Runs 55 to 58 are conducted for the wide waterway layout with an entrance width of 150 meters, a length of 19 meters and an angle of 120 degrees. The lateral approach distance is 12 meters. Forward and backward manoeuvres were performed. The backward runs are again split into an a-part and b-part. In addition, flow velocities of 1.0, 2.0 and 2.5 m/s were used.

Table 4-10: Assessment of runs 55-58.

Run nr.	Dir	Man	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time (min)	Speed peak (m/s)		
55	Up	In	1.0	+	+	+	+	+	2-3	1.6	55	+
56	Up	In	2.5	+	+	+	+	+	2-3	1.6	81	+
57a	Down	Stop	1.0	+	X	+	+	+	1-2	1.6*	X	+
57b	Up	Back in	1.0	+	+	+	-	+	6-7	-0.9	71	
58a	Down	Stop	2.0	+	X	+	+	+	1-2	2.3*	X	+
58b	Up	Back in	2.0	+	+	+	-	+	5-6	-0.9	86	

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

Run 55 and 58 satisfy all the criteria. For run 57 and 58 the same explanation holds as for runs 40 up to 48, 53 and 54. Figure 4-14 shows the track plots of run 56 and 58.

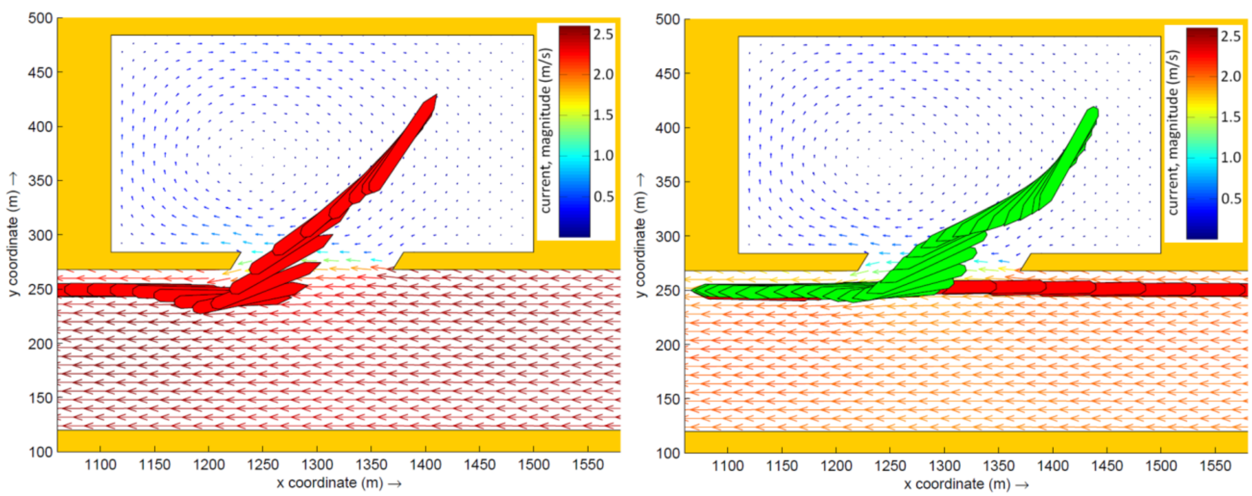


Figure 4-14: Track plots of run 56 (left) and run 58 (right). Part a (red) and b (green) of run 58 are displayed.

4.2.8 Assessment of runs 59-60

Runs 59 and 60 are conducted for a wide waterway layout with an entrance width of 90 meters, a length of 60 meters and an angle of 120 degrees. The lateral approach distance is 12 meters. A forward and a backward manoeuvre are conducted for flow velocities of respectively 2.5 and 2.0 m/s. The backward runs are again split into an a-part and b-part.

Table 4-11: Assessment of runs 59-60.

Run nr.	Dir (-)	Man (-)	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time	Speed peak (m/s)		
59	Up	In	2.5	+	+	+	+/-	+	3-4	1.9	83	+
60a	Down	Stop	2.0	+	X	+	+	+	1-2	2.3*	X	+
60b	Up	Back In	2.0	+	+	+	-	+	6-7	-0.9	90	

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

During the stopping manoeuvre run 59 uses 70 percent of the bow thruster capacity circa 1 minute continuously. A slightly reduce of bow thruster use is not problematic. The entrance width of 90 meters is just sufficient for run 60. The assessment for run 60 is similar as for the other backward runs. The track plots of run 59 and 60 are shown in figure 4-15.

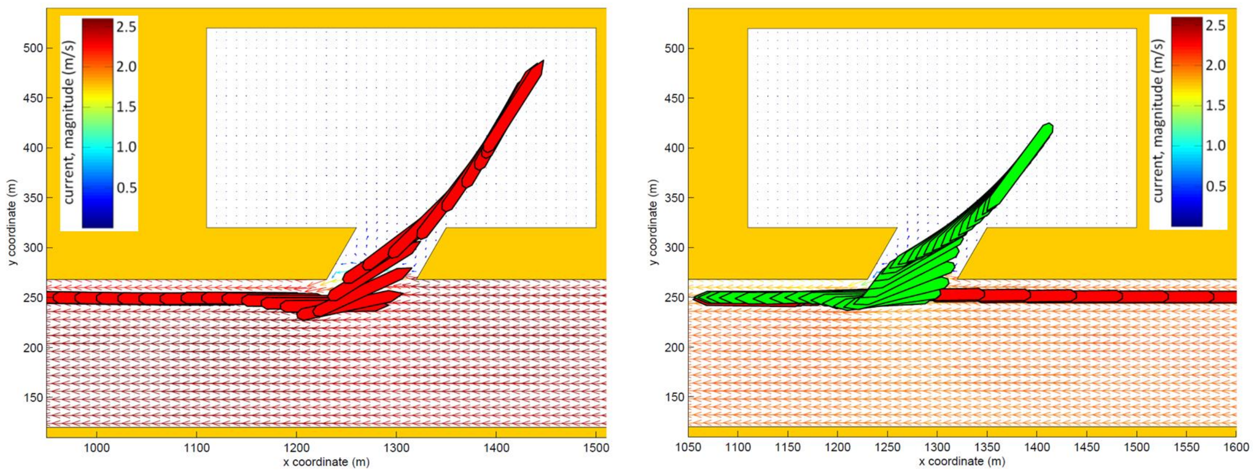


Figure 4-15: Track plots of run 59 (left) and run 60 (right).

4.2.9 Assessment of runs 61-64

Runs 61 to 64 are performed for approaching a lock approach harbour located parallel to the waterway axis. The wide waterway layout is used for these simulations. The entrance length is 8 meters with an angle of 90 degrees. This allows the ships to manoeuvre sideways through the 200 meters wide entrance. The lateral approach distance is 12 meters. The variable parameters are the flow velocity and the sailing direction of the ships. The track plots of run 61 to 64 are shown in figure 4-16 and figure 4-17.

Table 4-12: Assessment of runs 55-58.

Run nr.	Dir	Man	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time	Speed peak (m/s)		
61	Up	In	1.0	+	+	+	+	+	4-5	1.0*	104	+
62	Up	In	2.5	+	+	+	+	+	3-4	1.7	110	+
63	Down	In	1.0	+	+	+	+/-	+	2-3	2.2	161	+
64	Down	In	2.5	+	+/-	+	+/-	+	1-2	3.4	171	+/-

*The speed peak of the turning manoeuvre is at the start of the manoeuvre.

For runs 61 and 62 all the criteria are met. For run 63 and 64 the bow thruster criterion is slightly exceeded during the stopping manoeuvre. As explained before, using slightly less of the bow thruster capacity is not problematic. Moreover, this adaptation is not influencing the other parts of the run. For run 64 the safety distance in the entrance is exceeded, because the ship comes too close to the downstream entrance bank. However, sufficiently extra space is available in the entrance. When starting the turning manoeuvre into the port earlier this can solve the exceeding of the manoeuvring space criterion. This adjustment will not have a significant effect on the output of the run. Therefore, the obtained results of this run are suitable to compare with other runs. It should be mentioned that for the arrivals sailing downstream a perfect timing is required to obtain a safe manoeuvre. Starting the turning manoeuvre slightly earlier or later can result in an unsafe situation.

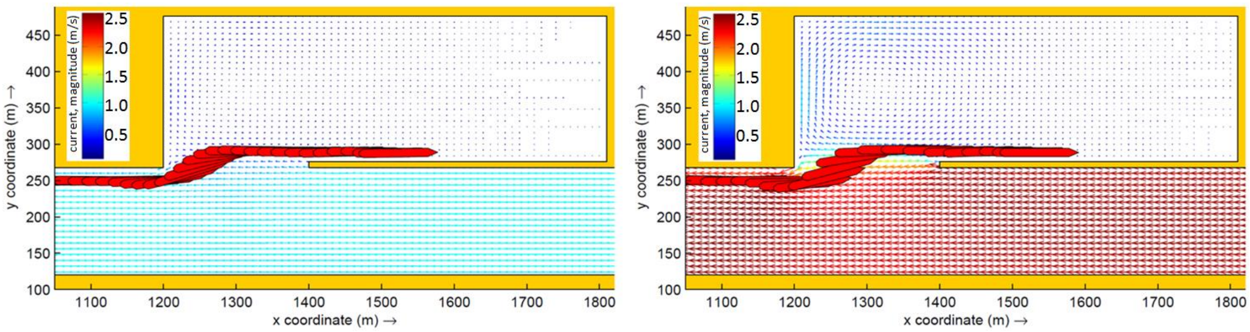


Figure 4-16: Track plots of run 61 (left) and run 62 (right).

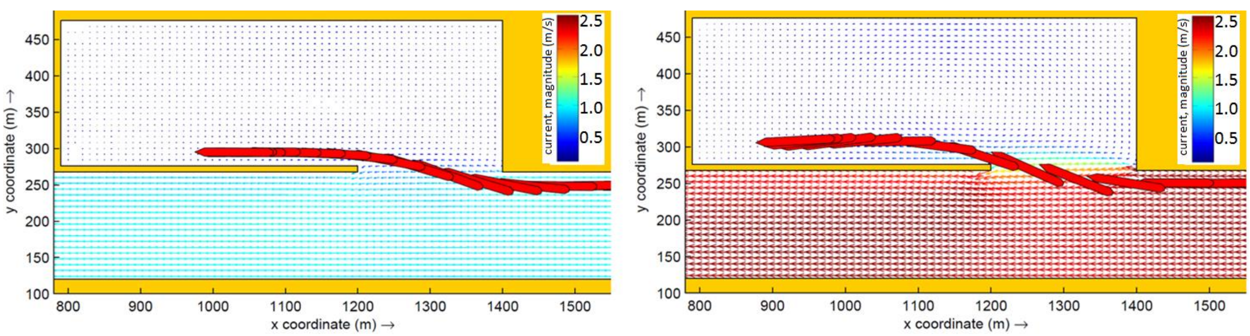


Figure 4-17: Track plots of run 63 (left) and run 64 (right).

4.2.10 Assessment of runs 65-66

The runs 65 and 66 are runs where the ship is manoeuvring into the port. Both runs are displayed in figure 4-18. The wide waterway layout is used with an entrance width of 150 meters, a length of 60 meters and an angle of 120 degrees. The lateral approach distance is about 12 meters. For both runs a current of 2.5 m/s is used. However, for run 65 a scenario with flooded entrance dams was simulated. The water depth above the dams is 1 meter and the water depth in the entrance is 7 meters. This is also illustrated in figure 3-8. For runs 65 and 66 a current field of 2.5 m/s used, modelled with Delft3D and not scaled with the SHIPMA scaling factor in the input files. Both runs are assessed as sufficiently safe.

Table 4-13: Assessment of run 65-66.

Run nr.	Dir (-)	Man (-)	Uc (m/s)	Manoeuvring space		Controllability			Manoeuvre		$W_{e,req}$ (m)	Total
				Waterway	Entrance	Steering	Bow Thruster	Stopping	Time	Speed peak (m/s)		
65	Up	In	2.5	+	+	+	+	+	3-4	1.6	84	+
66	Up	In	2.5	+	+	+	+	+	3-4	1.9	82	+

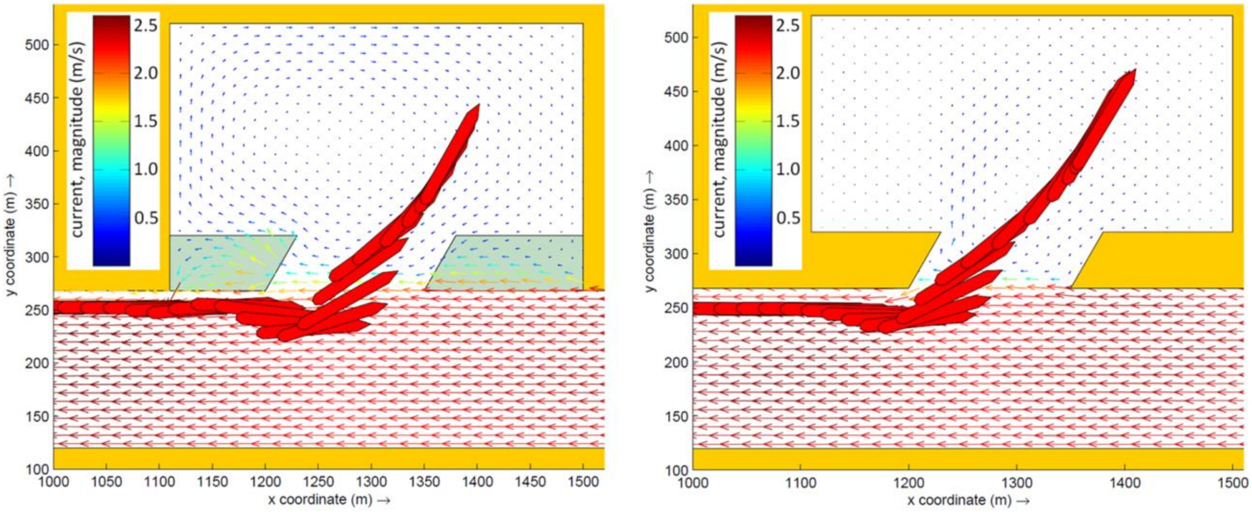


Figure 4-18: Track plots of run 65 (right) and run 66 (left).

4.3 Conclusions

SHIPMA runs were conducted for a narrow (runs 1 to 8) and a wide layout (runs 9 to 66). The waterway widths are respectively 48 meters and 148 meters. The narrow layout consists of an entrance width of 150 meters, an entrance length of 60 meters and an entrance orientation perpendicular to the waterway axis. For the wide waterway layout variable values were used for the entrance width, length and orientation. In all the simulated scenarios a loaded CEMT class Va ship was used.

From all the evaluated runs, 5 runs were assessed as insufficiently safe. Namely, runs 3, 4, 17, 20 and 21. When comparing these runs with other runs it should be taken into account that the output of these runs was obtained by an unsafe manoeuvre. As a consequence, the output is less correct. It should be taken into account that a comparison between a safe and unsafe runs is less objective than a comparison between safe runs.

Besides the runs that are assessed as insufficiently safe, the safety of several runs was assessed as critical. It is expected, based on various reasons, that these runs still provide correct results. Replacing these runs with a sufficiently safe run, will not affect (or slightly affect) the output of the runs. These runs can still be used for comparison with other runs. The following runs were assessed as critical:

- Runs 1, 2, 7 and 8 are conducted for the narrow waterway layout. These runs require a slightly larger waterway width. In case the waterway width cannot be enlarged, then a slightly wider entrance is also sufficient. A slight increase of the waterway or entrance width will not have a major effect on the output of these runs.
- Run 27 requires an entrance width of 151 meters instead of the available 150 meters. Increasing the entrance width with one meter will not have a significant effect on the output of the run.
- In run 64 the ship came slightly too close to the downstream entrance bank. Sufficiently extra entrance width was available. Starting the turning manoeuvre earlier can avoid the exceedance of the manoeuvring space criterion. This adjustment will not have a significant effect on the output of the run.

All the backward manoeuvres into the port were assessed as sufficient. These are the runs 40 up to 48, 53, 54, 57, 58 and 60. However, the bow thruster criterion was significantly exceeded. This full use of bow thruster capacity was needed to conduct these manoeuvres, because the other steering tools cannot be used when sailing backwards. According to MARIN, backward SHIPMA simulations with a maximum use of the bow thruster capacity perform reliable results (personal communication, 2017). In addition, these backward manoeuvres exceeded the allowed manoeuvring time. However, the used waterway width is small for these manoeuvres. Hence, exceeding the manoeuvring time criterion is not problematic regarding hindering the through going traffic on the waterway.

In addition, it appeared that:

- The narrow layout is critical for providing safe navigation, taking into account flow velocities between 1.0 and 2.5 m/s. Only the departure manoeuvres sailing in upstream direction were assessed as sufficiently safe.
- Arrival manoeuvres sailing downstream are more difficult than arrival manoeuvres sailing upstream, when taking an entrance angle of 90 degrees into account.
- For the wide waterway layout and a flow velocity of 2.5 m/s, it was not possible to conduct a forward manoeuvre into the port when sailing downstream, using an entrance width of 150 meters, a length of 60 meters and an orientation perpendicular to the waterway axis. For the same layout, taking into account a flow velocity of 1.0 m/s, it was shown that a forward manoeuvre into the port with a large lateral approach distance (122 meters) is undesired. This manoeuvre uses too much time and space to perform the turning manoeuvre into the port, see figure 4-8.
- It was not possible to conduct backward manoeuvres for flow velocities larger than 2.0 m/s. The relative flow velocity for these manoeuvres is larger than 3.0 m/s, assuming a ground speed of 0.5 m/s. For these situations the available bow thruster force is 0 kN. Hence, performing a turning manoeuvre into the port is not possible.
- For arrivals sailing downstream into the port, significant larger ship speeds were used compared to the arrivals when sailing upstream. When using these run results, it should be taken into consideration that skippers can prefer a lower ship speed.

5

Model results analysis

With the fast-time simulation program SHIPMA several scenarios were simulated. The run results were assessed in chapter 4. In this chapter the simulation output is further elaborated. The objective of this research is to determine the smallest possible entrance width. The influence of the different design parameters, included in the simulation study, on the entrance width are discussed in this chapter.

The simulation study was divided in two main groups. Runs 1 to 21 belongs to Group 1 and runs 22 to 66 to Group 2. The runs 22 to 66 were all assessed as suitable for comparison with other runs. Therefore, this group of runs is used to analyse the trends for different design parameters. In Group 1, several runs were assessed as insufficiently safe in chapter 4. Comparing these runs with other safe runs can provide unreliable results. Therefore, these runs are not used for trend analysis. The runs, which are assessed as insufficient, are still used to compare the different simulated scenarios. However, when such a run is used, it is mentioned that this run was assessed as insufficient and thus can provide an inaccurate result.

The analysis in this chapter is purely based on the results of the fast-time simulation study with SHIPMA. The conclusions in this chapter can therefore differ from a practical situation. The interpretation of the presented conclusions in this chapter is discussed in chapter 6.

First, in paragraph 5.1 the different manoeuvres and the influence of the waterway width are discussed. Based on these findings, several assumptions are made and used for the next paragraphs. Consequently, the presented results and trends in paragraphs 5.2 to 5.6 are only valid for the assumptions made in paragraph 5.1.

In paragraph 5.2 the influence of the entrance angle is analysed. Paragraph 5.3 presents the influence of the entrance length. The flow velocity is discussed in paragraph 5.4. The influence of increasing or decreasing the entrance width itself is analysed in paragraph 5.5. Paragraph 5.6 shows the effect of flooded entrance dams. The manoeuvres from up- and downstream into a lock approach harbour are analysed in paragraph 5.7.

Finally, in paragraph 5.8 the conclusions of the analysed design parameters are presented. Furthermore, the most efficient entrance width and layout is described. In addition, other peculiarities that are the result of the analyses in this chapter are summarised.

5.1 Ship manoeuvres and waterway width

In this paragraph the results of different forward manoeuvres used in the fast-time simulation study are analysed. In chapter 4 was concluded that the manoeuvres on the narrow waterway were more difficult and thus require a larger entrance width than the manoeuvres on the wide waterway. So, the available space on the waterway is an important aspect which influences the execution of a manoeuvre. Restricted manoeuvring space can limit the possibilities for a ship to manoeuvre safely in or out of the port. This is also in line with the conclusion from chapter 2.

For this reason, the influence of both aspects on the required entrance width is discussed simultaneously in this paragraph. The backward manoeuvres, conducted during the simulation study, are not discussed in this paragraph. The results of these manoeuvres are described in paragraph 5.2.

As described before in section 3.3.6, a distinction was made between four main types of forward manoeuvres. The results of these four manoeuvres will be discussed in sections 5.1.1 to 5.1.4.

In section 5.1.5 the different manoeuvres are compared. The waterway width is taken into account to establish the decisive manoeuvres for each side of the port entrance.

In section 5.1.6 the assumptions used for the next paragraphs of this chapter are described.

In this paragraph two layouts, the narrow and wide layout, are used to discuss the ship manoeuvres and the waterway width. Both layouts have an entrance angle of 90 degrees and an entrance width of 150 meters. The differences are:

- Narrow layout: waterway width of 48 meters and entrance length of 20 meters.
- Wide layout: waterway width of 148 meters and entrance length of 60 meters.

As a result of the simulation study, it appeared that the sensitivity of the entrance length parameter is small. Therefore, the influence of the entrance length is neglected for these simulations. Paragraph 5.3 discusses the influence of the entrance length in more detail.

5.1.1 Arrival scenarios, sailing upstream

In table 5-1 and table 5-2 the required waterway widths and entrance widths, for the simulated arrival scenarios when sailing in upstream direction, are shown for respectively a current of 1.0 and 2.5 m/s. The lateral approach distance between the port entrance and the ship at the start of the turn is added to the tables. In figure 3-17 is indicated how the lateral approach distance is defined.

Table 5-1: Results of arrival scenarios, sailing upstream and a flow velocity of 1.0 m/s.

Run nr.	Layout waterway	Lateral approach distance (m)	Required waterway width (m)	Required entrance width (m)
1*	narrow	12	50	67
11*	wide	12	63	60
10	wide	74	111	50
9	wide	121	148	50

*Run assessed as ‘critical’ in chapter 4.

Table 5-2: Results of arrival scenarios, sailing upstream and a flow velocity of 2.5 m/s.

Run nr.	Layout waterway	Lateral approach Distance (m)	Required waterway width (m)	Required entrance width (m)
2*	narrow	14	49	91
15	wide	12	57	90
14	wide	76	99	84
13	wide	124	146	85

*Run assessed as ‘critical’ in chapter 4.

Based on these results, it is clear that for larger flow velocities a wider entrance is required in order to manoeuvre safely through the entrance. When manoeuvring into the port the stern of the ship is pushed to the downstream bank of the entrance. This will cause an external turning moment on the ship. This principle is explained in more detail in appendix B. To limit this turning moment, the ship has to manoeuvre under a certain angle through the flow gradient. For a larger flow velocity this angle needs to be larger, this results in a larger required entrance width.

Furthermore, it appears that when a wider waterway is used, this is favourable for the used space in the entrance. However, for an approach distance of 12 meters the differences are small between the two waterway layouts for flow velocities of 2.5 m/s.

5.1.2 Arrival scenarios, sailing downstream

In table 5-3 and table 5-4 the required waterway width and entrance width, for the simulated arrival scenarios for sailing in downstream direction, are shown for respectively a current of 1.0 m/s and 2.5 m/s. The lateral approach distance between the port entrance and the ship at the start of the turn is added to the tables.

Table 5-3: Results of arrival scenarios, sailing downstream and flow velocity of 1.0 m/s.

Run nr.	Layout waterway	Lateral approach distance (m)	Required waterway width (m)	Required entrance width (m)
3*	narrow	13	50	140
19	wide	12	65	102
18	wide	74	114	68
17	wide	122	150	54

*Run assessed as 'critical' in chapter 4.

Table 5-4: Results of arrival scenarios, sailing downstream and flow velocity of 2.5 m/s.

Run nr.	Layout waterway	Lateral approach distance (m)	Required waterway width (m)	Required entrance width (m)
4**	narrow	12	53	199
21**	wide	22	75	196
20**	wide	97	149	162

**Run assessed as 'insufficient' in chapter 4.

From the simulation results follows that for a larger flow velocity a wider entrance is required. In addition, the required waterway is also larger for the flow velocity of 2.5 m/s.

Furthermore, it turns out that if a larger lateral approach distance is used on the waterway, the required entrance width is reduced significantly for a flow velocity of 1.0 m/s. Also a clear difference between the run on the narrow and the wide waterway layout for the same approach distance is visible. In the wide layout, the stern of the ship has more space to deflect when turning into the port. This is illustrated in figure 5-1, on the wide waterway a larger width can be used for the turning manoeuvre. This aspect is contributing to a more efficient turning manoeuvre compared to the narrow waterway layout.

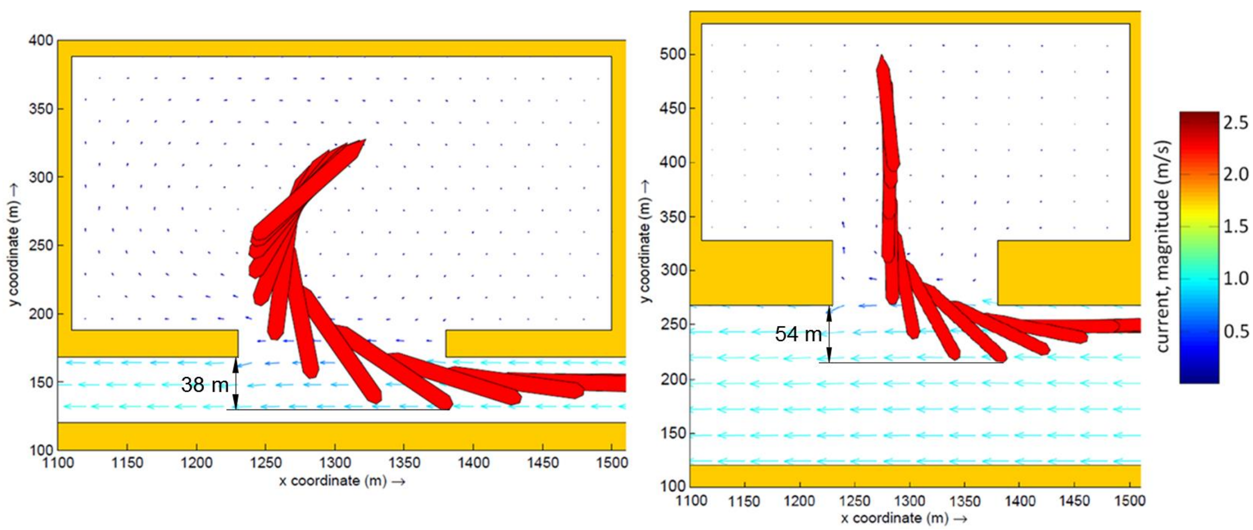


Figure 5-1: The used waterway width indicated for run 3 (left) and run 19 (right).

For the scenarios with a flow velocity of 2.5 m/s, it was not possible to conduct a safe run for an entrance width of 150 meters. Although the entrance width of 150 meters was not sufficient, it can be observed that a run with a large lateral approach distance (run 20) requires a considerably smaller entrance width. As discussed before in section 4.2.2 and shown in figure 4-9, the major drawback of such a manoeuvre is the large area required on the waterway to execute such a manoeuvre.

5.1.3 Departure scenarios, sailing downstream

In table 5-5 and table 5-6 the required waterway widths and entrance widths, for the simulated departure scenarios when sailing in downstream direction, are shown for respectively a current of 1.0 and 2.5 m/s.

Table 5-5: Results of departure scenarios, sailing downstream and a flow velocity of 1.0 m/s.

Run nr.	Layout waterway	Required waterway with (m)	Required entrance width (m)
7*	narrow	48	76
12	wide	100	50

*Run assessed as 'critical' in chapter 4.

Table 5-6: Results of departure scenarios, sailing downstream and a flow velocity of 2.5 m/s.

Run nr.	Layout waterway	Required waterway width (m)	Required entrance width (m)
8*	narrow	54	107
16	wide	88	77

*Run assessed as 'critical' in chapter 4.

It can be observed that a larger entrance width is required for larger flow velocities. Besides, the use of a larger waterway width can reduce the required entrance width significantly. When crossing the gradient with a low speed, the ship will be forced to the downstream bank of the port entrance. With a larger ship speed this effect can be countered, this principle is illustrated in figure 5-2. The disadvantage of a larger speed in the entrance is a larger turning area needed on the waterway. When the width of the waterway is not sufficient to execute this manoeuvre, the ship has to start turning in the port entrance. A turning manoeuvre in the port entrance requires a larger entrance width than sailing straight through the port entrance.

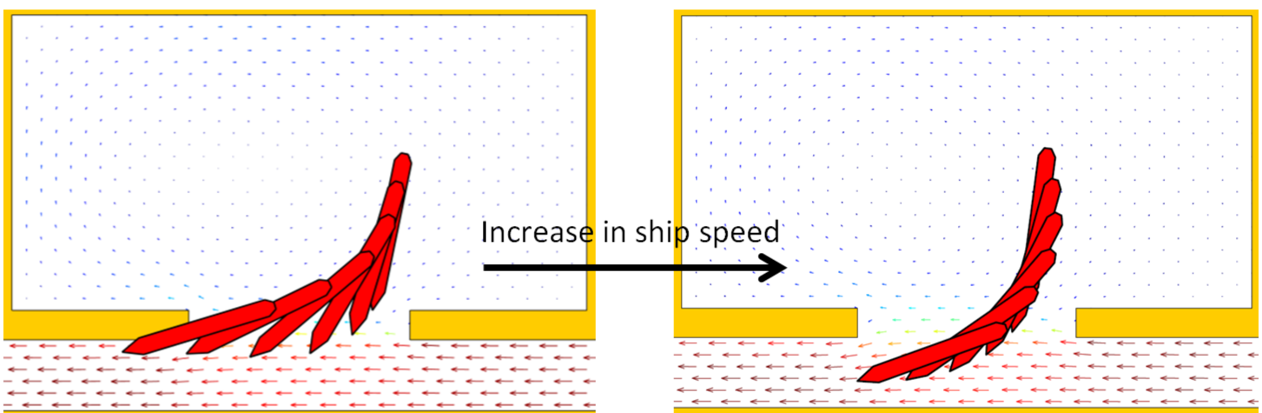


Figure 5-2: Schematisation of the effect of an increase in ship speed when manoeuvring out of the port in downstream direction. The shown ship behaviour is modelled with SHIPMA.

5.1.4 Departure scenarios, sailing upstream

In table 5-7 the required entrance width, for the simulated departure scenarios for sailing in upstream direction, are shown for currents of 1.0 and 2.5 m/s. The required widths on the waterway are included in the table. For both runs the narrow waterway width was used.

Table 5-7: Results of departure scenarios, sailing upstream for the narrow waterway layout.

Run nr.	Flow velocity (m/s)	Required waterway width (m)	Required entrance width (m)
5	1.0	46	84
6	2.5	44	101

For the simulated scenarios the required waterway widths are similar. The difference between the two runs is the required entrance width. It can be observed that a larger flow velocity increases the required entrance width significantly. Simulations for the wide waterway layout were not conducted, because the arrivals when sailing downstream require considerable larger entrance widths. These arrivals are therefore clearly the decisive manoeuvres. This is explained in more detail in the next section.

5.1.5 Decisive manoeuvres

In the previous sections the simulation results of runs 1 to 21 were analysed. These runs were conducted for flow velocities of 1.0 and 2.5 m/s. In this section the decisive manoeuvres related to the available waterway width are established.

In order to determine the decisive manoeuvres for the optimisation the port entrance, the different manoeuvring directions have to be compared with each other. By comparing the arrival scenarios sailing upstream with the departure scenarios in downstream direction, the decisive manoeuvres at the downstream side of the port entrance can be established. To determine the decisive manoeuvres for the upstream side of the port entrance, the arrivals sailing downstream and the departures in upstream direction should be compared. For an overview of the different manoeuvre types, see section 3.3.6 and figure 3-16.

As a result of the simulations, it appeared that for the arrival manoeuvres generally a larger lateral approach distance is desired to reduce the required entrance width for the arrival scenarios. The major drawback of a large lateral approach distance is the large area needed on the waterway to execute a turning manoeuvre into the port. These manoeuvres have to cross the waterway and thus possible other through going traffic. This aspect was also described in the study on the port of Haaften, see section 2.2.1. In order to avoid incidents with through traffic it is more desired to perform a turning manoeuvre with a lateral approach distance close to the port entrance.

A departure manoeuvre is generally easier to time with trough traffic than with arrival manoeuvres. Therefore, it is assumed that it is safe to execute departure manoeuvres which require significant more waterway width. Based on these aspects, the arrival scenarios with a close lateral approach distance of 1B are compared with the departures that require significant more waterway width. However, it should be mentioned that for overnight harbours it is possible that many ships want to leave the port around the same time. For these situations it is harder to time the departure manoeuvre with the trough traffic, because there is more pressure to leave the port as soon as possible.

The determined decisive manoeuvres for each side of the port entrance are illustrated with a flow chart in figure 5-3. The arrivals and departures for the downstream and upstream side of the port entrance are discussed below.

Downstream side of port

The departure manoeuvres are decisive when there is a narrow waterway. For a wider waterway the arrival manoeuvres are decisive. In table 5-8 and table 5-9 the required waterway width and entrance width are shown for the arrivals and departures. The following can be noticed:

- For manoeuvres with a limited waterway width of approximately 50 meters the departures require an extra entrance width of approximately 10 to 15 meters.
- For manoeuvres with available waterway width of roughly 90 to 100 meters or larger, the arrivals require an extra entrance width of approximately 10 to 15 meters.

Based on these two observations, it is expected that the transition point for the decisive manoeuvre is between an available waterway width of 50 and 90 meters. The waterway width which belongs to this transition point cannot be precisely established with the conducted simulations.

Table 5-8: Results of arrival scenarios, sailing upstream.

Run nr.	Layout waterway	Flow velocity (m/s)	Required waterway width (m)	Required entrance width m)
1	narrow	1.0	49	67
2	narrow	2.5	49	91
11*	wide	1.0	63	60
15	wide	2.5	57	90

*Run assessed as 'critical' in chapter 4.

Table 5-9: Results of departure scenarios, sailing downstream.

Run nr.	Layout waterway	Flow velocity (m/s)	Required waterway width (m)	Required entrance width (m)
7*	narrow	1.0	48	76
8*	narrow	2.5	54	107
12	wide	1.0	100	50
16	wide	2.5	88	77

*Run assessed as 'critical' in chapter 4.

Upstream side of port

In table 5-10 and table 5-11 the arrival and departure scenarios are shown. The arrivals require considerable larger entrance widths. Even the arrivals for a wider waterway require larger entrance widths than the departures on the narrow waterway. Besides, the required waterway width is larger for the arrivals than for the departures. From the results can be concluded that the arrival scenarios are clearly more decisive than the manoeuvres out of the port.

Table 5-10: Results of arrival scenarios, sailing downstream.

Run nr.	Layout waterway	Flow velocity (m/s)	Required waterway width (m)	Required entrance width m)
3*	narrow	1.0	50	140
4**	narrow	2.5	53	199
19	wide	1.0	65	91

*Run assessed as 'critical' in chapter 4.
**Run assessed as 'insufficient' in chapter 4.

Table 5-11: Results of departure scenarios, sailing upstream.

Run nr.	Layout waterway	Flow velocity (m/s)	Required waterway width (m)	Required entrance width (m)
5	narrow	1.0	46	84
6	narrow	2.5	44	101

From the tables can be concluded that from all the manoeuvres the most decisive ones are the arrival scenarios sailing downstream. These manoeuvres require a wider entrance width than the arrivals sailing upstream and all the departures. However, for certain situations it is possible that a ship can turn downstream of the port entrance. This downstream turn is possible when the waterway is sufficiently wide and the manoeuvre is not unsafe with respect to the trough going traffic. For these situations the arrivals sailing upstream or the departures sailing downstream, depending on the available waterway width, are the most decisive manoeuvres. Therefore, it is important to study the influence of manoeuvres on the required waterway width at the upstream and the downstream side of the port.

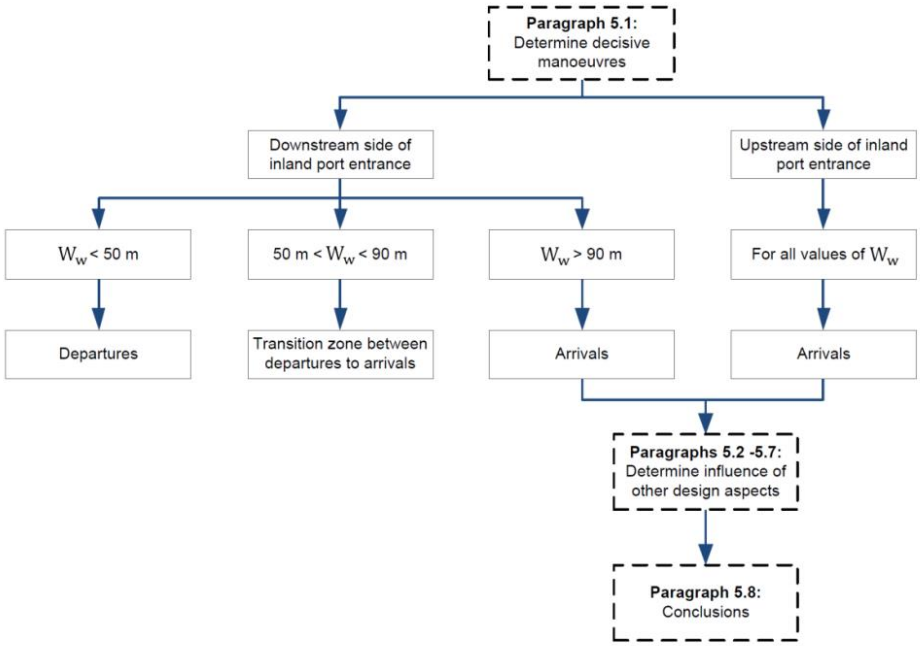


Figure 5-3: Flow chart of decisive manoeuvres determined in paragraph 5.1 for each side of the port entrance and used for the next paragraphs. The decisive manoeuvres are related to the available waterway width (W_w).

5.1.6 Assumptions for next paragraphs

In paragraph 5.1.5 the results of runs 1 to 21 were discussed in order to determine the decisive manoeuvres for each side of the port entrance and the influence of the waterway width on the different manoeuvres. In the next paragraphs, other simulation results (run 22 to 66) are included to study the influence of the other design parameters.

The runs 22 to 66 are all arrival scenarios and executed for the wide waterway layout. An overview of the characteristics of these conducted runs is shown in appendix F. The required width on the waterway for these manoeuvres is between 40 and 70 meters. However, the waterway width is considerably wider, namely 148 meters. As described in section 5.1.5, when the available waterway width for the departure manoeuvres is larger than 90 meters, the arrival scenarios are more decisive. For the wide waterway layout this waterway width is available. Based on this, it is assumed that it is unnecessary to conduct simulations for departure scenarios, whereas these are not decisive. Note that the discussed results and trends in the next paragraphs only hold for available waterway widths larger than 90 meters. This is illustrated in the flow chart in figure 5-3.

As described before, the manoeuvres with a larger approach distance are more desirable in order to design the smallest entrance width. However, the used space on the waterway is significant for these types of manoeuvres. Besides, crossing the entire waterway is not desired with respect to nautical safety. The through traffic should be hindered as less as possible in order to avoid traffic incidents. With respect to avoiding incidents with the trough traffic, the approach distance as close as possible to the port entrance is more preferred. As explained in section 3.4.1, this minimum approach distance should be equal to 1B (11.6 meters) in order to satisfying the safety criterion for manoeuvring space on the waterway. When in practise a situation occurs where it is possible to approach a port from a larger lateral distance, the manoeuvre will require a smaller swept path in the entrance. As a consequence, this situation is less decisive than an approach distance of 1B.

With respect to avoiding traffic incidents and simulating the most decisive situations, it was decided to take only the close approach distance of 1B into consideration for the runs 22 to 66.

5.2 Entrance angle

During the simulation study, scenarios with different entrance angles were simulated. Forward and backward arrivals into the port are used to determine the most efficient orientation of an entrance. A waterway width of 148 meters was used for these simulations. The required width on the waterway for these manoeuvres was 70 meters or less. The different angels were simulated for an entrance length of approximately 60 meters. As a consequence of the chosen grid size for modelling the current fields and bottom profiles with Delft3D, the lengths are between 59.4 and 60.0 meters. These small deviations in entrance length have an insignificant effect on the required entrance length. The sensitivity of the entrance length parameter is discussed in paragraph 5.3.

All the forward manoeuvres are set up with a similar working method. Besides, all the used runs were assessed as sufficiently safe in chapter 4. The run results are therefore suitable for comparisons. For example, it is possible that the absolute value of the measured swept paths deviate from situations in the real world. However, the observed trends are reliable.

5.2.1 Forward manoeuvres

The SHIPMA results for the forward manoeuvres for sailing up- and downstream are shown in figure 5-4. In this figure, trend lines are added to the run results. The minimum required entrance width and corresponding angle is indicated for each trend line. In appendix E the formulas for each trend line and the trend line fit to the acquired data (R^2 value) are presented.

When sailing upstream with a flow velocity of 1.0 m/s, the smallest entrance width is 52 meters for an angle of 121 degrees. For a current of 2.5 m/s, the minimum width is 78 meters for an angle of 124 degrees. Furthermore, figure 5-4 shows that for each angle the difference between the required entrance widths are approximately the same for currents of 1.0 and 2.5 m/s.

When sailing in downstream direction with a flow velocity of 1.0 m/s, the smallest required entrance width is 78 meters for an angle of 48 degrees. For a flow velocity of 2.5 m/s only the required entrance width for an angle of 90 degrees was simulated. Although this run was assessed as insufficient, the result is added to figure 5-4 to give an indication of the required entrance width in such a situation. The difference between the required width for 1.0 and 2.5 m/s is significant. This difference is much larger than in case of the arrivals when sailing upstream.

Furthermore, from figure 5-4 follows that the smallest entrance width for sailing upstream is considerably smaller than sailing downstream. The most efficient angles of the upstream and downstream arrivals are not the same. An angle of circa 50 degrees is efficient for arrivals sailing downstream and inefficient for arrivals sailing upstream and for an angle of 120 degrees the opposite holds.

Another efficient angle could be determined for flow velocities of 1.0 m/s. When taking into account the up- and downstream arrivals, an angle of 65 degrees results in a minimum entrance width of 83 meters (intersection point between the blue and green lines in figure 5-4). Around this angle the required entrance widths for the arrivals sailing upstream and downstream are similar.

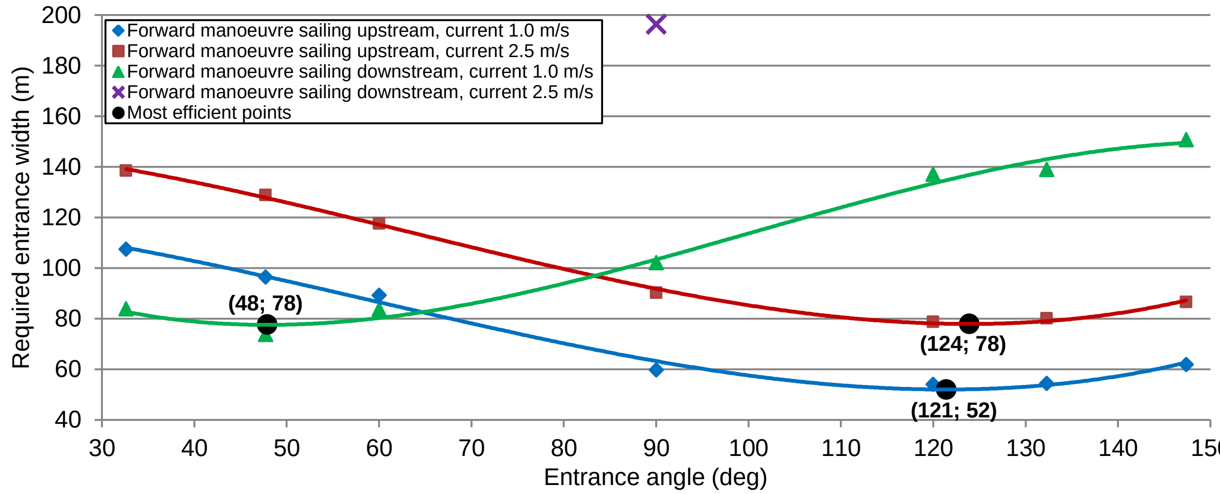


Figure 5-4: Relation between required entrance width and angle for forward manoeuvres into the port. The run results are indicated with the coloured markers.

Besides the optimisation with respect to nautical aspects, it is desired to reduce the siltation in ports as much as possible. An angle smaller than 90 degrees will contribute to larger siltation rates, which makes this orientation undesired with respect to minimising the siltation in ports. In contrary, an angle larger than 90 degrees will reduce the siltation significantly. The influence of the entrance geometry to siltation in a port along a river is explained in paragraph 2.3 of this report. When optimising the entrance angle with respect to minimising siltation and nautical safety an entrance angle of circa 120 degrees is most favourable. For an angle of 120 degrees, the arrivals sailing downstream have to turn downstream of the port entrance or approach the port with a backward manoeuvre. The backward manoeuvres are discussed in the next section.

5.2.2 Backward manoeuvres

An angle larger than 90 degrees is preferred for the arrival scenarios sailing upstream and with respect to minimising siltation. Since the arrival scenarios sailing downstream require a considerably larger entrance width for angles larger than 90 degrees, another solution should be found for these manoeuvres. By using backward manoeuvres instead of forward manoeuvres for the arrivals sailing downstream, the required entrance width can be reduced significantly for these arrivals. Note that a backward manoeuvre is conducted by a stopping manoeuvre downstream of the port entrance, followed by a manoeuvre with stern first through the entrance. This means that a backward manoeuvre is approaching the port from downstream. Hence, the ship is sailing in upstream direction into the port. In the simulation study, the backward manoeuvres were conducted for flow velocities between 1.0 and 2.0 m/s. As explained in section 4.2.4, it was not possible to conduct backward manoeuvres for lager flow velocities.

Figure 5-5 shows the simulation results for the backward manoeuvres into the port. The results of the forward manoeuvres, shown in figure 5-4, are added to figure 5-5. In appendix E the formulas for each trend line and the trend line fit to the acquired data (R^2 value) are shown.

For a backward manoeuvre with a flow velocity of 1.0 m/s, the smallest required width is 69 meters for an angle of 121 degrees. This entrance width is smaller than the minimum width (78 meters) for a forward manoeuvre into the port when sailing downstream.

For a backward manoeuvre with a flow velocity of 2.0 m/s, the smallest width is 86 meters for an angle of 118 degrees. Forward manoeuvres for a flow velocity of 2.0 m/s were not included in the simulations. However, the differences for the forward manoeuvres between flow velocities of 1.0 and 2.5 m/s are significantly larger than those for the backward manoeuvres between flow velocities of 1.0 and 2.0 m/s. Based on these results, it is expected that for a flow velocity of 2.0 m/s a backward manoeuvre requires a considerably smaller entrance width compared to a forward manoeuvre with a flow velocity of 2.0 m/s.

Furthermore, it can be observed that the backward manoeuvres require larger entrance widths than the forward manoeuvres when sailing upstream. This is an expected result, because for the backward manoeuvres only the bow thruster is available to steer the ship. In addition, the trend lines reveal that the most efficient points for the forward manoeuvres when sailing upstream and backward manoeuvres are around 120 degrees.

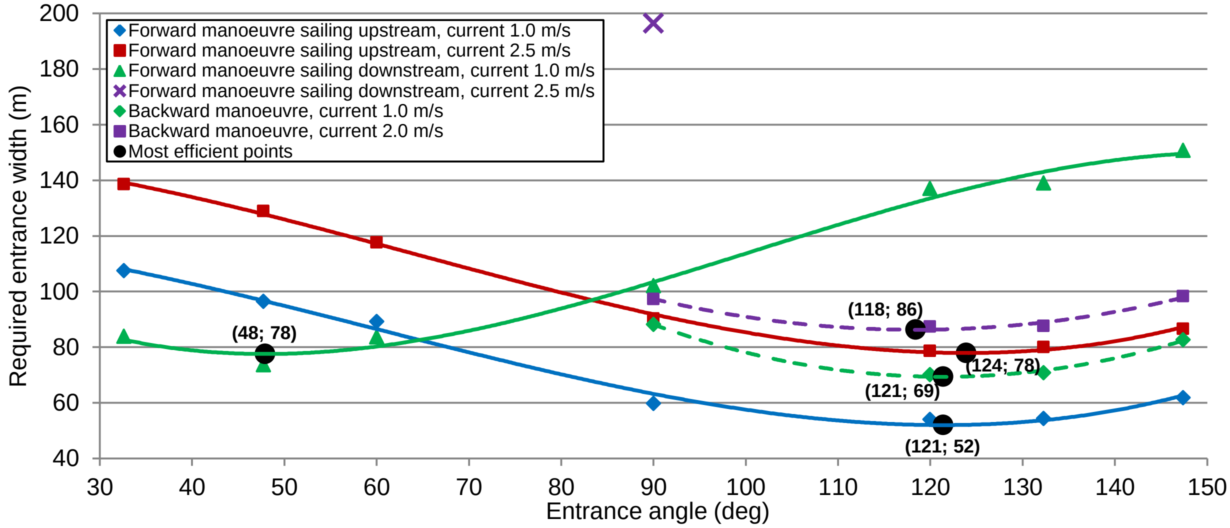


Figure 5-5: Relation between required entrance width and angle for arrivals. The run results are indicated with the coloured markers.

5.2.3 Sensitivity of the entrance angle parameter

In figure 5-4 and figure 5-5 can be observed that around the most efficient angles the sensitivity of the entrance angle is low. Deviations of plus or minus 10 degrees around the most efficient angels will result in a slight increase in required entrance width. The sensitivity of the entrance angle increases considerably when the entrance angle is not close to the most efficient point. For example for the arrivals sailing upstream and a current of 1.0 m/s, a difference of circa 10 meters occurs between entrance angles of 60 and 70 degrees.

5.3 Entrance length

The influence of the entrance length on the required width is studied for lengths of 19, 60 and 120 meters. The entrance width is 150 meters. The orientation for the 60 and 120 meter entrance is 120 degrees. For the 19 meter entrance this is 122 degrees. This difference is due to the chosen grid size for modelling the current fields with Delft3D. As explained in paragraph 5.2, the sensitivity of the entrance angle parameter is low around a value of 120 degrees. Therefore, the difference of 2 degrees will not have a significant effect on the results used for this paragraph.

5.3.1 Forward manoeuvres

In table 5-12 and table 5-13 the required entrance width corresponding to each entrance length is shown for the forward manoeuvres, sailing upstream, into the port. The current conditions of 1.0 and 2.5 m/s are used for these runs.

Table 5-12: Forward manoeuvre, flow velocity 1.0 m/s.

Run nr.	Le (m)	RE width (m)
55	19	55
31	60	54
51	120	54

Table 5-13: Forward manoeuvre, flow velocity 2.5 m/s.

Run nr.	Le (m)	RE width (m)
56	19	81
37	60	79
52	120	82

The required entrance widths are approximately the same for each entrance length. Apparently, the entrance length is not affecting the swept path. Figure 5-6 shows the manoeuvres through the entrances for the forward manoeuvre with a flow velocity of 2.5 m/s. The turn of the ship into the entrance is determining the required width. After this turn the ship can sail through the entrance, with a heading parallel to the entrance banks. This manoeuvre induces that the entrance length is not affecting the required width. For the current of 1.0 m/s a similar explanation holds.

The small differences in the required widths for the different lengths could be caused by the deviations in the used measurement method or the chosen settings for the autopilot. The difference in entrance angle for the entrance length of 19 meters, can also contribute to the small deviations.

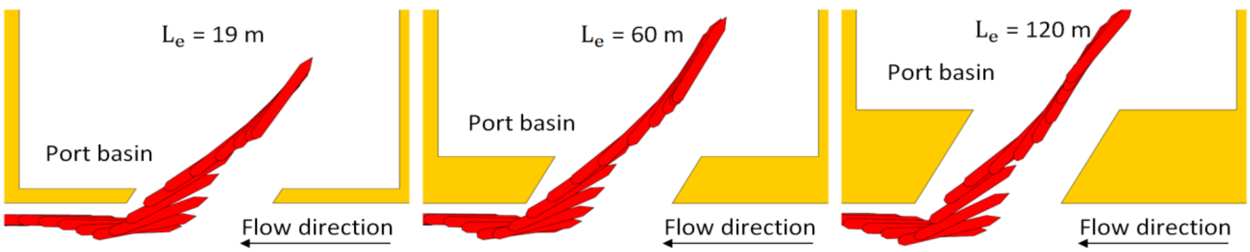


Figure 5-6: Forward manoeuvres from downstream direction into the port for different entrance lengths. Entrance lengths of 19 m (left), 60 m (middle) and 120 m (right) are shown for a flow velocity of 2.5 m/s.

5.3.2 Backward manoeuvres

In table 5-14 and table 5-15 the required entrance width for each entrance length is shown for the backward approaches. As explained in paragraph 5.2, these approaches are replacing the forward manoeuvres into the port when sailing downstream in order to reduce the entrance width. The current conditions of 1.0 and 2.0 m/s were used for these simulations.

Table 5-14: Backward manoeuvre, flow velocity 1.0 m/s.

Run nr.	Le (m)	RE width (m)
57	19	71
41	60	70
53	120	70

Table 5-15: Backward manoeuvre, flow velocity 2.0 m/s.

Run nr.	Le (m)	RE width (m)
58	19	86
45	60	87
54	120	94

For the flow velocity of 1.0 m/s, no significant difference in required entrance width for the different entrance lengths is visible. A similar explanation as is given for the forward manoeuvres in the previous section holds. In contrary, for the backward manoeuvres with a current of 2.0 m/s a more significant effect can be observed. The entrance length of 120 meters requires a wider entrance compared to the length of 19 and 60 meters.

As explained before, see section 3.3.1 and figure 3-4, the bow thruster force is decreasing for an increasing relative water velocity around the ship. With a current of 2.0 m/s, the relative water velocity in front of the entrance is large, which results in a small bow thruster force. This force is not large enough to steer the ship with a heading parallel to the entrance banks through the entrance. In figure 5-7 the manoeuvres through the entrances are shown for different entrance lengths. It can be observed that the ships approach the entrance almost sidewards. When the entire ship is in the entrance, the current forces on the bow of the ship are reduced strongly. Thereafter, it is possible to turn to a heading parallel to the entrance banks. This turn requires additional space.

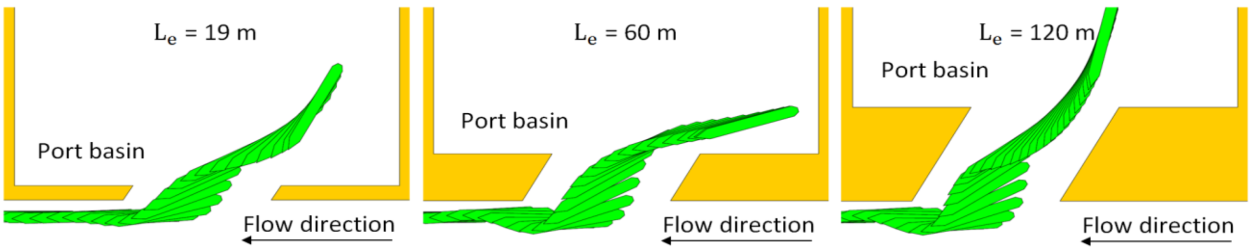


Figure 5-7: Backward manoeuvres from downstream direction into the port for different entrance lengths. Entrance lengths of 19 m (left), 60 m (middle) and 120 m (right) are shown for a flow velocity of 2.0 m/s.

For entrance length up to 60 meters, it is possible to turn in the port basin. For the entrance length of 120 meters, the ship has to turn in the entrance. As a consequence the required entrance width will increase. For a length of 110 to 120 meters and larger, the turning manoeuvre is performed completely in the entrance. Hence, an extra increase in entrance length will not affect the required entrance width any further.

5.3.3 Eddy in entrance

The different entrance lengths cause different current patterns around the port entrance and in the basin. For the entrance length of 120 meters, an eddy arises in the entrance and in the port basin. For the entrance lengths of 19 and 60 meters, an eddy only arises in the port basin. The current patterns are illustrated in figure 5-8 for a current of 2.5 m/s in the waterway.

The velocity magnitude of these eddies is smaller than 0.5 m/s. For the entrance of 120 meters, the ships have to cross this eddy when sailing through the entrance. However, because of the small velocities, the influence of this eddy on the ship behaviour is hardly noticeable. Hence, the swept path of the ship is not affected by this eddy. It should be mentioned that for a skipper these eddies can be more problematic. However, this aspect cannot be studied with SHIPMA, whereas the effects of an actual human operator are not included in the model.

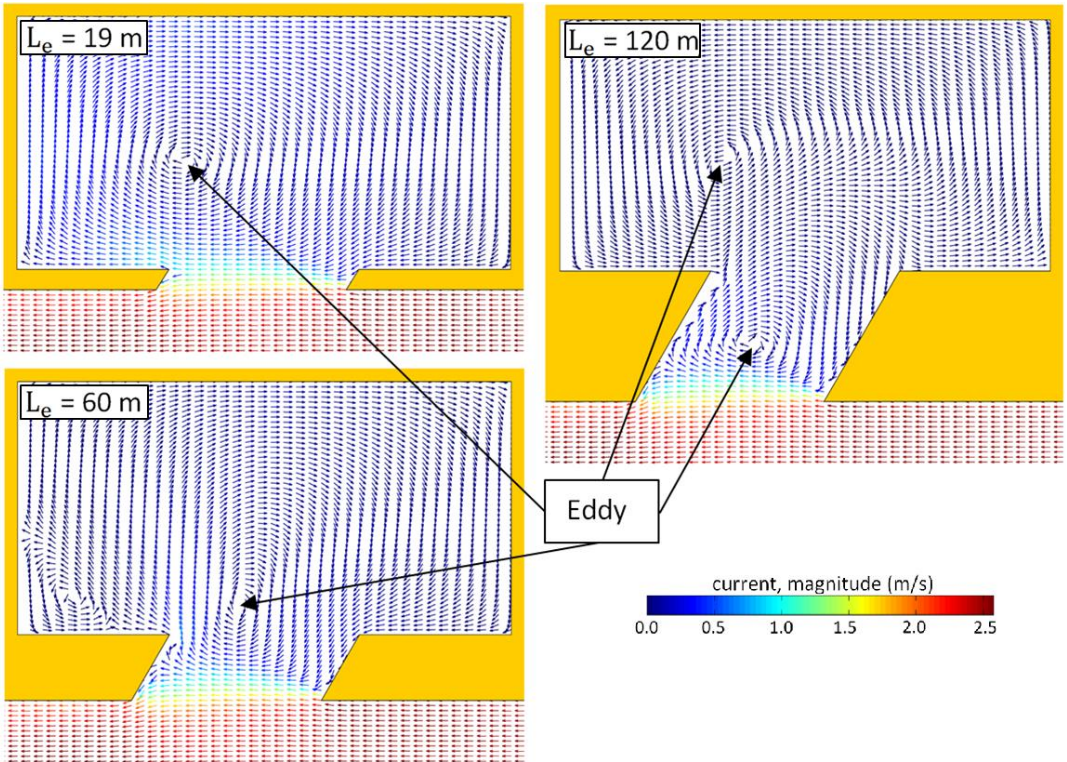


Figure 5-8: Overview of eddies in port basins and entrance for different entrance lengths, for a current of 2.5 m/s in the waterway. The entrance width is 150 meters and the entrance angle is 120 degrees for every layout.

5.3.4 Sensitivity of entrance length parameter

The simulation results showed that the influence of the entrance length is negligible when manoeuvring forward into the port from downstream direction, with current conditions between 1.0 and 2.5 m/s. Therefore, it can be stated that the sensitivity of the entrance length parameter on the simulation results is very low for the forward manoeuvres from downstream direction. For the backward manoeuvres the same low sensitivity is observed for a current condition of 1.0 m/s.

Within the range of 60 to 120 meters of entrance length, the backward manoeuvres with a flow velocity of 2.0 m/s show a slight increase in required entrance width for an increase in entrance length. An entrance width of circa 7 meters larger is required for a 120 meters entrance length compared to a 60 meters entrance length. For this situation the sensitivity is small, but noticeable.

5.4 Flow velocity

As was concluded in paragraph 5.1, an increase in flow velocity induces an increase in the required entrance width. In this paragraph the relation between these velocities and the required entrance width is analysed in more detail. First, the influence of the current for the entrance angle of 120 degrees is described. Subsequently, the differences between the 90 and 120 degrees entrance are elaborated. Finally, the sensitivity of the flow velocity is discussed.

It should be mentioned that the flow velocities in front of the port entrance are smaller than the velocities downstream of the port entrance. As described before in section 3.3.4, the magnitude of the flow field is measured downstream of the entrance. However, the velocity in front of the entrance is 10 to 20% smaller. For example, in case a flow velocity of 1.0 m/s is discussed, the flow velocity around the ship in front of the entrance is 0.8 to 0.9 m/s. An overview of the magnitudes around the port entrance for the used flow fields of 1.0 up to 2.5 m/s is shown in appendix D.2.3.

5.4.1 Entrance angle of 120 degrees

For the entrance angle of 120 degrees, scenarios with current conditions of 1.0, 1.5, 2.0 and 2.5 m/s were simulated. The wide waterway layout, an entrance length of 60 meters and a width of 150 meters were used; the only variable parameter in these simulations was the flow velocity. The results for the forward and backward manoeuvres are shown in figure 5-9.

Although a limited amount of data points were gathered from the simulation study, a clear linear relation is shown. In appendix E the formulas for each trend line and the trend line fit to the acquired data (R^2 value) are shown.

Furthermore, figure 5-9 shows that the backward manoeuvres require a significantly larger entrance width than forward manoeuvres from downstream. The difference is circa 20 meters. These differences are the results of the available steering tools for the manoeuvres: for the backward manoeuvre only the bow thruster can be used to control the ship, in case of a forward manoeuvres the rudder and power burst were used which provide a better control.

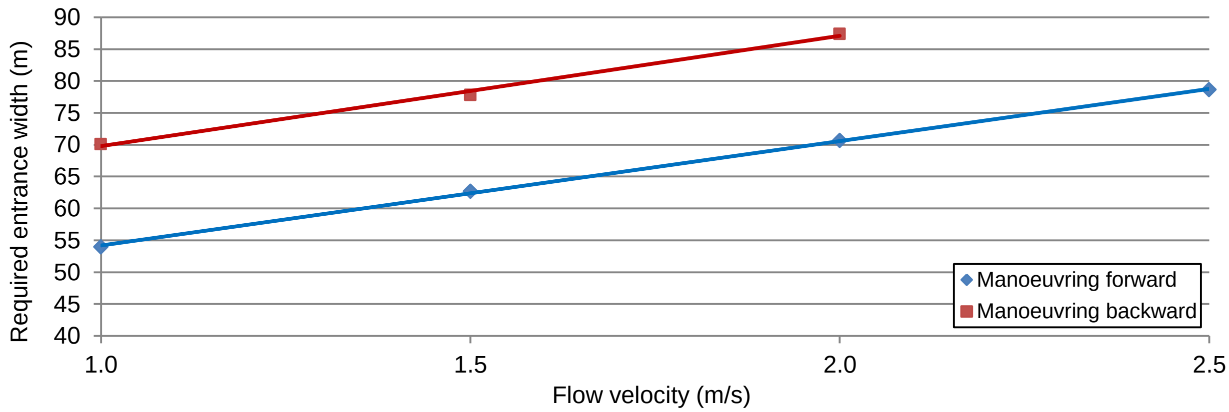


Figure 5-9: Relation between flow velocity and the required entrance width. Entrance length is 60 meters and angle of 120 degrees. The simulation results are indicated with the coloured markers.

5.4.2 Entrance angle of 90 degrees versus 120 degrees

The data points gathered with the conducted simulations for the forward and backward manoeuvres for entrance angles (α) of 90 and 120 degrees are shown in figure 5-10. For the 90 degrees entrance only 2 data points for the forward and backward manoeuvres are obtained with the simulation study. Based on these points it cannot be observed what the relation is between the flow velocities and required entrance widths. It is assumed that, similar to the 120 degrees data points, a linear relation holds. The linear relations are extrapolated to a flow velocity of 0.0 m/s. In appendix E the formulas for each trend line and the trend line fit to the acquired data (R^2 value) are shown.

Since the backward manoeuvres for current condition of 2.5 m/s were not possible to conduct, it is not legitimate to extrapolate for larger values. It should be mentioned that extrapolating the results of the forward manoeuvres can provide wrong results. Scenarios with flow velocities larger than 2.5 m/s were not included during the simulation study. Hence, the ship behaviour in current fields with larger flow velocities is unknown.

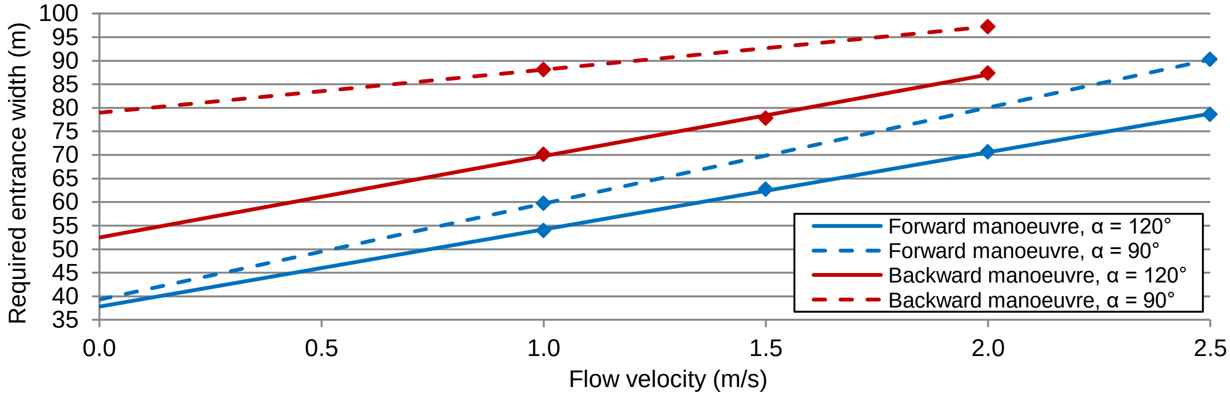


Figure 5-10: Relation between flow velocity and the required entrance width for entrance angles of 90 and 120 degrees.

Figure 5-10 shows that for forward manoeuvres and an increasing flow velocity, the required width for the 90 degrees layout is increasing more than for the 120 degrees layout. Around 0.0 m/s the required widths are approximately equal and for 2.5 m/s the difference is roughly 10 meters. This observed trend could be explained. When approaching the entrance for the 90 degrees layout, the heading of the ship is more perpendicular to the flow. As a consequence, the exposed surface of the ship's hull is larger, which causes a larger current force on the ship compared to an entrance of 120 degrees. The current force is related to the flow velocity squared, explained in appendix C, which causes a stronger increase for the 90 degrees entrance.

By contrast, this trend is not visible in figure 5-10 for the backward manoeuvres. For these manoeuvres the 120 degrees layout is increasing more. Furthermore, for 0.0 m/s the difference between the two angles is significant. This unexpected result can be caused by the chosen set-up for the manoeuvres. It is assumed that the linear relation for the 120 degrees data points is more accurate than for the 90 degrees line, because only two data point were used for the 90 degrees trend line. Moreover, the space usage on the waterway is small for the backward manoeuvres, because the manoeuvres are more sidewards into the port than for forward manoeuvres. As a consequence, the exposed surface of the ship to the current is smaller.

Extra simulations are required to determine the precise relations for different flow velocities and entrance angles. It is expected that the error is induced by the simulations for the 90 degrees simulations. For the 120 degrees entrance, the relation is based on three run results. In addition, the slope is similar to the slope of the forward manoeuvres for the 120 degrees entrance. Therefore, it is assumed that the results for the backward manoeuvres for an angle of 120 degrees are more reliable.

5.4.3 Sensitivity of the flow velocity parameter

Based on the simulation results, a linear relation holds between the flow velocities and the required entrance widths. As a consequence, the sensitivity of the flow velocity parameter is the same for every flow velocity. For an entrance angle of 120 degrees, a deviation of plus (minus) 0.5 m/s causes an increase (decrease) of the required entrance width of circa 8 meters. This means that when designing a port entrance, the chosen design flow velocity is influencing the port design significantly.

5.5 Entrance width

As mentioned before, the smallest entrance width occurs for an entrance angle of 120 degrees. For a forward manoeuvre sailing in upstream direction and a flow velocity of 2.5 m/s, an entrance width of 79 meters is required. For a backward manoeuvre, as replacement of the forward manoeuvre when sailing downstream, a width of 87 meters is required for a flow velocity of 2.0 m/s. These runs were conducted for an entrance width of 150 meters. Based on these two run results, the entrance width can be reduced significantly. A scenario with an entrance width of 90 meters was simulated to analyse the effect of a reduced entrance width on the width required for safe navigation. The results for the reduced entrance width and the entrance width of 150 meters are shown in table 5-16. For all simulated scenarios an entrance length of 60 meters and an angel of 120 degrees were used.

Table 5-16: Run results for an entrance width of 90 and 150 meters.

Run	Available entrance width (m)	Required waterway width (m)	Required entrance width (m)
Forward manoeuvre (run 59)	90	53	83
Forward manoeuvre (run 37)	150	53	79
Backward manoeuvre (run 60)	90	43	90
Backward manoeuvre (run 45)	150	49	87

5.5.1 Reduced entrance width versus wide entrance

The required entrance widths for the reduced entrance width (90 meters entrance) are 3 to 4 meters larger than for the entrance with a width of 150 meters, see table 5-16. The small differences can be caused by the differences in current pattern and magnitude around the entrance. In figure 5-11 the flow pattern around the port entrances are shown. The flow velocities in front of the port entrance, indicated with Zone A, are slightly larger for the entrance width of 90 meters; a difference of less than 0.2 m/s. The current gradient for the 150 meters entrance is wider than in case of the 90 meters entrance, indicated with Zone B. As a consequence, the cross current in the entrance is lightly stronger for the entrance with a width of 150 meters.

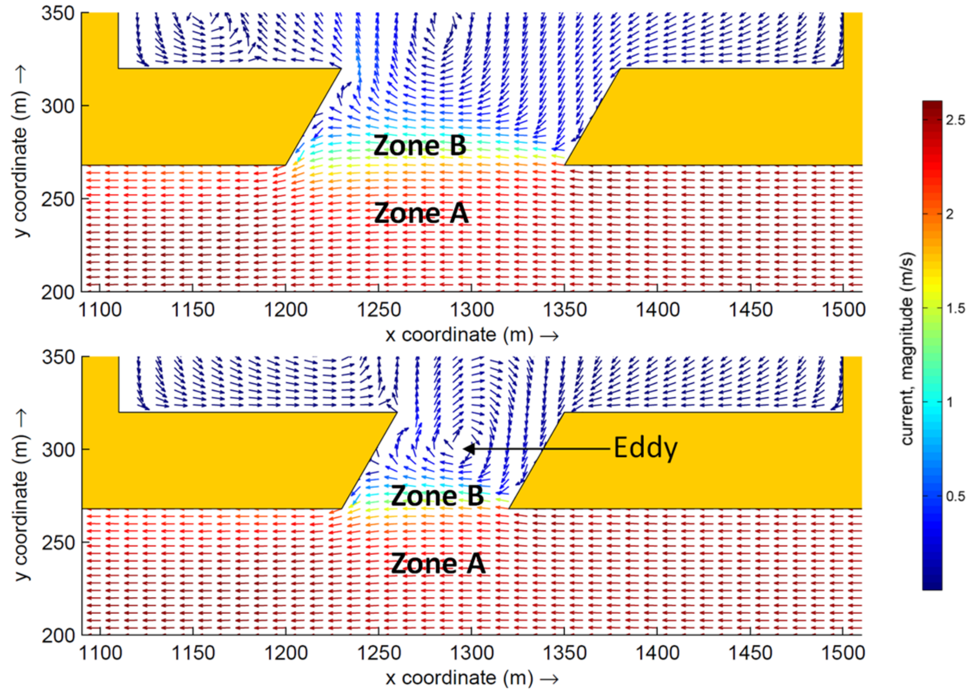


Figure 5-11: Close-up of current fields around port entrance for entrance width of 150 meters (up) and 90 meters (bottom).

Forward manoeuvres

For the forward manoeuvre into the port, the moment on the ship caused by hydrodynamic hull forces has a significant lager peak in the port entrance for the reduced entrance width than the entrance width of 150 meters. Figure 5-12 shows the moment on the ship due to hydrodynamic hull forces for both forward manoeuvres. Furthermore, the moment due to bank suction forces is shown. It can be observed that the magnitude of the bank suction forces is approximately the same. The reduced entrance width has no significant influence on the moment due to banks suction. By contrast, around the entrance a significant difference can be observed in the moment due to hydrodynamic hull forces. The larger required swept path for the 90 meters entrance, compared to the 150 meters entrance is a consequence of the larger moment on the ship in the entrance. This larger moment is caused by the stronger current in front of the entrance and the narrower flow gradient in the entrance.

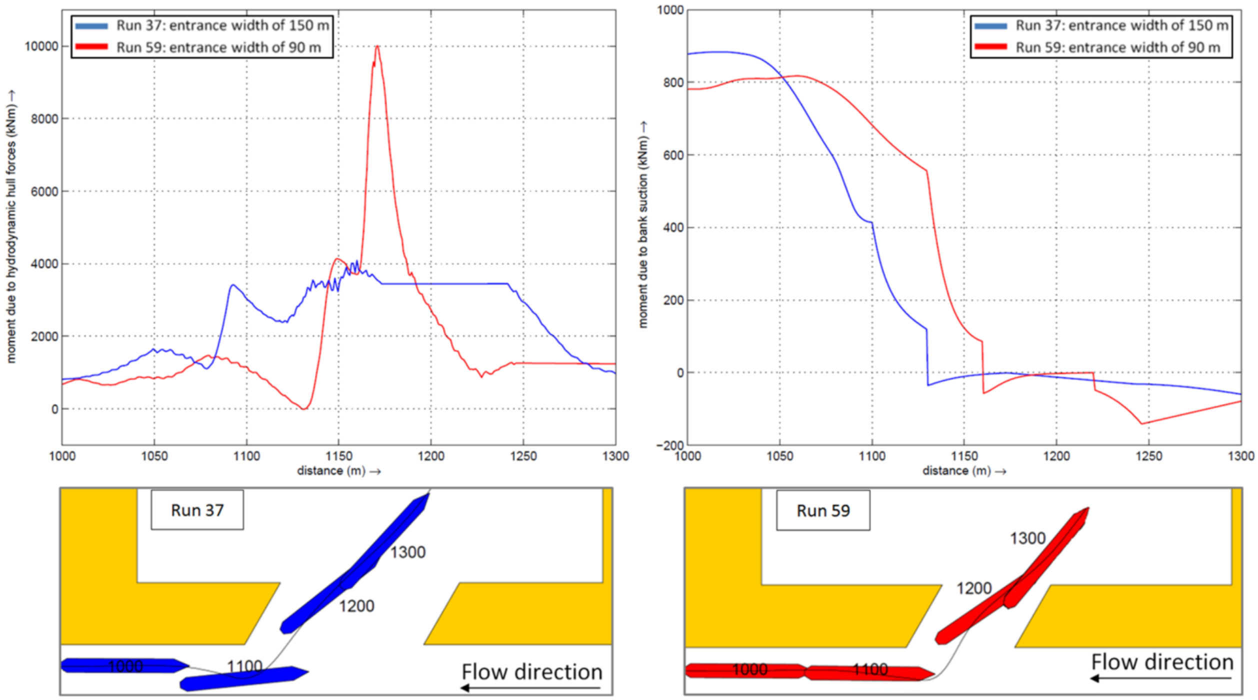


Figure 5-12: Moments caused by hydrodynamic hull forces (top left) and bank suction forces (top right) for the forward manoeuvres, runs 37 and run 59, into the port. The moments are plotted against the track distance. The position of the ship along the track is illustrated for both runs (left and right below).

Backward manoeuvres

For the backward manoeuvres into the port, the moments due to hydrodynamic hull forces are larger for the 150 meters entrance than for the 90 meters entrance. This is shown in figure 5-13. This is unexpected, because the flow gradient in the entrance is wider for this layout. Thus, in line with the explanation for the forward manoeuvres, a smaller moment is expected compared to the entrance with a width of 90 meters. However, during the set-up of the run for the 90 meters scenario this larger moment was avoided by choosing another manoeuvre through the entrance. Figure 5-13 shows the different manoeuvres through the entrances with a width of 150 and 90 meters. Although the chosen manoeuvre for the 90 meters entrance reduces the moment due to hydrodynamic hull forces on the ship, the manoeuvre requires a slightly larger swept path. In addition, it should be mentioned that for the backward manoeuvres the bank suction forces were not calculated by SHIPMA.

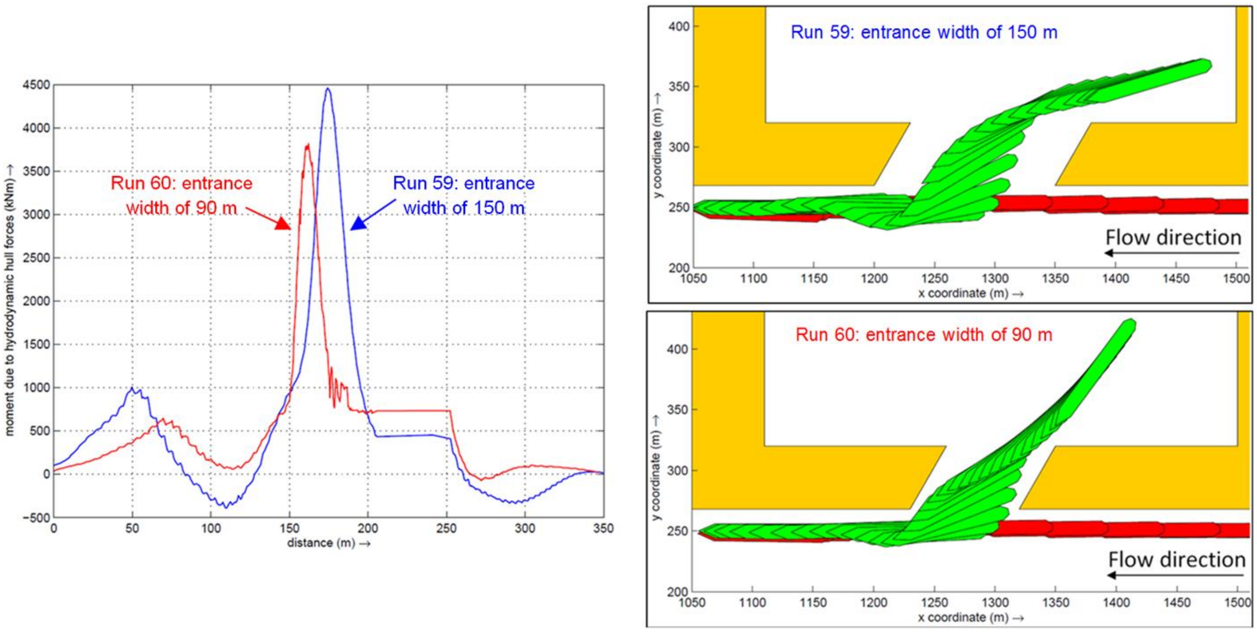


Figure 5-13: Moment caused by hydrodynamic hull forces for the backward manoeuvres, runs 45 and 60, into the port (left). Track plots for both runs are indicated (right figures). The forward part (green) and backward part (red) of the run are indicated.

Influence of eddy

The entrance with a width of 90 meters has a larger length/width ratio than the 150 meters entrance. As a consequence an eddy arises in the entrance for the reduced entrance width scenario. This is shown in figure 5-11. The velocity magnitudes are small; less than 0.5 m/s. Therefore, the effect of the eddy on the ship manoeuvre is hardly noticeable. This effect is negligible compared to the influence of the flow gradient. As mentioned before in section 5.3.3, these eddies can be problematic for a skipper.

5.5.2 Sensitivity of the entrance width parameter

In table 5-16 is shown that a reduction of 60 meters in entrance width, results in an increase of the swept path of 3 to 4 meters. The precise relation between the entrance width and the swept path of the ship in the entrance cannot be determined based on this limited amount of results. However, these results indicate that the sensitivity of this parameter is low.

5.6 Flooded entrance dams

The effect of the flooded entrance dams is simulated for one forward manoeuvre into the basin with an entrance length of 60 meters, an angle of 120 degrees and a width of 150 meters. In this paragraph this scenario is compared to a similar simulated scenario with dry entrance dams. For both runs a current field of 2.5 m/s, modelled with Delft3D and not a scaled field from 1.0 m/s to 2.5 m/s, is used. Bot runs can be compared to each other, because the same modelling methods are used. Note that there is a difference in the current patterns compared to the scaled current fields, see appendix D.2.1. This should be taken into consideration when comparing the results of run 65 and 66 with the other runs.

The simulation results are shown in table 5-17. A difference of 2 meters in the required entrance width can be observed. The flooded entrance scenario is less favourable.

Table 5-17: Overview of required waterway width and entrance width for flooded and dry entrance dams scenarios.

Run	Required waterway width (m)	Required entrance width (m)
Flooded entrance dams (run 65)	60	84
Dry entrance dams (run 66)	54	82

In figure 5-14 the track plots with current fields for both scenarios and a plot with the differences in the current field around the port entrance are shown. In Zone A, the zone above the white dashed line, the flow velocities of the flooded scenario are larger than those for the dry scenario. In Zone B, the zone below the white dashed line, the flow velocities of the flooded scenario are smaller. These slightly smaller velocities are the consequence of the larger local widening in the waterway compared to the dry scenario.

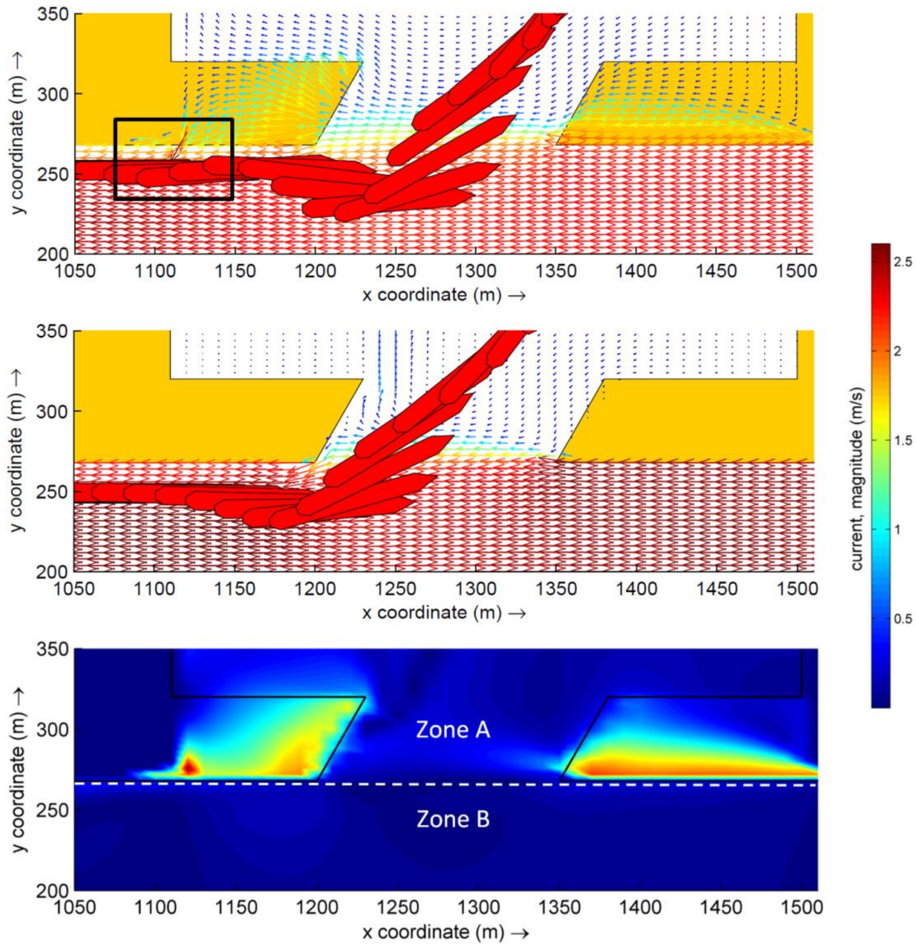


Figure 5-14: Track plots close-up around port entrance for flooded entrance dams scenario (top) and dry entrance dams scenario (middle). The differences between the magnitudes in the current fields for both scenarios are indicated (bottom).

In the flooded scenario the ship is exposed to larger transverse flow velocities downstream of the entrance, indicated with the black box in figure 5-14. First, these velocities cause a large force on the bow of the ship and consequently on the stern of the ship. The ship responds to this situation by a rotation of the bow to port side of the ship and subsequently a rotation to starboard side. Then the ship has to turn to port side again in order to manoeuvre safely into the entrance. As a consequence of these rotations, the required waterway width is larger for this scenario. The larger velocity downstream of the bank is the result of the chosen bottom profile for Delft3D. An abrupt transition between the low (flooded) dams and the high lying (dry) banks was modelled. A more gradual transition from wet to dry banks would reduce the velocities significantly. When correcting this modelling effect, the required waterway width for the flooded scenario will be more similar to the dry scenario.

The flow velocities in front of the entrance are 0.0 to 0.2 m/s smaller for the flooded scenario. As was shown in paragraph 5.4, an increase in flow velocity will cause an increase in the required entrance width. In contrary, the cross current in the entrance is 0.0 to 0.3 m/s larger for the flooded scenario. The differences in the required entrance width for both scenarios are small.

The differences in required entrance waterway width are small. Based on these results it can be concluded that flooded entrance dams are not a significant improvement or deterioration for a port entrance. However, only one scenario with flooded entrance dams was taken into account. It is possible that for another layout the results are more different. For example, for a layout with larger water depths in the entrance and above the entrance dams, the keel clearance of the ship is larger. As a consequence the flow velocities close to the bottom are less important than the flow velocities around the water surface. Hence, the average flow velocities and patterns around the ship's hull will be different compared to current pattern illustrated in figure 5-14. In addition, it is possible that for certain situations, besides the entrance dams between the basin and waterway, other parts of the port are also flooded. These will change the current pattern around the entrance considerably. Additional simulations are required to study these layouts.

5.7 Lock approach harbours

In the simulation study, 4 runs were conducted for layouts similar to an approach harbour before locks parallel to a waterway axis. Only forward manoeuvres into the lock approach harbour were simulated. For the arrivals into the lock approach harbour, it is important that a manoeuvre is used that provide a heading in the direction of the lock chamber. Then a ship can approach the lock chamber easily after arriving in the lock approach harbour. Therefore, for a lock chamber located parallel to the waterway axis, a sideward manoeuvre is desired to sail through the entrance of the lock approach harbour. See figure 3-6 and figure 3-7 for an indication of a lock approach harbour parallel to the waterway axis and the used schematisation in the simulation study.

Simulations were conducted for flow conditions of 1.0 and 2.5 m/s. The entrance width of the lock approach harbour is 200 meters and the length is 8 meters. The required entrance and waterway widths for each run are indicated in table 5-18. The required basin length is also included in the table. In figure 3-7 is shown how the basin length (L_b) is defined.

Table 5-18: Overview of run results of lock approach harbours.

Run	Flow velocity (m/s)	Required basin length (m)	Required waterway with (m)	Required entrance width (m)
Sailing upstream (run 60)	1.0	28	42	104
Sailing upstream (run 61)	2.5	29	46	110
Sailing upstream (run 62)	1.0	31	44	161
Sailing upstream (run 63)	2.5	49	47	171

All the runs require a similar waterway width in order to manoeuvre safely into the lock approach harbour. The arrivals sailing upstream require considerably smaller entrance widths compared to the arrivals sailing downstream. This is line with the other results presented earlier in this chapter.

The used space in the basin is relatively small compared to the modelled basin. Based on these results the basin length can be reduced significantly, see table 5-18. The required basin lengths are between 28 to 49 meters and the available basin is length is 200 meters. It should be mentioned that when adjusting the basin length, the current pattern will change in the entrance. Hence, based on the simulation results, the required basin length cannot be determined precisely.

Furthermore, the entrance width of 200 meters used for the runs is larger than required. According to the simulation results, an entrance width of 104 to 110 meters is sufficient for arrivals sailing upstream. For the arrivals sailing downstream a minimum width of 161 to 171 meters is required.

The entrance lengths of the entrances are small. Hence, the entrance can be seen as an entrance width an angle of 0 or 180 degrees. The 0 degrees entrance is for the arrivals sailing downstream and the 180 degrees entrance for the arrivals sailing upstream. In paragraph 5.2 the relation between the entrance angle and required entrance width and the most efficient angles are shown in figure 5-5. The manoeuvres into the lock approach harbours are added to this figure, the result is shown in figure 5-15.

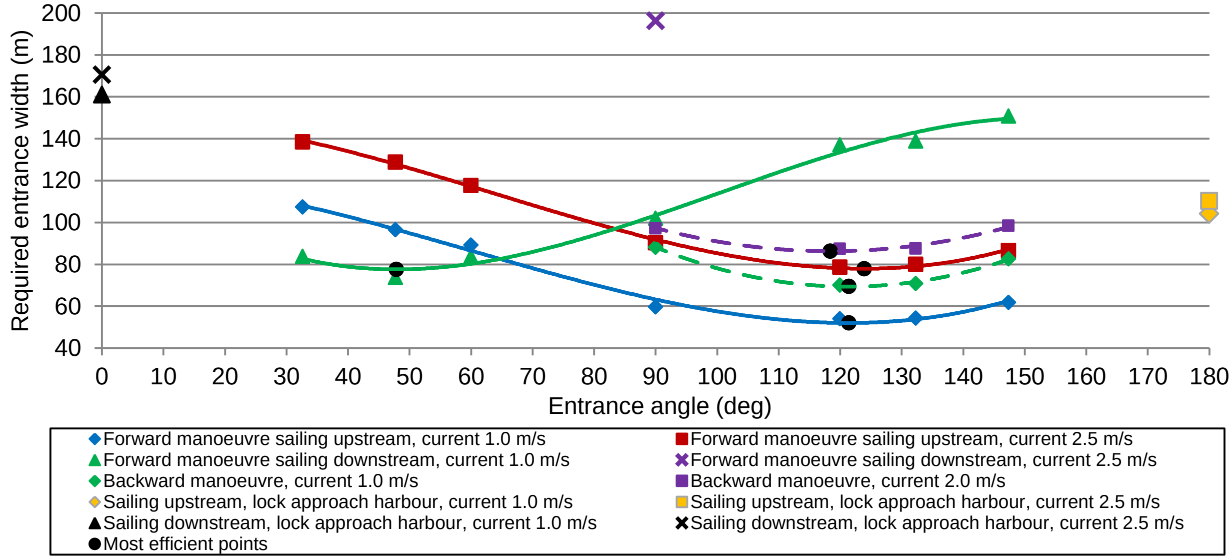


Figure 5-15: Relation between required entrance width and angle. Figure 5-5 is adjusted by adding the results for the lock approach harbours. The simulation results are indicated with the coloured markers.

First, it should be mentioned that the angles discussed in paragraph 5.2 and figure 5-5 are gathered by using a different method to set-up the manoeuvres. For the lock approach harbours the manoeuvres through the entrance are almost sidewards, whereas in the other runs the manoeuvres through the entrance are performed with a heading of the ship more parallel to the entrance banks. In addition, a significant smaller entrance length was used for the lock approach harbours. In paragraph 5.3 was concluded that the sensitivity of the entrance length is very small. However, only the influence of the entrance length was analysed for forward manoeuvres sailing upstream and backward manoeuvres as replacement of the forward manoeuvres sailing downstream. So, the effect of the entrance length on the required width when sailing downstream and manoeuvring forward into the port was not included.

Despite the differences, figure 5-5 shows that:

- The required entrance widths for the lock approach harbours increase slightly when the flow velocity increases. These increases are much smaller than for the 120 and 90 degrees entrance, discussed in section 5.4.2. As a consequence of the smaller influence of the current on the ship's hull, the smaller increases are an expected result. This aspect is explained in section 5.4.2.
- The arrivals when sailing upstream into the lock approach harbour, for current conditions of 1.0 and 2.5 m/s, require a larger entrance width than the most efficient entrance orientation of approximately 120 degrees.

- The arrival when sailing downstream into the lock approach harbour for current of 1.0 m/s requires a larger entrance width than the most efficient entrance orientation of approximately 50 degrees. It is even less efficient than all required entrance widths for angles between 30 and 150 degrees.
- The arrival when sailing downstream into the lock approach harbour for a current of 2.5 m/s requires a smaller entrance than for an angle of 90 degrees. The precise relation between the entrance angle and the required entrance width for a current of 2.5 m/s is not determined in this research; only a run for an angle of 90 degrees was conducted. Although, these scenarios were not simulated, the available results indicate that for a flow velocity of 2.5 m/s, it can be more favourable to manoeuvre sideward through the entrance when sailing downstream. Furthermore, the length of the entrance is an important parameter that determines which type of manoeuvre is more favourable. Additional simulations are required for a more detail analysis.

5.8 Conclusions

It should be noted that not all possible design parameters were included in the simulation study of this research. Only the included design parameters in the simulation study are discussed here. The influence of these parameters is described in section 5.8.1. Based on these outcomes, the most efficient entrance is described in section 5.8.2. In addition, in section 5.8.3 the conclusions regarding the lock approach harbours are presented.

5.8.1 Influence of design parameters

The observed influences of the different design parameters are shown in this paragraph. First, the results with respect to the ship manoeuvres and waterway width are described. The results of the other design parameters are only valid for waterway widths larger than 90 meters, because only simulated arrival scenarios were used to study these design parameters. This is explained below.

Ship manoeuvres and waterway width

The manoeuvrability of the ships is influenced by the available waterway width. In general, a wider waterway contributes to a smaller required entrance width. For the simulated departure scenarios it was shown that a larger waterway width reduces the required entrance width significantly. For the arrival scenarios it appeared that:

- Manoeuvring from a large lateral approach distance into the port requires a smaller entrance width than manoeuvring from a small lateral distance into the port.
- The arrival scenarios for sailing downstream require a significant larger entrance width than the arrivals when sailing upstream.

The major drawback of a large lateral approach distance is the large area needed on the waterway to execute a turning manoeuvre into the port. Furthermore, crossing a large part of the waterway can possibly cause hinder to other traffic on the waterway. In order to avoid incidents with through traffic, it was decided to use only arrival scenarios with a lateral approach distance as close as possible to the port entrance. When taking the established safety criterion for manoeuvring space into account, the minimum distance is about 12 meters. Moreover, the manoeuvres with a small approach distance are more decisive than manoeuvres with a large approach distance.

For the upstream side of the port entrance, it was established that the arrivals are more decisive than the departures. For the downstream side of the port, this depends on the available waterway width:

- For a waterway width smaller than 50 meters, the departures are the decisive manoeuvres.
- For a waterway width larger than 90 meters, the arrivals are the decisive manoeuvres.

- Between a waterway width of 50 and 90 meters, a transition point is expected where the decisive manoeuvre switches from departures to arrivals. This precise point cannot be determined based on the simulation results. Additional simulations are required to determine the transition point more precisely.

From all the forward manoeuvres in and out of the port, it was determined that the arrivals sailing downstream are the most decisive manoeuvres. For these arrivals, it is for certain situations possible to turn the ship downstream of the port entrance and approach the port sailing upstream. This downstream turn is possible when the waterway is sufficiently wide and the manoeuvre is not unsafe with respect to the trough going traffic. For these situations the arrivals sailing upstream or the departures sailing downstream, depending on the available waterway width, are the most decisive manoeuvres.

Entrance angle

From the simulation results, it can be concluded that the entrance angle can influence the required entrance width considerably. The following most efficient entrance angles were determined for the arrival scenarios:

- Downstream sailing, forward manoeuvre into the port and current of 1.0 m/s: 50 degrees.
- Downstream sailing, backward manoeuvre into the port and currents of 1.0 to 2.0 m/s: 120 degrees.
- Upstream sailing, forward manoeuvre into the port and currents of 1.0 to 2.5 m/s: 120 degrees.

For the arrivals sailing downstream, it was shown that a backward manoeuvre is significantly more efficient than a forward manoeuvre into the port. These backward manoeuvres are slightly less efficient than the forward manoeuvres into the port for the arrivals sailing upstream. So, an entrance angle of approximately 120 degrees is more desired with respect to minimising the required entrance width and providing nautical safety. This is indicated in figure 5-16.

Moreover, the entrance angles around 120 degrees are more desired than the entrance angle of 50 degrees with respect to minimising siltation. As was concluded in chapter 2, an entrance angle larger than 90 degrees is more efficient regarding minimising the siltation compared to an entrance angle smaller than 90 degrees.

The trend lines based on the simulation results are shown in figure 5-16 for the backward manoeuvres for arrivals sailing downstream and forward manoeuvres for arrivals sailing upstream. It is shown that the sensitivity around the most efficient points is low.

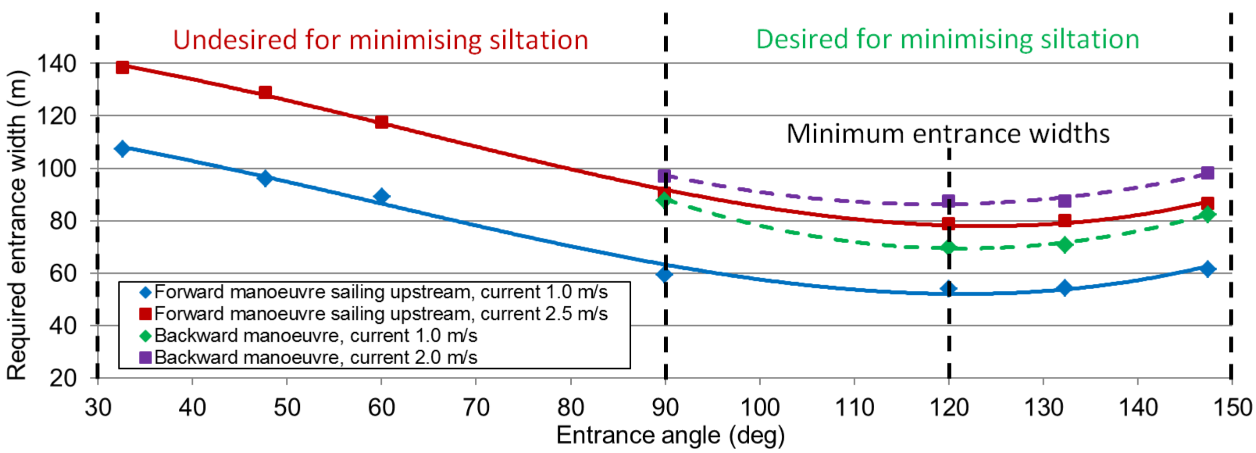


Figure 5-16: Relation between entrance angle and required entrance width. The run results are indicated with the markers. The most efficient angles with respect to nautical safety and minimising siltation are indicated.

Entrance length

The influence of the entrance length was analysed for arrival scenarios. Forward manoeuvres were used for arrivals sailing upstream and backward manoeuvres for arrivals sailing downstream. The forward manoeuvres were conducted for flow velocities of 1.0 and 2.5 m/s and the backward manoeuvres for 1.0 and 2.0 m/s. Layouts with an entrance angle of 120 degrees were used. It was found that:

- For the forward manoeuvres, a smaller or larger entrance length is not affecting the required entrance width. The swept path of the ships is largest in the first part of the port entrance. Therefore, a further increase in entrance length is not affecting the required entrance width.
- For the backward manoeuvres and a flow velocity of 1.0 m/s a similar explanation holds as for the forward manoeuvres.
- For the backward manoeuvres and a flow velocity of 2.0 m/s a minor effect was observed for entrance lengths between 60 to 120 meters. For this scenario, the required width for the 60 meter entrance is circa 7 meters smaller than for an entrance with a length of 120 meters.

It should be mentioned that forward manoeuvres for the arrival scenarios when sailing downstream were not included in the simulation study for different entrance lengths. Therefore, the effect of the entrance length in combination with these arrivals is not established. Additional simulations are required to determine the effect of the entrance length for these arrivals.

Flow velocity

As a result of the study it was concluded that when the flow velocity increases the required entrance width increases. In addition, it was shown that a linear relation holds between the flow velocities and the required entrance widths. The sensitivity of this parameter is significant. For an entrance angle of 120 degrees, a deviation of plus (minus) 0.5 m/s increases (decreases) the required entrance width with circa 8 meters.

Entrance width

For a reduced entrance width, the current pattern around the port entrance changes. As a consequence, the required entrance width increases when the entrance width decreases. However, the sensitivity of this parameter is low. For an entrance angle of 120 degrees, the difference between an entrance width of 150 meters and 90 meters was only 3 to 4 meters.

Eddies in entrance

For two layouts an eddy arose in the port entrance. This happened for an entrance width of 150 meters and a length of 120 meters and for an entrance width of 90 meters and a length of 60 meters. The length/width ratio was larger for these situations than for the other layouts. The magnitudes of these eddies were smaller than 0.5 m/s. It appeared that for these small velocities, the required entrance width was not affected by these eddies. It should be mentioned that for a skipper these eddies can be more problematic. However, this aspect was not included in the simulation study, whereas the influence of an actual human operator is not included in the SHIPMA model.

Flooded entrance dams

For the simulated scenario with the flooded entrance dams, only small differences were observed in the current field in front of the entrance and in the entrance; the velocity magnitude differences are smaller than 0.3 m/s. The simulation results showed that flooded entrance dams are not a significant improvement or deterioration with respect to the required entrance width. However, it should be mentioned that only one layout, illustrated in figure 3-8, with flooded entrance dams was used. Other layouts and other water depth conditions can create different situations. Additional research is required to study the influence of flooded entrance dams on the required entrance width.

5.8.2 Minimum entrance width and most efficient layout

The minimum required entrance widths for the flow velocities between 1.0 and 2.5 m/s are shown in table 5-19. These minimum entrance widths are provided for an entrance angle of 120 degrees (see figure 5-16) and an entrance length of 60 meters. The presented minimum entrance widths are only valid when the arrivals sailing upstream are more decisive than the departures sailing downstream, because most of the design parameters are only studied for arrival scenarios. As explained in the previous section, this holds for available waterway widths of 90 meters or larger.

Table 5-19: Overview of determined minimum entrance widths for flow velocities between 1.0 and 2.5 m/s.

	Forward manoeuvre, arrival sailing upstream		Backward manoeuvre, arrival sailing downstream	
Entrance width:	**150 m**	**90 m**	**150 m**	**90 m**
Current: 1.0 m/s	54 m	-	70 m	-
Current: 1.5 m/s	62 m	-	78 m	-
Current: 2.0 m/s	71 m	-	87 m	90 m
Current: 2.5 m/s	79 m	83 m	-	-

For this most efficient situation, the forward manoeuvres into the port when sailing in downstream direction are replaced by backward manoeuvres. Backward manoeuvres for flow velocities larger than 2.0 m/s were not possible to conduct, due to the limited influence of the bow thruster for these situations. For the arrivals sailing upstream, only a scenario with an entrance width (90 meters) similar to the required width was used for a flow velocity of 2.5 m/s. For the arrivals sailing downstream this scenario was only simulated for a flow velocity of 2.0 m/s. For the scenarios with other flow velocities the required entrance widths were obtained by using an entrance width of 150 meters.

Based on the sensitivity of the other studied design parameters, the determined required entrance widths are mainly sensitive for deviations in the flow velocity.

5.8.3 Lock approach harbours

For the simulated arrival scenarios into the lock approach harbours, it was shown that the required entrance widths for flow velocities of 1.0 and 2.5 m/s are similar. Furthermore, the arrivals when sailing upstream require an entrance width of 104 to 110 meters and when sailing upstream a width of 161 to 171 meters is required. These required widths are significantly larger compared to the most efficient layout presented in the previous section.

In this chapter the manoeuvres into the approach harbour sailing downstream were compared with the other simulated arrival scenarios sailing downstream and manoeuvring forward into the port. The simulation results indicate that for small entrance lengths and large flow velocities, it can be more favourable to manoeuvre sideways through the entrance compared to a heading more parallel to the entrance banks. However, additional simulations are required to study the differences between sideway manoeuvres and manoeuvres with a heading parallel to the entrance banks. Furthermore, the length of the entrance is an important parameter that determines which type of manoeuvre is more favourable. It should be noted that for a lock approach harbour the location of the lock chamber is important for the chosen manoeuvre into the approach harbour.

In addition, basin lengths between 30 to 50 meters were required for these manoeuvres. A basin length of 200 meters was used for the simulations. So, a significant smaller basin length should be sufficient. When reducing the basin length, the current pattern around the entrance will change. This can affect the manoeuvres. Hence, additional simulations are required to determine the required basin length more precisely.

6

Discussion

In this research the minimum entrance width for an inland port was determined by performing a fast-time simulation study with SHIPMA. In addition, the influence of several design parameters was studied. In this chapter, the acquired results based on the performed simulation study will be discussed. First the interpretation of the simulation results will be discussed in paragraph 6.1. Thereafter, in paragraph 6.2 the results based on the performed simulation study are compared to the existing design rules and the results of previous entrance studies. In the simulation study only a rectangular shaped entrance layout was used. Paragraph 6.3 discusses the possibilities to use other entrance shapes than the rectangular ones.

6.1 Interpretation of the results

Ship types

In the simulation study only scenarios were simulated with the loaded CEMT class Va ship. As a result of the analysed previous entrance studies it was concluded that a larger ship requires generally a larger entrance width. Besides, manoeuvres with pushed convoys were more difficult to perform than with other ships. Based on these results it is expected that the determined most efficient entrance in this research is sufficiently wide for smaller ships and insufficiently wide for larger ships than the loaded Va ship. However, the precise relation between other ship types and the required entrance width is not established in this research. Additional research is required to determine the precise relation between the required entrance width and other ship dimensions and types. In order to determine the relation between different ship types, the influence of the wind should be included for ships with a large wind area.

Waterway width and approach distance

The simulation study was set up in two groups of simulations. From Group 1 it was concluded that arrival scenarios are the most decisive manoeuvre for a waterway wider than 90 meters. The simulated scenarios of Group 2 were only arrivals. Mainly the results of Group 2 were used to achieve the objective of this research. Hence, the conclusions are only valid for waterways larger than 90 meters. In addition, it appeared that a transition point for the decisive manoeuvres (departures or arrivals) occurs between a waterway width of 50 and 90 meters. Additional research is required to establish the precise transition point. When this point is determined, the validity range of the research results can be enlarged.

The lateral approach distance that was chosen for the simulations of Group 2 was as close as possible to the shore; circa 1B. The simulation study showed that a larger approach distance is favourable with respect to minimising the entrance width. So, for local situations where skippers use often a larger approach than 1B, the results of this study are conservative. However, it should be noted that a skipper decides which approach distance is used to enter the port. As a consequence, the most conservative approach distance should be used to design the entrance.

Flow velocity

The simulation results showed that the influence of the flow velocity on the required entrance width is large. A small difference in the input of a current field can affect the outcome. In this research a fictional layout was used for the simulation study. In this layout no irregularities were included. For local situations, the conditions will be more irregular. As a consequence, the flow velocities around the port entrance can be larger or smaller than was showed in this research. The used flow fields for this research have magnitudes of 10 to 20% smaller in front of the port entrance compared to downstream. When for a local situation these differences are larger or smaller, this will affect the required entrance width.

Moreover, the flow velocity was defined as the average flow velocity around the hull of the ship. The used water depth/draught ratio (h/T) was 1.3. Therefore, the difference between the depth average velocity and draught integrated velocity is small. When this ratio becomes larger, the difference between depth average and draught integrated velocity will increase.

Water depth

An h/T ratio of 1.3 was used for the mathematical ship model during the simulations, since other ratios were not available for this ship model. The minimum required ratio for CEMT class Va ships according to WG2011 is 1.4 for a normal waterway profile. For a narrow profile this ratio is 1.3. A larger ratio will enlarge the ease of manoeuvring. The simulation results are therefore on the safe side. In general, for large flow velocities the water depth is larger and thus the h/T ratio is larger. It is expected that the most efficient entrance angle will not differ much when the h/T ratio is larger, because the following simplified relation holds for the current forces on the ship's hull (Ligteringen & Velsink, 2012; OCIMF, 2010):

$$F = \frac{1}{2} \cdot C_c \cdot \rho \cdot v^2 \cdot A_c$$

The current force coefficient (C_c) will decrease for a larger h/T ratio and thus the forces on the ship are reduced. This contributes to an increased manoeuvrability. As explained before, when the current velocity decreases, the required entrance width decreases. This water velocity around the ship's hull (v) is also related to the forces on the ship's hull. Although, the required width is changing, the most efficient angle is similar. Therefore, it is expected that the same holds for an increased h/T ratio; the required width is decreasing, but the most efficient entrance angle remains the same.

In chapter 2, previous entrance studies to the ports of Haaften and Lobith were described. In these studies it was mentioned that for flow velocities between 1.7 and 2.0 m/s, water depths of circa 11 meters are expected. For these conditions, the h/T ratio is significantly larger. As a consequence, the manoeuvrability in these situations is better than used in the simulation study. So based on the chosen h/T ratio, it is expected that the determined minimum required safe entrance width is not fully optimised yet, the chosen h/T ratio is more conservative. These overestimations can be different for each local situation. More research is required to determine the relation between the h/T ratio and the required entrance width.

Eddies

As a result of the analysis of the simulation results, it was concluded that the influence of eddies, with a magnitude smaller than 0.5 m/s, on the required entrance width was negligible. However, it should be mentioned that for a skipper these eddies can be more problematic. However, this aspect cannot be studied with SHIPMA, whereas the effects of an actual human operator are not included in the model. Additional research is required to study the effect of eddies on the required entrance width.

Wind

As described in section 3.3.5, the wind forces, in case of a loaded ship, are small compared to the current forces. For relative water velocities of 1.0 m/s the wind forces are about 10% of the current forces. For larger velocities the wind forces are hardly noticeable for a loaded CEMT class Va ship compared to the current forces. It should be mentioned that when manoeuvring in or out of a port, a moment is required to make a turning manoeuvre. This yaw rotation was not included in the simplified current and wind calculations presented in appendix C. The simplified calculations give only an indication of the magnitudes of the current and wind forces.

For the most efficient entrance, determined in this research, forward and backward manoeuvres into the port were used. Forward manoeuvres for the arrivals sailing upstream and backward manoeuvres for the arrivals sailing downstream. Both manoeuvres are sailing through the entrance against the flow direction. Hence, the relative water velocity is large; at least 1.5 m/s when taking into account a ground speed of 0.5 m/s and a flow velocity of 1.0 m/s. As a consequence, the wind forces are less than 5% of the current forces, see appendix C for the calculation results of the wind and current forces on the hull of the ship.

For other ship types such as unloaded ships and container ships, which are exposed to larger wind forces and smaller current forces, the influence of the wind is considerably more important. The total wind and current forces on the loaded CEMT class Va ship are larger. Therefore, it is expected that for fast-time simulations with unloaded ships and container ships, smaller entrance widths are required compared to the loaded Va ship.

The influence of wind gusts and the reaction of a human operator on these fluctuations cannot be determined with SHIPMA. The wind gusts can influence the required entrance width. Additional research with real-time simulations is required to study the magnitude of this effect.

Furthermore, it should be noticed that the wind direction is an important factor that determines whether the influence of the wind is favourable or unfavourable for a manoeuvre. This can be different for every local wind climate and manoeuvres to be conducted. Besides, it is questionable whether the maximum wind speed will occur simultaneously with the maximum flow velocity. These aspects are not included in this research, but should be included when designing an inland port entrance.

Waves

SHIPMA is also capable of including the influence of waves (MARIN & Deltares, 2015). At inland waterways wind waves are small in height and short of period, therefore the wave drift forces are small and insignificant for manoeuvring. Hence, the influence of waves was not included in the simulation study.

SHIPMA limitations

The simulations study is performed by conducting fast-time simulations with SHIPMA. SHIPMA is not suitable for detailed design and taking into account human interference. This means that the results are only applicable for an initial indication of the entrance design for an inland port. The decisions made by an actual human operator to anticipate on sudden changes in the wind speed or flow velocities cannot be simulated with SHIPMA. Visibility aspects are not included in this research and can be different for each local situation. In addition, ship-ship interactions are not taken into account by SHIPMA.

The set-up of a SHIPMA run is an important factor for the acquired output of the run. Different users can obtain different results when simulating the same scenario; this means similar environmental conditions and ship type. The chosen manoeuvring track, propeller revolutions and automatic pilot settings along this track depend on the user. So, this part of the set-up is more subjective; the acquired results can be different for each user. Hence, the absolute values of the required entrance width, determined by the simulation study, should not be used as accurate results. By contrast, it is expected that the observed trends based on the simulation output are more reliable, because the runs are set up in a similar manner and by the same user. The used method to seek for the most efficient run was described in section 3.3.6. In addition, the bow thruster was not used during the forward manoeuvres into or out of the port. Only for the stopping manoeuvres in the basin the bow thruster was used. The use of bow thruster when manoeuvring in or out of the port can contribute to a more efficient run.

Additional research with real-time simulations is required to study the influence of the aspects that cannot be studied with SHIPMA simulations.

6.2 Research results related to previous studies

Existing guidelines

As mentioned before, according to WG2011 the entrance width should be 4B, for currents up to 0.5 m/s. This is in agreement with a width of circa 46 meters for the used ship model during the simulation study in this research. Another design rule was suggested by PIANC et al. (2014). PIANC et al. advise to design an entrance with a width equal to or larger than the overall length of the design ship, in order to prevent the possibility of the ship becoming stranded across the entrance in case of an incident. So, this rule is in agreement with an entrance width of 108 meters for the used mathematical ship model.

In figure 6-1 the results for the minimum required entrance width are plotted. The results presented in table 5-19 are used. The data points are indicated with the cross markers. The relation between the flow velocity and the required entrance width, divided by the beam of the ship, is shown. The forward and backward manoeuvres into the port entrance for an entrance angle of 120 degrees are plotted. Linear trend lines (solid lines) are added and extrapolated to a flow velocity of 0.5 m/s. The two design rules are added to this figure.

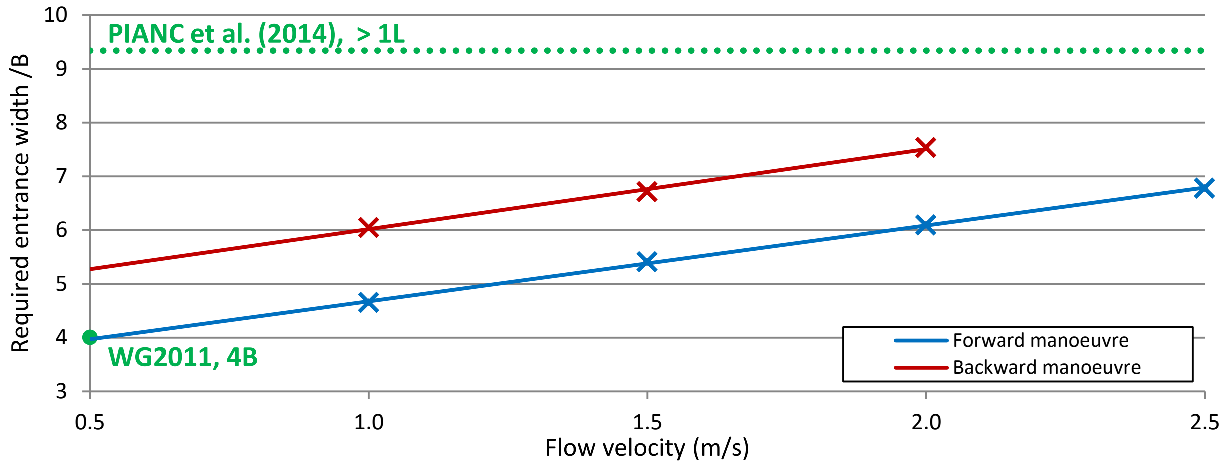


Figure 6-1: Relation between flow velocity and required entrance width for 120 degrees entrance. The design rules of WG2011 and PIANC et al. (2014) are included in this figure.

When comparing the simulation results with the 1L rule of PIANC et al. (2014), then it can be concluded that this design rule is more conservative compared to the minimum required entrance width determined in this research. This is not an unexpected outcome, because the 1L rule is not created with respect to minimising the entrance width as much as possible.

In figure 6-1 can be observed that the linear relation for the forward manoeuvre is in line with the WG2011 rule of 4B. A backward manoeuvre for a flow velocity of 0.5 m/s requires a larger entrance width than 4B, namely 5.3B. For flow velocities up to 0.5 m/s, it is not unlikely that a forward manoeuvre for an arrival scenario sailing downstream is more favourable compared to a backward manoeuvre. Figure 6-1 shows that the 4B rule is in agreement with the SHIPMA results of this research. However, it should be noted that the simulation results are for an entrance angle of 120 degrees and the 4B rule is normally applied for entrances perpendicular to the waterway axis, because the 4B rule is for a situation without current.

Based on the simulation study results, the relation between the entrance angle and required entrance width was plotted, for flow velocities between 1.0 and 2.5 m/s. Assuming that a similar relation holds for the forward manoeuvres into the port sailing upstream for a current of 0.5 m/s, then it is possible that the entrance width can be more efficient than the 4B rule. This is illustrated in figure 6-2.

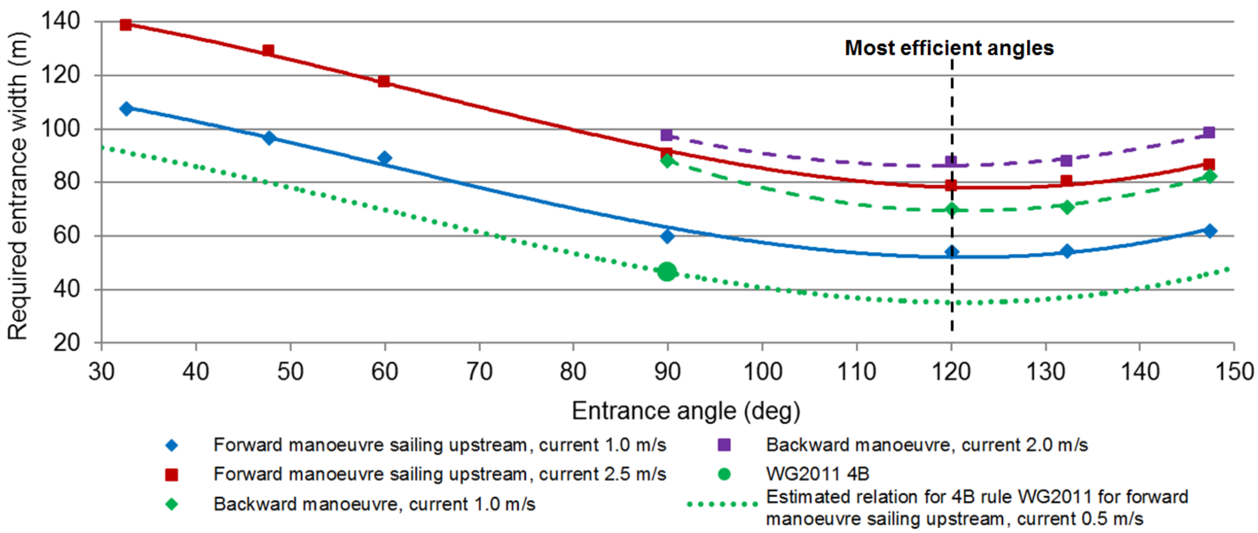


Figure 6-2: Determined relations between entrance angle and required entrance width based on simulation results. Estimated relation for 4B rule from WG2011 is added.

Figure 6-2 shows that an entrance angle of circa 120 degrees is most efficient for a current of 0.5 m/s. For this angle arrivals sailing downstream are less favourable. For these manoeuvres a backward manoeuvre can be used. However, a backward manoeuvre with a flow velocity up to 0.5 m/s and an entrance angle of 120 degrees is probably less efficient than the 4B rule with a 90 degrees entrance angle. Based on this analysis, a 120 degrees entrance is only more favourable compared to the 4B rule in case arrivals sailing downstream can turn downstream of the port entrance and approach the port in upstream direction. Additional simulations are required to study the required entrance width more accurately for backward and forward manoeuvres for a 120 degrees entrance and a flow velocity up to 0.5 m/s.

Previous entrance studies

The results from the analysed previous entrance studies are shown in figure 6-3. The minimum required entrance widths that followed from the simulations study in this research are included in the figure. The relation between the flow velocities and the required entrance widths is plotted. In the first plot, the required entrance widths are divided by the beam of the design ships. In the second plot, the entrance widths are divided by the overall lengths of the design ships. The arrivals sailing upstream (squares) and downstream (triangles) are indicated. If one result is given for both up- and downstream, this is indicated with a circle. Other design parameters are not included in the figure. As a consequence, the differences in the figure are not purely based on the relation between the flow velocity and required entrance width. However, this gives an impression of the results obtained by different simulation studies. The chosen values based on the different simulations studies are presented and explained in appendix A.

When comparing the results from previous entrance studies with the simulation results from this research the following similarities and differences can be observed:

- If the flow velocity increases the required entrance width increases, this is visible for all data.
- The arrivals when sailing downstream require larger entrance widths compared to arrival scenarios sailing upstream. This trend is visible for the literature data and the data gathered by the simulation study in this research. For the literature data, it is visible that for large flow velocities the difference between the required entrance widths for arrivals upstream and downstream is larger than for small flow velocities. This trend is not visible for the simulation results from this research. This difference can be the consequence of the used backward manoeuvres instead of forward manoeuvres for the arrivals sailing downstream. Both arrival scenarios are sailing against the flow direction into the entrance. So, the chosen method in this research is more favourable with respect to minimising the entrance width for larger flow velocities.
- As was mentioned before in paragraph 2.5, the entrance width of the Thijsse Egg layout for the Euro-Hafen Emsland-Mitte is large, because this entrance is located along a narrow waterway. The Thijsse Egg layout at the intersection of the Waal and Amsterdam-Rijnkanaal indicates that a smaller entrance can be obtained if the waterway is wider. The entrance width of this Thijsse Egg is indicated with the plus marker in figure 6-3.
- A similar fit for the simulation results in the literature data is shown for the required entrance widths divided by the beam as for the overall length of the ship. It should be noted that this can differ if 2-barge pushed convoys were included. For example, a pushed convoy of 2 barges wide and 1 long contains a relatively larger beam and smaller length than other ship types. For a pushed convoy of 1 barge wide and 2 barges in length the opposite holds. Only for the Thijsse Egg of the Waal and Amsterdam-Rijnkanaal a pushed convoy was used to determine the ratio between the entrance width and ship dimensions. However, this was a 4-barge pushed convoy. The length/beam ratio for this ship is approximately similar as for the other used ship types.

In this research it was attempted to find the minimum entrance width. In the other entrance studies, the main goal was to check whether an existing or new layout is sufficiently safe. Hence, it is expected that the required entrance widths determined in this research are smaller. However, this trend is only slightly visible for the larger flow velocities, when comparing the backward manoeuvres with the arrivals sailing downstream. The other results are more or less in agreement with the other entrance studies. It is possible that the chosen set-up for the simulation study in this research is less favourable and therefore shows a similar result. For example, the chosen h/T ratio and the close lateral approach distance are aspects that can contribute to a significantly smaller entrance width, when less conservative values were used in the simulation study.

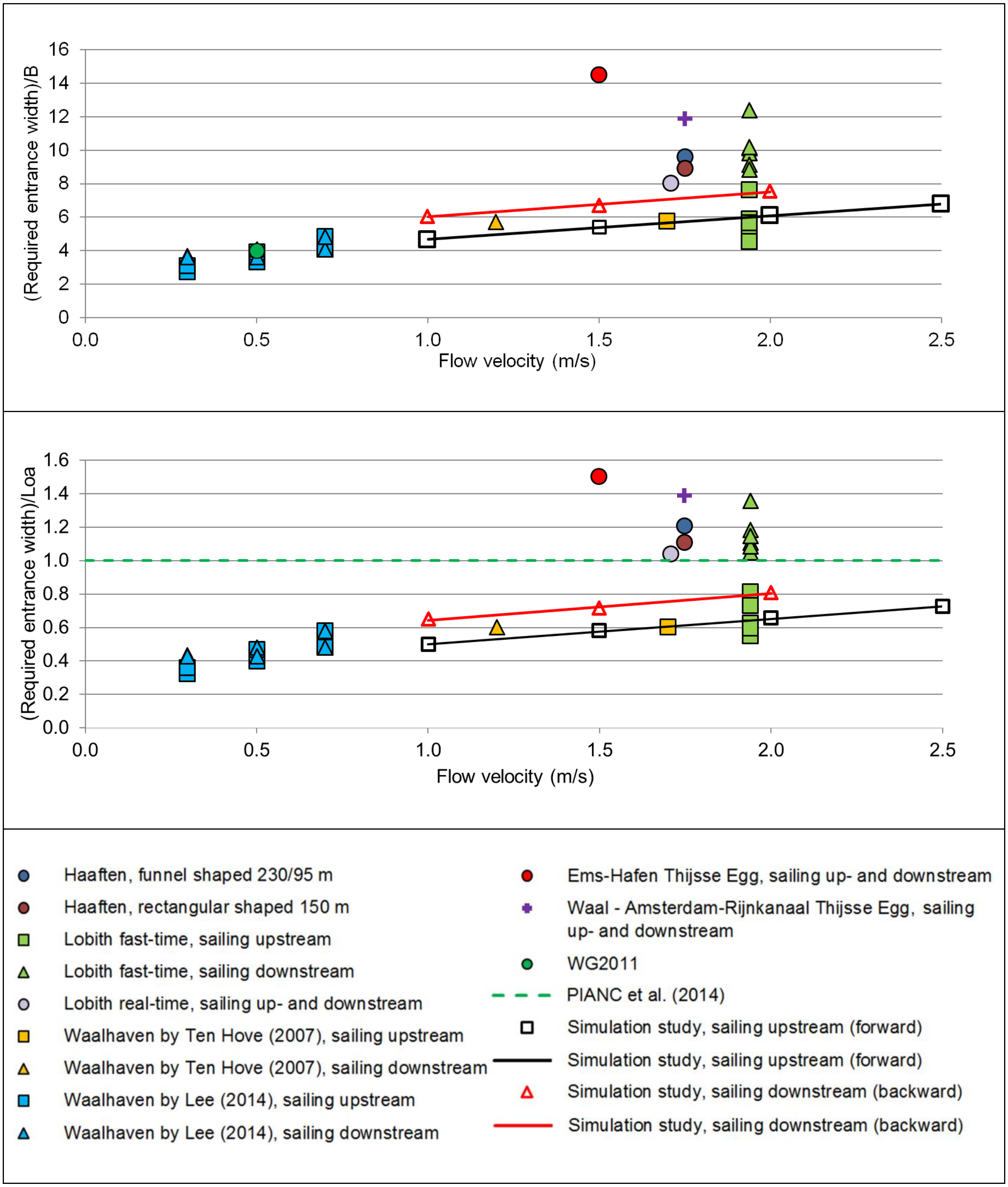


Figure 6-3: Overview of results of previous entrance studies and determined most efficient entrance widths in the simulation study of this research. The required entrance width is plotted against the flow velocity.

6.3 Further optimisation of entrance shape

In chapter 2, three different entrance layouts were mentioned: the rectangular entrance, funnel shaped entrance and the Thijsse Egg entrance. In the simulation study only a rectangular entrance layout was used. As a result of the literature study, this layout was chosen as the most favourable layout.

In this paragraph, the possibilities of the other two layouts are discussed. In addition, another entrance layout is proposed that can contribute to an even more efficient entrance layout. The simulation results for the rectangular entrance are used to evaluate the possibilities for other entrance shapes. The current patterns around these new entrances are different than for a rectangular entrance. Therefore, it should be mentioned that the shown dimensions in this paragraph are only rough indications. Additional research is required to obtain more accurate results for these entrance layouts and to study the feasibility.

6.3.1 Funnel shaped entrances

In this section the possibility of a funnel shaped entrance instead of a rectangular shaped entrance for the most efficient layout, determined in chapter 5, is discussed. In addition, it is possible that for specific situations, backward manoeuvres are not desired. Therefore, the funnel shaped and rectangular entrance are also discussed for only forward manoeuvres.

Optimising the minimum rectangular entrance

As described before in paragraph 5.3, the largest swept path occurs at the first part of the entrance for arrival scenarios. At this point the ship is turning into the entrance and this causes the large swept path. After this turn the ship can sail with a heading parallel to the entrance banks through the entrance. In figure 6-4 the most efficient situation determined in chapter 5 is shown for the forward (run 59) and backward manoeuvre (run 60) through the rectangular entrance with an angle of 120 degrees and a length of 60 meters. Flow velocities of respectively 2.5 and 2.0 m/s were used.

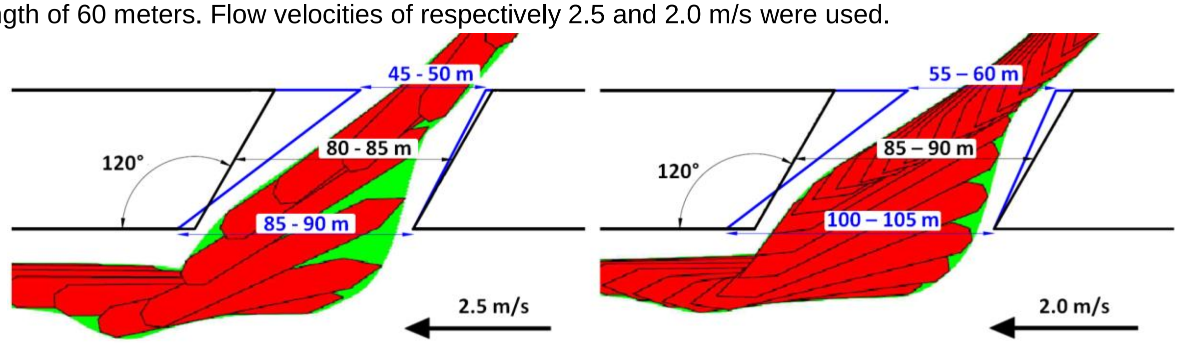


Figure 6-4: Rectangular shaped entrance and possible funnel shaped entrance for forward (left) and backward (right) manoeuvre.

A more funnel shaped entrance can reduce the entrance wide at the basin significantly, but at the waterway the mouth is wider. The average widths of the funnel shaped entrances are slightly smaller than the widths of the rectangular shaped entrances. In chapter 2 was concluded that a wider mouth is more desired for departure manoeuvres, but a funnel shaped entrance is less desirable for arrival manoeuvres, because the orientation is more difficult for the skippers. Moreover, an asymmetrical entrance is also a deterioration of the orientation. A solution should be found for these orientation aspects. For example, beacons around the entrance. In addition, it is possible that a stronger eddy arises in the funnel shaped entrance than in the rectangular entrances. This can decrease the manoeuvrability.

It is expected that the differences between these two entrances are small. The most efficient layout can be chosen by using real-time simulations for both situations.

In addition, the siltation rate is lower for a funnel shaped entrance compared to a rectangular shaped entrance with similar entrance widths at the waterway. For these situations the entrance mouth is larger for the funnel shaped entrance and the width at the basin is significantly smaller. So, based on these observations it cannot be established which entrance layout is more desired with respect to minimising siltation. A more advanced siltation study is required to determine the most efficient layout with respect to minimising siltation.

Forward manoeuvres more preferred

In figure 6-5, forward manoeuvres for flow velocities of 1.0 and 2.5 m/s are shown. Based on these runs, two funnel shaped entrances can be made for these situations. The required widths for the rectangular entrances are circa 100 and 200 meters for currents of respectively 1.0 and 2.5 m/s. The funnel shaped entrances require significant larger widths at the waterway and significant smaller widths at the basin entrance. The average widths of the funnel shaped entrances are considerably smaller. For these situations a funnel shaped entrance can be more favourable than a rectangular shaped entrance. However, again real-time simulations and siltation calculations are needed to determine which situation is more favourable.

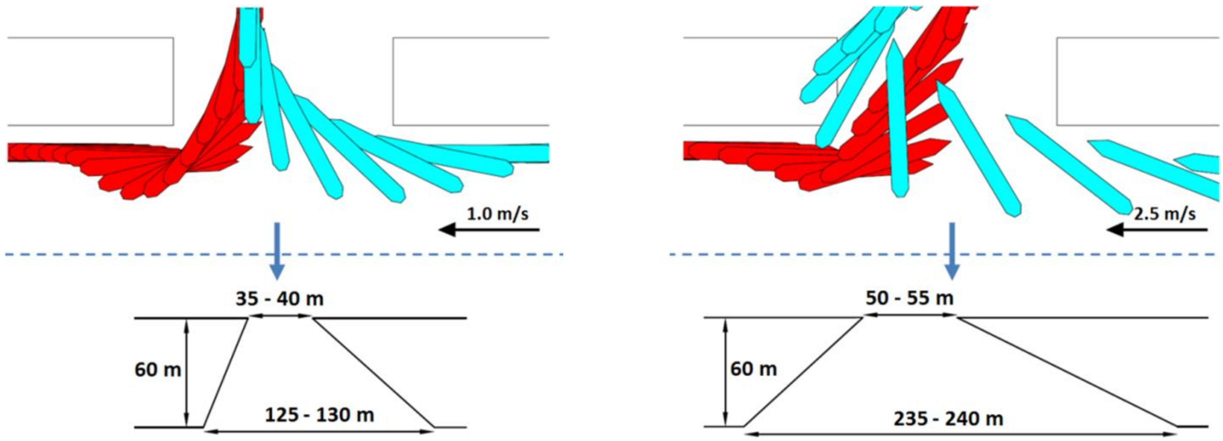


Figure 6-5: Example of possible funnel shaped entrances instead of rectangular entrances for flow velocities of 1.0 (left) and 2.5 m/s (right), taking into account only forward manoeuvres.

As described before in chapter 5, the required entrance widths for forward manoeuvres into the port, when sailing in downstream direction, are significantly larger than for arrivals sailing upstream. Moreover, for a flow velocity of 2.5 m/s, a considerably wide entrance is required. Therefore, an intermediate solution is shown in figure 6-6. For this layout the upstream corner of the most efficient layout determined in chapter 5 is adjusted. For this layout it is possible to manoeuvre forward into the port for flow velocities of 1.0 m/s. For larger flow velocities between 1.0 and 2.0 m/s, a backward manoeuvre is required and for a flow velocity of 2.5 m/s a U-turn should be made downstream of the port entrance.

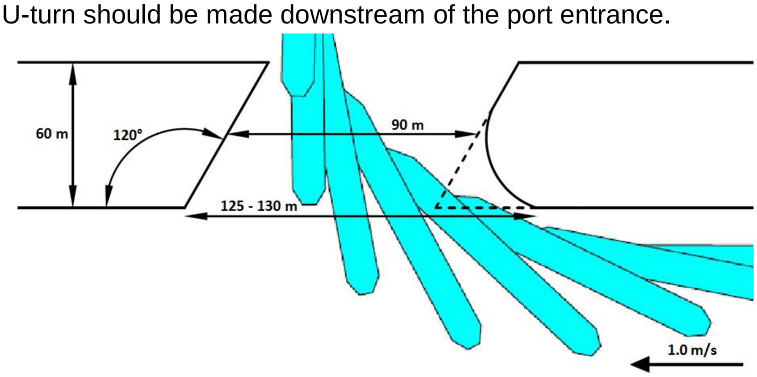


Figure 6-6: Example of adjustment of the upstream corner to provide a safe entrance for arrivals when sailing downstream, taking into account forward manoeuvres for flow velocities up to 1.0 m/s.

6.3.2 Thijsse Egg entrances

The Thijsse Egg entrance consists of two entrances with an elliptical basin between these two entrances. The entrance length at the waterway is small and can therefore be compared with an entrance with an angle of 90 degrees. However, because the small entrance lengths, sideway manoeuvres through this entrance are also possible. This is comparable with the manoeuvres into the lock approach harbour, discussed in paragraph 5.7. The obtained simulation results for arrival manoeuvres sailing downstream are shown in table 6-1. The arrivals sailing upstream are not taken into consideration in this paragraph, because these arrivals are less decisive.

First, the possibilities for a Thijsse Egg layout are shown when backward manoeuvres are allowed. Thereafter, the possibilities are shown in case only forward manoeuvres are taken into account.

Table 6-1: Obtained simulation results for arrival manoeuvres sailing downstream.

Manoeuvre	Entrance angle (deg)	Flow velocity (m/s)	Required entrance width (m)
Forward	90	1.0	102
Forward	90	2.5	196*
Forward	180 (lock approach harbour)	1.0	161
Forward	180 (lock approach harbour)	2.5	171
Backward	90	1.0	88
Backward	90	2.0	97

*Run was assessed as unsafe. Therefore, the obtained required entrance width can be less accurate compared to the other results.

Manoeuvring backward into Thijsse Egg

In figure 6-7 a schematisation of a backward manoeuvre into a Thijsse Egg layout is shown. When manoeuvring backward into the Thijsse Egg, an entrance width ($W_{e,TE}$) of 88 to 97 meters is required for flow velocities between respectively 1.0 and 2.0 m/s, when applying the simulation results for a rectangular entrance to the Thijsse Egg entrance. In order to determine the precise entrance width, additional simulations are required for a Thijsse Egg layout.

After arriving in the elliptical basin, the ship has to turn and can sail forward through the entrance into the port. In order to make a safe turn, a sufficiently wide elliptical basin is required. The dimensions of the basin width (W_b), basin length (L_b) and the width of the entrance to the port ($W_{e,port}$) cannot be determined based on the simulation study results. It should be taken into account that the flow velocity in the basin can be significantly larger than in a normal port basin. When one large eddy arises in the elliptical basin, a strong circular flow can occur in the basin. This can affect the turning manoeuvre in the basin. Additional research is required to study the dimensions of the Thijsse Egg.

Normally, the Thijsse Egg layout is used from a viewpoint of minimising siltation. As explained in chapter 2, the circular flow in the basin ensures that the flow velocity decreases around the entrances are limited. In general, when the velocity decreases are low, the siltation rate is limited around the entrance. However, the entrance width of the most efficient entrance determined in this research is considerably smaller. In general, a smaller entrance is more favourable with respect to limiting the siltation. Additional research is required to check if the Thijsse Egg is a more favourable layout than the most efficient entrance determined in this research.

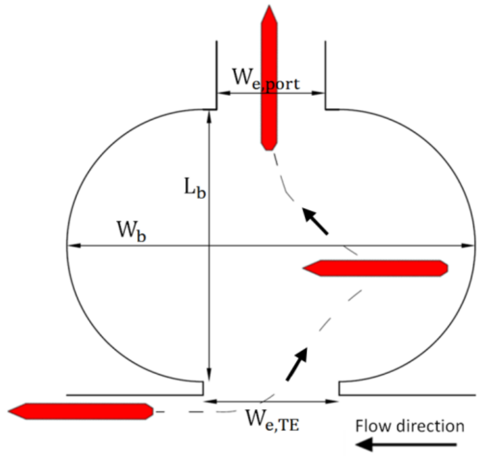


Figure 6-7: Schematisation of backward manoeuvre into Thijsse Egg.

Manoeuvring forward into Thijsse Egg

The Thijsse Egg layout is used as entrance for ports, but also as connection between two waterways. For such situations it can be desired to manoeuvre forward through the Thijsse Egg. A backward manoeuvre requires significantly more time and can be undesired at an intersection of two waterways with other trough going traffic.

When sailing downstream into the Thijsse Egg, a significant entrance width is required. For a sideward manoeuvre a smaller entrance width is required compared to a manoeuvre with a heading parallel to the entrance banks. However, the required length to lower the ship speed and turn in the Egg basin is larger. Therefore, a manoeuvre with a heading more parallel to the entrance banks can be more favourable in order to limit the required basin width. Further research is required to study the required basin width and the most favourable manoeuvre through the entrance.

Based on the results of this research the minimum required entrance width for the Thijsse Egg basin is circa 170 to 200 meters for a flow velocity of 2.5 m/s. For a flow velocity of 1.0 m/s, this is circa 100 meters. As a result of the Euro-Hafen Emsland-Mitte study it was concluded that an entrance width of 163 meters was required for a flow velocity of 1.5 m/s, see section 2.2.4. Based on these outcomes, it can be concluded that these entrance widths are significantly larger than for the most efficient entrance determined in this research, see the results of chapter 5. However, this type of entrance can be useful when forward manoeuvres are required and the siltation should be minimised.

6.3.3 Sheltered area downstream of entrance

In the analysis of the simulation study results, it was shown that the flow velocity is an important parameter which is influencing the required entrance width. Backward manoeuvres for flow velocities larger than 2.0 m/s were not possible due to a limited bow thruster capacity for large relative water velocities. A decrease of the flow velocity just downstream of the port entrance, can contribute to an easier manoeuvre. Moreover, when the velocities around the downstream entrance dam are decreased significantly, a backward manoeuvre with a flow velocity of 2.5 m/s can be possible. In order to create an area with lower flow velocities, a sheltered area should be created downstream of the entrance and just in front of the entrance. An example of a layout with a sheltered area is schematised in figure 6-8.

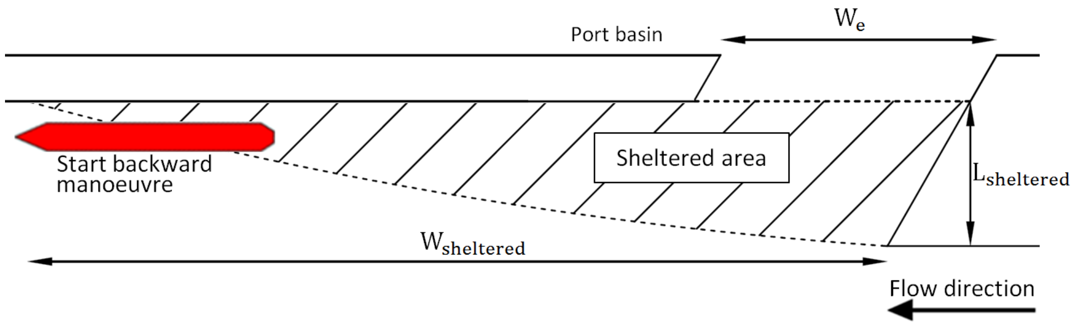


Figure 6-8: Schematisation of sheltered area downstream of entrance.

This type of layout is less favourable for sailing downstream and manoeuvring forward into the port. As was concluded in chapter 2, this type of layout is not desired with respect to the orientation of a skipper. However, when only backward manoeuvres are used for arrivals sailing downstream, this layout is useful. Moreover, as a results of the reduced flow velocity this layout can possibly provide safe navigation when manoeuvring backward into the port for flow velocities of 2.5 m/s. Furthermore, this layout is forcing skippers to stop downstream of the port entrance and sail backwards through the entrance. Therefore, it is not expected that skippers use a forward manoeuvre when sailing downstream. For the most efficient entrance determined in chapter 5, it is more likely that a skipper approaches the port with a forward manoeuvre when sailing downstream instead of a backward manoeuvre. This can result in dangerous situations, whereas the situation is not designed for forward manoeuvres. In addition, a reduced flow velocity downstream of the entrance will also contribute to an easier manoeuvre into the port for sailing upstream and manoeuvring forward into the port.

Additional research is required to determine the required width ($W_{sheltered}$) and length ($L_{sheltered}$) of the sheltered area in order to sufficiently decrease the flow velocities in the sheltered area. Besides, the nautical safety for this new layout should be studied. Furthermore, a morphological study is required to analyse the siltation around this port entrance.

7

Conclusions and recommendations

In paragraph 7.1 the conclusions of this research are presented. Paragraph 7.2 describes the recommendations for further research.

7.1 Conclusions

The objective of this research was to find the minimum required nautical safe entrance width for generic situations for inland ports along flowing waters in non-tidal areas. To determine this minimum width, the influence of different design parameters was studied. Moreover, the determined most efficient entrance layout should be a realistic result with respect to minimising siltation. The main research question was:

What is the minimum required nautical safe entrance width and what is the most efficient entrance layout for an inland port along non-tidal waterways?

In addition to this main research question, three sub-questions were formulated:

1. What entrance layout is efficient with respect to limiting the siltation in and around an inland port in non-tidal areas?
2. What is the influence of the different design parameters on the minimum required nautical safe entrance width?
3. Is it possible to create generic design rules for inland port entrances along flowing waters in non-tidal areas?

Sub-question 1 was answered in this research by studying previous research. Sub-question 2 was answered by performing a fast-time simulation study with SHIPMA. This simulation model was used to compare different scenarios. In total 66 different scenarios were simulated. SHIPMA is not suitable for detailed design and manoeuvres in which the interaction of two ships and skippers should be taken into account. Moreover, human interference is not included in the model. Instead of an actual human operator an autopilot is used. The ship manoeuvres and autopilot settings are set up by the user. As a consequence, the chosen set-up is subjective. So, different users can obtain different results. Due to these model limitations, the obtained simulation results give only an indication of the required entrance widths. Since the SHIPMA runs were set up in a similar way and by the same user, it is expected that the observed trends for the different design parameters, included in the simulations study, are reliable. The answer to sub-question 3 is given based on the answers for the other research questions.

In section 7.1.1 the research questions are answered. Thereafter, in section 7.1.2 the interpretation of the research results is discussed.

7.1.1 Minimum entrance width and most efficient entrance layout

The in this research determined minimum required entrance widths, for flow velocities between 1.0 and 2.5 m/s, are shown in table 7-1. In figure 1-2 is shown how the different design parameters included in the simulation study are defined.

Table 7-1: Overview of required entrance widths for an entrance angle of 120 degrees and a length of 60 meters.

Current	Forward manoeuvre, arrival sailing upstream	Backward manoeuvre, arrival sailing downstream
1.0 m/s	54 m	70 m
1.5 m/s	62 m	78 m
2.0 m/s	71 m	87 m
2.5 m/s	79 m	-

The simulation study showed that the minimum safe entrance width is provided for an entrance angle of 120 degrees. A rectangular entrance layout with a rectangular cross-sectional area was used in the simulation study. For the determined most efficient layout, the forward manoeuvres into the port when sailing downstream were replaced by backward manoeuvres. Backward manoeuvres were not possible to conduct for flow velocities larger than 2.0 m/s. For larger flow velocities the bow thruster was not effective enough as a consequence of the too large relative water velocity around the hull of the ship. For these situations, a ship should turn downstream of the port entrance and enter the port with a forward manoeuvre sailing upstream.

Based on the simulation study results, the influence of several design parameters were analysed for the most efficient layout. It was shown that the flow velocity is the most important parameter that is affecting the required entrance width for the most efficient layout. A linear relation was observed between the required entrance width and the flow velocity. As is visible in table 7-1, a deviation of plus (minus) 0.5 m/s in flow velocity increases (decreases) the required entrance width with circa 8 meters.

Furthermore, it was shown that the sensitivity of the entrance angle, entrance length and the entrance width is small for the determined most efficient entrance layout. For the entrance angle, a deviation of 10 degrees resulted in only a minor increase of the required entrance width. For entrance lengths between 60 and 120 meters, a small increase in required width was observed for an increase in entrance length. This was only observed for a backward manoeuvre taking into account a flow velocity of 2.0 m/s. For this scenario, the required width for the 60 meter entrance, shown in table 7-1, was circa 7 meters smaller than for an entrance with a length of 120 meters. For other scenarios no sensitivity was noticed. For the entrance width an increase in required entrance width of circa 4 meters was observed for reducing the entrance width from 150 to 90 meters.

For the most efficient layout, one scenario with flooded entrance dams was simulated instead of the used dry entrance dams for the other simulations. Only small changes in the current pattern around the entrance were observed. The simulation results showed that flooded entrance dams are not a significant improvement or deterioration with respect to the required entrance width. It should be mentioned that other layouts with flooded entrance dams can cause different results. More situations should be studied in order to determine the sensitivity of this design aspect.

With respect to the chosen entrance orientation and the cross-sectional area, the determined most efficient layout is also favourable regarding minimising the siltation. It was found in literature that an entrance angle of 120 degrees reduces the siltation in the port considerably compared to angles of 90 degrees or smaller. In addition, it was concluded that a rectangular shape of the cross-sectional area was more desired than a trapezoidal shape, taking a similar width on the bottom of the entrance into account.

As described above, the sensitivity of the entrance angle, length and width for the determined most efficient layout is small. Moreover, the results for the nautically optimised entrance angle do not conflict with the most efficient angles regarding minimising siltation. Purely based on these results, it should be possible to create a design rule that is applicable for many inland ports along flowing waters. These design rules should be related to different design flow velocities, whereas the flow velocity has a considerable influence on the required entrance width. It should be mentioned that not all the design parameters, which can possibly influence the required entrance width, were studied in this research. Hence, additional research is required before design rules can be created.

In addition, simulations for a narrow waterway were conducted. A waterway width of 48 meters was used. This is in agreement with the, by WG2011 recommended, minimum required dimensions for a normal waterway profile for CEMT class Va. The influence of the wind was not included in the simulation study. Therefore, the side wind increment was not added to this profile. It appeared that this narrow layout is too small to provide nautical safety for a loaded CEMT class Va ship and taking into account flow velocities between 1.0 and 2.5 m/s, an entrance width of 150 meters and a length of 20 meters. The used orientation of the entrance was perpendicular to the waterway axis.

Scenarios with an entrance layout comparable to a lock approach harbour, located parallel to the waterway axis, were also included in the simulation study. Manoeuvres sideways through the port entrance were used. When sailing upstream a required entrance width of circa 110 meters was required, taking into account flow velocities of respectively 1.0 and 2.5 m/s. For arrival scenarios sailing in downstream direction a width of circa 170 meters was required. These sideway manoeuvres are less favourable than the forward and backward manoeuvres, with a heading more parallel to the entrance banks, used for the determined most efficient entrance.

7.1.2 Interpretation of the research results

As a result of the performed simulation study, it was shown that for an available waterway width larger than 90 meters arrival manoeuvres sailing upstream are more decisive than departure manoeuvres sailing downstream. Furthermore, the arrivals sailing downstream are for every waterway width more decisive than departures sailing upstream. The most efficient layout was determined based on arrival manoeuvres. Hence, the in the previous section presented most efficient entrance, is only valid for an available waterway width larger than 90 meters.

The simulations showed that the used lateral approach distance is influencing the required entrance width significantly. For the determined most efficient situation an approach distance of 1B was used. So, for local situations in which skippers use often a larger approach than 1B, the results of this study are conservative. However, it should be noted that a skipper decides which approach distance is used to enter the port. As a consequence, the most conservative approach distance should be used to design the entrance.

The simulation study was performed for a loaded CEMT class Va ship. Based on simplified current and wind force calculations in this research, it was concluded that this loaded ship is the decisive ship for CEMT class Va. Pushed convoys were not taken into account. Wind conditions that were taken into account are exceeded 0.2 to 3% of the time per year. It turned out that the wind forces are less than 5% of the current forces for the determined most efficient entrance layout. It should be mentioned that for other ship dimensions and types the required entrance width will be different than for the loaded CEMT class Va ship.

The magnitude of the flow velocity was defined downstream of the port entrance. The magnitudes were 10 to 20% smaller just in front of the port entrance for the chosen waterway and entrance layouts in the simulation study. For local situations, more irregularities can exist in the layout around the port entrance.

As a consequence, a different magnitude and pattern of the current can arise. Moreover, in the simulation study the flow velocity was defined as the draught integrated velocity around the ship's hull. It should be noted that generally the water depth average velocity differs from the draught integrated velocity.

A water depth/draught (h/T) ratio of 1.3 was used for the mathematical ship model in the simulation study. Normally, for large flow velocities these ratios are larger. Note that generally for large river discharges the flow velocities are large, but also the water depths are large. A larger h/T ratio will improve the manoeuvrability of a ship. Hence, the provided results are conservative with respect to the chosen h/T ratio. The relation between the h/T ratio and the required entrance width was not studied in this research.

For the conducted fast-time simulations for the forward manoeuvres, the bow thruster was only used for the stopping manoeuvre when arriving in the port basin. Using the bow thruster during the turning manoeuvre in or out of the port can contribute to a more efficient manoeuvre. For the backward manoeuvres the bow thruster was used during the entire manoeuvre, since this was the only available tool to steer the ship for propeller revolutions astern.

7.2 Recommendations

In this research an insight is given in the most efficient entrance layout in order to provide the minimum required safe entrance width. In this paragraph recommendations are presented to obtain a more extensive insight.

The simulation study was performed with SHIPMA. Consequently, the SHIPMA limitations apply also for this research. In order to establish the differences between real situations and the acquired research results, the following is recommended.

- Performing a real-time study for the determined most efficient scenarios, presented in table 7-1. With these simulations human interference can be included. Then, the differences between the fast-time simulation results from this research and a real-time study can be established.
- It is expected that the observed trends, for the different design parameters included in this research, are significantly more reliable than the determined entrance widths. To increase the reliability of the observed trends, it is recommended to conduct real-time simulations to check the correctness of the observed trends.
- Eddies that arose in the entrances for several simulated scenarios in this research were not influencing the required entrance width. However, this can influence the ship manoeuvre when an actual human operator is steering. Therefore, it is recommended to conduct real-time simulations to study the influence of eddies in the entrance on the required entrance width.

Many aspects can influence the required entrance width and the most efficient layout. The influence of several design parameters was studied. However, not all the aspects that can possibly influence the entrance width of an inland port were studied. The following is recommended:

- Only the loaded CEMT class Va ship was used in the simulation study. By conducting fast-time simulations for the determined most efficient situation, with other ships, the relation between the ship dimensions can be analysed. With this can be verified whether it is legitimate to relate the required entrance width to the beam (or length) of the design ship. In addition, simulations with pushed convoys, container ships and unloaded ships are required to study the differences with other ship types. It should be taken into consideration that for unloaded ships or container ships, the influence of the wind should be included to obtain realistic results. For these ship types, the wind is relatively more important than for the loaded Va ship.

- Based on simplified current and wind force calculations, it was assumed that the loaded CEMT class Va ship is the most decisive ship compared to the unloaded Va ship and the container Va ship. Moreover, it was determined that the wind force is relatively small compared to the current force on the loaded Va ship. However, wind gusts can influence the ship manoeuvres. The influence of wind gusts and the reaction of a human operator on these fluctuations cannot be determined with SHIPMA. It is recommended to conduct additional research on the influence of the wind on the required entrance width. With this can be verified whether the made assumptions, based on the simplified current and wind force calculation in this research, are correct.
- An h/T ratio of 1.3 was used during the simulation study. As described in section 7.1.2, it is expected, that this ratio provides conservative results for many local situations. A better insight into the relation between the h/T ratio and the required entrance width can contribute to more efficient entrance design. Additional fast-time simulations are required.
- As mentioned in section 7.1.2, the simulation results are only valid for an available waterway width larger than 90 meters. Based on the simulation results, a transition point is expected between 50 and 90 meters. Additional fast-time simulations are required to find this point. This can increase the validity range for the results of this research. In addition, for waterways smaller than this transition point departure manoeuvres in downstream direction are required to determine the minimum required entrance width.
- In this research only one scenario with flooded entrance dams was simulated. More scenarios should be simulated to study the differences between flooded and dry entrance dams. Other layouts and other water depth conditions should be included.
- When sailing in upstream direction with a current of 0.5 m/s, it is possible that an entrance angle of 120 degrees is more favourable than the advised 4B rule by WG2011 for a 90 degrees entrance, see figure 6-2. However, it is expected that for an angle of 120 degrees the forward and backward manoeuvres for the arrivals sailing downstream are probably less efficient. Additional simulations are required to determine whether a smaller entrance width than the 4B rule is possible for currents up to 0.5 m/s.
- It is possible that due to the shape or size of the basin the manoeuvres through the entrances are influenced. This aspect was not studied in this research, because a sufficiently large basin was used in the simulation study to provide a sufficiently large stopping distance for the ships. Additional simulations are required for different basin to study the influence of the basin on the required entrance width.
- In the simulation study only a rectangular shaped entrance was used. This layout was chosen, because this provides the best orientation for the skippers. However, other entrance shapes could be used. It is possible that a funnel shaped entrance or Thijsse Egg layout is more favourable in certain situations. Several possibilities were discussed in paragraph 6.3. Additional research, regarding nautical safety and minimising siltation, is required to study the possibilities of these proposed entrance layouts.
- In this research was mainly focussed on the optimisation with respect to nautical safety. Although the determined most efficient entrance angle of 120 degrees is favourable regarding minimising siltation, additional research to the siltation of inland ports can contribute to a further optimisation regarding minimising siltation.

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A

Results of recently performed entrance studies

Figure A-1 Figure 2-11 and Figure 6-3 of this report, a graphical overview is given of the results of several previously performed studies on inland port entrances. The flow velocities of each simulation and the required entrance width, divided by the beam of the ship, are used to create a graphical overview of the results. In addition, the required entrance widths divided by the overall lengths of the ships are included in the graphical overview. In this appendix choices that were made to create these overviews are explained.

The fast-time and real-time simulation results of the analysed entrance studies in paragraph 2.2 are shown in Table A-1 to Table A-7. The overall length (L_{oa}) and beam (B) are indicated for each ship type. The shape of the entrance is also indicated. For the funnel shaped entrances, the entrance width at the waterway (W_1), the entrance width at the port basin (W_2) and the average width ($W_{e,avg}$) are indicated. The average entrance width, entrance length (L_e) and the entrance angle (α) are indicated for every simulated scenario. Furthermore, the used sailing direction (dir) and the flow velocity (U_c) are included in the tables.

For the studies of Haaften, Lobith real-time, Waalhaven by Ten Hove and Euro-Hafen Emsland-Mitte, the required swept paths (W_{sp}) in the entrance were not explicitly mentioned. Therefore, the largest ship was used, for which safe navigation was provided, in combination with the average entrance width to calculate the required entrance width ($W_{e,req}$).

For Lobith fast-time simulations no safety margins were included, only the used swept paths were given in this study. For these simulation results a safety margin of 1B (0.5B on both sides of the ship) was added. This is in line with the safety margin used for the performed fast-time simulation study for this research, see section 3.4.1. For the Waalhaven study performed by Lee, a safety margin of 8 meters was included by Lee.

In the simulation studies different wind scenarios were included. Moreover, different depth/draught ratios were used. These aspects are not taken into account in the overviews. It should be noted that the graphical overviews provide only an indication of the relation between the flow velocities and the required entrance widths.

Only one Thijsse Egg layout is included in the tables. Besides, this Thijsse Egg entrance is situated along a small waterway. As a consequence the required entrance width is larger than for a situation with a wider waterway. In order to provide a better understanding of the Thijsse Egg layouts with respect to the other layouts, the Thijsse Egg on the intersection between the Waal and Amsterdam-Rijnkanaal is added. In Figure A-1 an overview of the intersection is shown. Close to the Thijsse Egg the Prins Bernhard locks are located. The Prins Bernhard locks are suitable for CEMT class VIb ships (RWS, 2017). Therefore, a Rhinemax ship can use this lock and should be able to sail safely through the Thijsse Egg. Moreover, the dimensions of these locks are also suitable for a 4-barge pushed convoy. This type of ship is more decisive than the Rhinemax ship. Hence, only the 4-barge pushed convoy is added to the graphical overviews. In Table A-8 the characteristics of this Thijsse Egg layout are shown.

Table A-1: Overview of results of study Haaften, funnel shaped entrance.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Container VIa	135.0	16.9	Funnel	95	230	162.5	200	120	Up/Down	1.75	-	-	9.6	1.20

Table A-2: Overview of results of study Haaften, rectangular entrance with width of 150 meters.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Container VIa	135.0	16.9	Rectangular	-	-	150	200	120	Up/Down	1.75	-	-	8.9	1.11

Table A-3: Overview of results of study Lobith, fast-time simulations.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Container Va	106.0*	11.35	Rectangular	-	-	135	20	90	Up	1.94	47	58.4	5.1	0.55
Container Va	106.0*	11.35	Rectangular	-	-	135	20	90	Up	1.94	75	86.4	7.6	0.82
Container Va	106.0*	11.35	Rectangular	-	-	135	20	90	Up	1.94	55	66.4	5.8	0.63
Container VIa	129.8	16.9	Rectangular	-	-	135	20	90	Up	1.94	78	94.9	5.6	0.73
Container VIa	129.8	16.9	Rectangular	-	-	135	20	90	Up	1.94	60	76.9	4.6	0.59
Container VIa	129.8	16.9	Rectangular	-	-	135	20	90	Up	1.94	60	76.9	4.6	0.59
Loaded Va	104.2*	11.40	Rectangular	-	-	135	20	90	Down	1.94	104	115.6	10.0	1.11
Loaded Va	104.2*	11.40	Rectangular	-	-	135	20	90	Down	1.94	130	141.6	12.2	1.36
Container Va	106.0*	11.35	Rectangular	-	-	135	20	90	Down	1.94	100	111.4	9.8	1.05
Container Va	106.0*	11.35	Rectangular	-	-	135	20	90	Down	1.94	104	115.4	10.2	1.09
Container VIa	135.0	16.9	Rectangular	-	-	135	20	90	Down	1.94	137	153.9	9.1	1.19
Container VIa	135.0	16.9	Rectangular	-	-	135	20	90	Down	1.94	132	148.9	8.8	1.15

*Length between perpendiculars is given instead of length overall.

Table A-4: Overview of result of study Lobith, real-time simulations.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Container VIa	129.8	16.9	Rectangular	-	-	135	20	90	Up/Down	1.71	-	-	8.0	1.04

Table A-5: Overview of results of study Waalhaven by Ten Hove.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Loaded Va	108.3	11.4	Funnel	40	90	65	80	100	Down	1.2	-	-	5.7	0.60
Loaded Va	108.3	11.4	Funnel	40	90	65	80	100	Up	1.7	-	-	5.7	0.60

Table A-6: Overview of results of study Waalhaven by Lee.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Loaded Va	96.0	11.4	Rectangular	-	-	40	50	90	Down	0.3	26	42.0	3.7	0.44
Loaded IV	80.0	9.5	Rectangular	-	-	40	50	90	Down	0.3	18	34.0	3.7	0.43
Loaded Va	96.0	11.4	Rectangular	-	-	40	50	90	Down	0.5	30	46.0	4.0	0.48
Loaded IV	80.0	9.5	Rectangular	-	-	40	50	90	Down	0.5	18	34.0	3.7	0.43
Loaded Va	96.0	11.4	Rectangular	-	-	40	50	90	Down	0.7	30	46.0	4.1	0.48
Loaded IV	80.0	9.5	Rectangular	-	-	40	50	90	Down	0.7	30	46.0	4.9	0.58
Loaded Va	96.0	11.4	Rectangular	-	-	40	50	90	Up	0.3	15	31.0	2.7	0.32
Loaded IV	80.0	9.5	Rectangular	-	-	40	50	90	Up	0.3	13	29.0	3.0	0.36
Loaded Va	96.0	11.4	Rectangular	-	-	40	50	90	Up	0.5	22	38.0	3.3	0.40
Loaded IV	80.0	9.5	Rectangular	-	-	40	50	90	Up	0.5	21	37.0	3.9	0.46
Loaded Va	96.0	11.4	Rectangular	-	-	40	50	90	Up	0.7	30	46.0	4.1	0.48
Loaded IV	80.0	9.5	Rectangular	-	-	40	50	90	Up	0.7	30	46.0	4.9	0.58

Table A-7: Overview of result of study Euro-Hafen Emsland-Mitte.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
Loaded Va	110	11.40	Thijsse Egg	-	-	165	-	90	Up/Down	1.5	-	-	14.5	1.50

Table A-8: Thijsse Egg layout for Waal and Amsterdam-Rijnkanaal connection.

Ship information			Entrance information						Dir	U_c (m/s)	W_{sp} (m)	$W_{e,req}$ (m)	$\frac{W_{e,req}}{B}$ (-)	$\frac{W_{e,req}}{L_{oa}}$ (-)
Type	L_{oa} (m)	B (m)	Shape	W_1 (m)	W_2 (m)	$W_{e,avg}$ (m)	L_e (m)	α (deg)						
4-barge pushed convoy	190	22.8	Thijsse Egg	-	-	270*	-	90	Up/Down	1.75**	-	-	11.8	1.42

*In Figure A-1 is shown that the entrance width is circa 300 meters. For this situation a slope of 1:4 for the entrance banks is assumed. According to WG2011 the maximum draught for CEMT class VIb is 4.0 meters. Only the entrance width with a depth equal or larger than the maximum draught is taken into account. The distance between the entrance banks and a water depth of 4 meters is therefore subtracted from the entrance width. At both sides of the entrance this is circa 16 meters. Hence, a required entrance width of 270 meters is assumed.

**The maximum flow velocity used in the study of Haaften was 1.75 m/s (Van Heel & Verheij, 2011). The Thijsse Egg is located circa 20 km upstream from Haaften, measured with Google Earth on June 3rd, 2017. Hence, a flow velocity of 1.75 m/s is used for the Thijsse Egg.

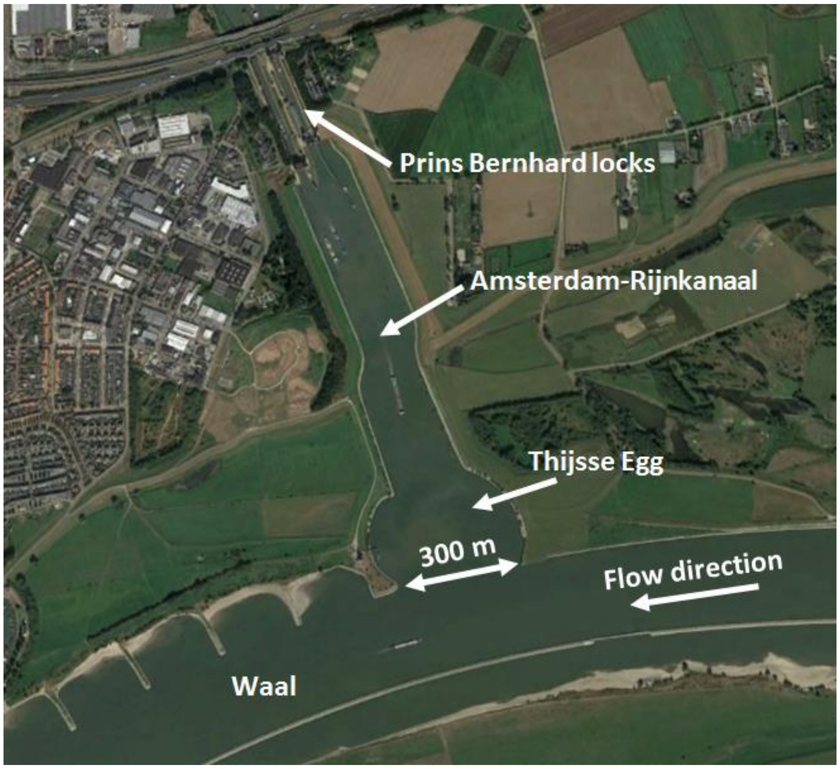

Figure A-1: Overview of Thijsse Egg layout for the connection of the Waal and Amsterdam-Rijnkanaal Source: Google Earth, retrieved on June 3rd, 2017.

B

Sailing in flow gradient

In this appendix, the ship manoeuvre through a flow gradient is briefly explained.

When a ship is sailing on a straight track in a constant cross flow, the ship will compensate by taking a heading not parallel to the track. The ship turns the bow more into the cross flow. This changed heading in combination with the constant cross flow, will keep the ship on the track. The used rudder angle is equal to zero for these situations (Kaarsemaker et al., 2010). This situation is illustrated in Figure B-1 (left).

In case a ship is sailing through a flow gradient, the ship has to turn in order to stay on the straight track. The flow field causes a rotation of the ship. A rotation in the opposite direction is required to counter the moment caused by the flow field. A certain rudder angle is required for this rotation in the opposite direction (Kaarsemaker et al., 2010). This situation is illustrated in Figure B-1 (right).

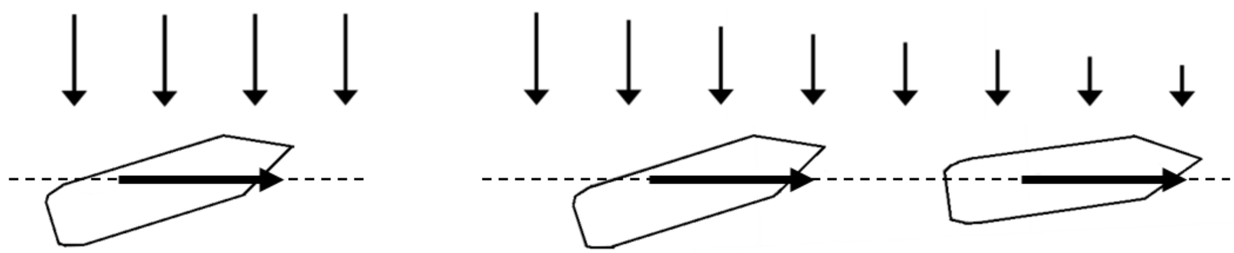

Figure B-1: Ship in constant cross flow (left) and ship in a flow gradient (right). Figure adjusted from Kaarsemaker et al. (2010).

When sailing into an inland port entrance, a ship has to cross a flow gradient in the port entrance. This is illustrated in Figure B-2. The current forces on the ship's hull cause a moment ($\mathrm{M_{cur}}$) on the ship. This moment is opposite to desired turning moment. Therefore, a ship should create a counter rotation. When sailing forward, this can be done by force caused by using a rudder angle ($\mathrm{F_{rud}}$) and possibly in combination with a power burst or bow thruster ($\mathrm{F_{bow}}$). When sailing backwards only the bow thruster is available. Therefore, these manoeuvres are more difficult than forward manoeuvres.

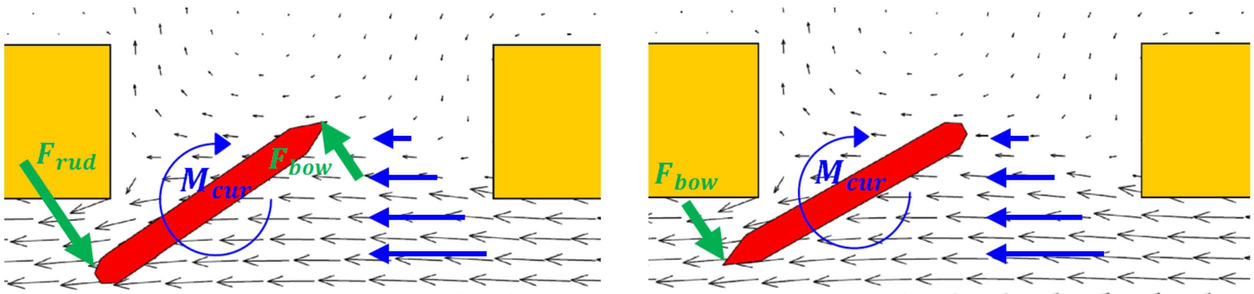

Figure B-2: Forces on ship when sailing through flow gradient into the port. Forward (left) and backward (right) manoeuvres into the port when sailing against the flow direction are shown.

C

Current and wind forces on ship

In this appendix, the magnitudes of two external forces on a sailing ship are estimated. Namely, the current and wind forces. With a simplified calculation method the current and wind forces are calculated on a loaded and unloaded ship CEMT class Va ship. A container ship is also used with approximately the same dimensions. The two questions that are answered in this appendix are:

- Which ship type is exposed to the largest forces?
- Is it appropriate to neglect the influence of the wind force for the ship that is exposed to the largest forces?

Based on the answers on these two questions it can be concluded whether it is possible to use one decisive ship type for the SHIPMA simulations.

In paragraph C.1 of this appendix the used calculation method is explained. The values of the parameters, in order to calculate the forces, are discussed in paragraph C.2. In paragraph C.3 the calculation results are presented. The conclusions are given in paragraph C.4.

Note: A simplified calculation method is used for the current forces. The calculated current forces in this appendix should not be used for other purposes than a relative comparison between the current and wind forces on a sailing inland ship.

C.1 Current and wind force calculations

When a ship is in a stationary course, the influence of a uniform current can be calculated by adding the flow velocity to the ship speed. However, the situation is rarely that simple. When the heading of the ship changes, the ship speed changes or the current is not uniform, the inertial forces cause a deviation from the simple calculation method (MARIN & Deltares, 2015).

In this appendix only the relative importance of the current and wind with respect to each other is determined. For this purpose the simplified calculation method can be used (MARIN, personal communication, 2017). Normally, this method is used for calculating the current and wind forces on moored ships. Therefore, this simplified method is not sufficient in order to calculate the current forces around a sailing ship accurately. However, it gives an impression of the magnitudes.

The current and wind forces on a moored ship can be calculated with a formula comparable to the forces on a plate in wind or flowing water (Ligteringen & Velsink, 2012). The forces are proportional to the cross-sectional area in the current or wind and the velocity squared. In general, every force on the ship's hull can be split into a force in longitudinal direction ($\mathrm{F_x}$) and in lateral direction ($\mathrm{F_y}$). When the current or wind is in longitudinal direction of the sailing ship, the longitudinal forces will be large. In case the current or wind is in lateral direction of the sailing ship the longitudinal forces are small. For the forces in transversal direction the opposite hold.

Splitting the current and wind forces in a longitudinal and transverse direction results in the following equations for the current and wind forces on the ship's hull (OCIMF, 2010; Ligteringen & Velsink, 2012):

Current forces:

$F_{xc} = \frac{1}{2} \cdot C_{xc} \cdot \rho_{water} \cdot U_c^2 \cdot T \cdot L_{bp}$;

$F_{yc} = \frac{1}{2} \cdot C_{yc} \cdot \rho_{water} \cdot U_c^2 \cdot T \cdot L_{bp}$, with:

C_{xc} = Longitudinal current force coefficient $(-)$
C_{yc} = Transverse current force coefficient $(-)$
ρ_{water} = Density of the water (kg/m^3)
U_c = Average current velocity over the under water part of the keel (m/s)
T = Ship draught (m)
L_{bp} = Length between perpendiculars (m)

Wind forces:

$F_{xw} = \frac{1}{2} \cdot C_{xw} \cdot \rho_{air} \cdot V_{wind}^2 \cdot A_T$;

$F_{yFw} = \frac{1}{2} \cdot C_{yw} \cdot \rho_{air} \cdot V_{wind}^2 \cdot A_L$, with:

C_{xw} = Longitudinal wind force coefficient $(-)$
C_{yw} = Lateral wind force coefficient $(-)$
ρ_{air} = Density of the air (kg/m^3)
V_{wind} = Average wind velocity (m/s)
A_T = Lateral cross section of the above water area of the ship (m^2)
A_L = Longitudinal cross section of the above water area of the ship (m^2)

Note that the in both equations for the current forces $D \cdot L_{BP}$ is used; for the longitudinal direction one would expect $T \cdot B$, where B is the beam of the ship. This is done for the ease of calculation (Ligteringen & Velsink, 2012). Furthermore, it should be noted that for moored ships, the relative water velocity around the ship's hull ($V_{rel,water}$) is equal to the flow velocity U_c. For the calculations in this appendix the ship speed is added to the flow velocity. Hence, U_c is replaced in the above presented formulas with $V_{rel,water}$. For the relative wind velocity ($V_{rel,wind}$) a similar explanation holds as for the relative water velocity; for the calculations V_{wind} is replaced by $V_{rel,wind}$.

C.2 Values of parameters

The characteristics of the loaded Va, unloaded Va and container Va ship which are used for the calculations are shown in Table C-1. The dimensions of the ships are slightly smaller than the maximum allowed dimensions of the CEMT class Va. However, the differences are small. Therefore, it is assumed that these ships provide a good indication of the influence of the different forces.

Table C-1: Characteristics of the ships.

Ship characteristic	Unit	Loaded ship, class Va	Unloaded ship, class Va	Container ship, class Va
L_{bp}	m	96.0	96.0	106.0
B	m	11.40	11.40	11.40
T	m	2.8	1.12	1.4
A_T	m^2	61	80	104
A_L	m^2	345	506	863
$H_{w,T}$*	m	5.4	7.0	9.1
$H_{w,L}$**	m	3.6	5.3	8.1

*Average height of the lateral cross section of the above water area of the ship, with: $H_{w,T} = A_T/B$.
**Average height of the longitudinal cross section of the above water area of the ship, with: $H_{w,L} = A_L/L_{bp}$.

The characteristics of the container ship are based on one of the ships used in the entrance study for the port of Lobith (De Jong et al., 2002c). The ship's characteristics for the loaded ship are provided by MARIN (2005). The draught for the unloaded ship is based on the unloaded/loaded ratio (circa 0.4) of the draughts of two other loaded (T = 3.79 m) and unloaded (T = 1.42 m) mathematical ship models of MARIN for CEMT class Va. The lateral and longitudinal cross-sectional areas above the waterline are estimated by adding the extra surface of the ship that is above the water line compared with the loaded ship:

$$A_{T-unloaded} = A_{T-loaded} + (T_{loaded} - T_{unloaded}) \cdot B = 80 \text{ m}^2$$
$$A_{L-unloaded} = A_{L-loaded} + (T_{loaded} - T_{unloaded}) \cdot L_{bp} = 506 \text{ m}^2$$

The current forces are calculated for relative water velocities between 0.5 and 5.0 m/s. A relative velocity of at least 0.5 m/s is taken into account to avoid controllability problems for a ship. A value of 5.0 m/s could be reached when a ship is sailing in upstream direction in a flow velocity of 2.5 m/s with a ground speed of 2.5 m/s. Note that flow velocities smaller than 1.0 m/s and larger than 2.5 m/s are beyond the scope of this research.

It is chosen to take a wind speed of 14 m/s into account. In the Netherlands, this value will be exceeded in 0.2 to 3% of the time in a year, depending on the location (Wieringa & Rijkoort, 1983). This wind speed is for an elevation of 10 meters. The average heights of the lateral and longitudinal cross sections of the ships, above the waterline, are considerably lower. The wind speed for these lower heights can be calculated with the following formula (OCIMF, 2010):

$V_w = v_w \left(\frac{10}{H_w}\right)^{1/7}$, where:

V_w = wind velocity at 10 m height (m/s)
v_w = the wind velocity at elevation H_w (m/s)
H_w = elevation above ground or water surface (m)

The corrected wind speeds for the different elevations are shown in Table C-2. The maximum assumed ground speed of the ships around the port entrance is 3.0 m/s. This ground speed is added to the wind speed, see Table C-2. This relative speed is used for every comparison with the relative water velocities between 0.5 and 5.0 m/s. It should be mentioned that for most of the conducted SHIPMA runs in this research a peak ground speed around the port entrance between 1.0 and 2.5 m/s was used, see appendix F. Therefore, the assumed relative wind speed is, for most of the conducted runs, an overestimation of the wind conditions.

Table C-2: Overview of corrected wind speeds and relative wind speeds.

	Loaded ship, class Va	Unloaded ship, class Va	Container ship, class Va
Wind speed in longitudinal direction (m/s)	12.8	13.3	13.8
Wind speed in lateral direction (m/s)	12.1	12.8	13.6
Relative wind speed in longitudinal direction (m/s)	15.8	16.3	16.8
Relative wind speed in later direction (m/s)	15.1	15.8	16.6

The densities used for the calculations are 1.0223 kg/m^3 for air (Ligteringen & Velsink, 2012) and 1000 kg/m^3 for water. The force coefficients for the loaded Va ship are provided by MARIN; these are: $C_{xc} = 0.28$, $C_{yc} = 3.28$, $C_{xw} = 0.55$, $C_{yw} = 0.77$ (MARIN, personal communication, 2017). According to OCIMF (2008) the current coefficients for an unloaded ship are lower than from a loaded ship. These differences are illustrated in Figure C-1. However, the coefficients for the unloaded ship were not available for this research. As a consequence, the same coefficients are used for the unloaded and container ship. Due to this assumption, the calculated current forces on the unloaded and container ship are larger than correct.

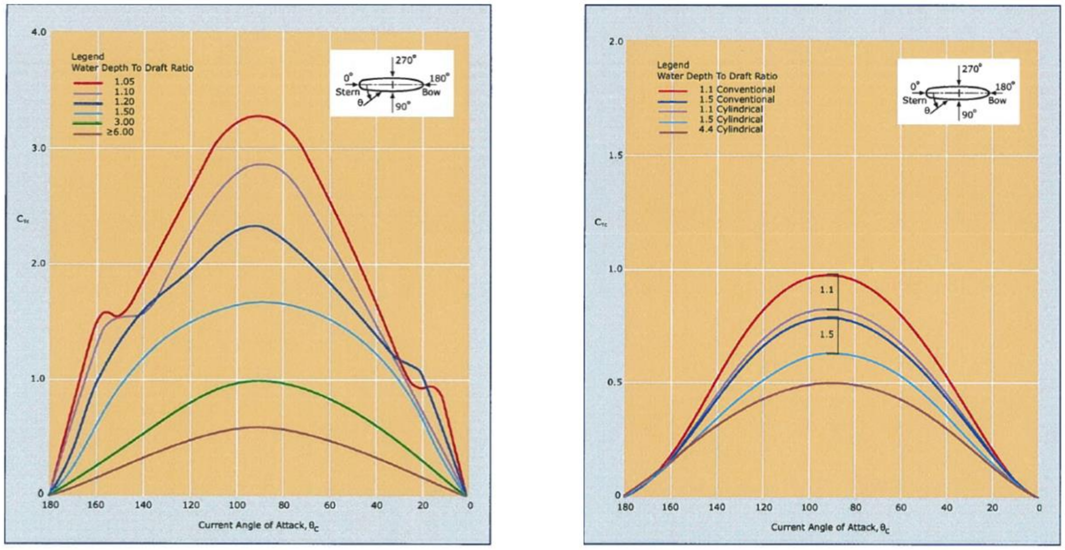

Figure C-1: Lateral current drag force coefficient (C_{yc}) for loaded tanker in the left figure and for ballasted tanker (40%·T) in the right figure (OCIMF, 2008).

C.3 Calculation results

The calculated current and wind forces are shown in Table C-3, Table C-4 and Table C-5. The current and wind forces in longitudinal direction (x-direction) and lateral direction (y-direction) are shown in these tables. In addition, the ratio between the current and wind forces and the sum of both forces for each direction are added. In Figure C-2 the sum of the forces in longitudinal direction is plotted as a function of the relative water velocity. In Figure C-3 this relation is plotted for the lateral direction.

From the tables and figures can be observed that the loaded ship is exposed to the largest forces. Only for a relative velocity of 0.5 m/s the forces are approximately the same for the loaded ship and the container ship. The forces on the unloaded ship are smaller. When the relative flow velocity is increasing, the forces on the loaded ship become relatively larger.

In Figure C-3 the ratio between the current and wind forces for the loaded ship are plotted. The current forces are 2 (longitudinal direction) and 4 (lateral direction) times larger than the wind forces for a relative water velocity of 0.5 m/s. For a velocity of 1.0 m/s, the wind force is about 10% of the current force in longitudinal direction and 7% of the current force in lateral direction. For velocities larger than 3.0 m/s the wind force is less than 1% of the current force in lateral direction. In longitudinal direction this occurs for velocities larger than 3.5 m/s.

Table C-3: Calculated forces on loaded ship.

$V_{rel,water}$ (m/s)	$V_{rel,x,wind}$ (m/s)	$V_{rel,y,wind}$ (m/s)	F_{xc} (kN)	F_{yc} (kN)	F_{xw} (kN)	F_{yw} (kN)	F_{xc}/F_{xw} (kN)	F_{yc}/F_{yw} (kN)	$\sum F_x$ (kN)	$\sum F_y$ (kN)
0.5	15.8	15.1	9	110	4	31	2	4	14	141
1.0	15.8	15.1	38	440	4	31	9	14	42	471
1.5	15.8	15.1	84	991	4	31	20	32	89	1022
2.0	15.8	15.1	150	1762	4	31	35	57	154	1793
2.5	15.8	15.1	235	2753	4	31	54	89	239	2784
3.0	15.8	15.1	338	3964	4	31	78	128	342	3995
3.5	15.8	15.1	460	5396	4	31	107	174	464	5427
4.0	15.8	15.1	600	7048	4	31	139	228	605	7079
4.5	15.8	15.1	760	8920	4	31	176	288	764	8951
5.0	15.8	15.1	938	11012	4	31	217	356	943	11043

Table C-4: Calculated forces on unloaded ship.

$V_{rel,water}$ (m/s)	$V_{rel,x,wind}$ (m/s)	$V_{rel,y,wind}$ (m/s)	F_{xc} (kN)	F_{yc} (kN)	F_{xw} (kN)	F_{yw} (kN)	F_{xc}/F_{xw} (kN)	F_{yc}/F_{yw} (kN)	$\sum F_x$ (kN)	$\sum F_y$ (kN)
0.5	16.3	15.8	4	44	6	53	1	1	10	97
1.0	16.3	15.8	15	176	6	53	2	3	21	229
1.5	16.3	15.8	34	396	6	53	6	7	40	449
2.0	16.3	15.8	60	705	6	53	10	13	66	758
2.5	16.3	15.8	94	1101	6	53	16	21	100	1154
3.0	16.3	15.8	135	1586	6	53	22	30	141	1639
3.5	16.3	15.8	184	2158	6	53	30	41	190	2211
4.0	16.3	15.8	240	2819	6	53	40	53	246	2872
4.5	16.3	15.8	304	3568	6	53	50	67	310	3621
5.0	16.3	15.8	375	4405	6	53	62	83	381	4458

Table C-5: Calculated forces on container ship.

$V_{rel,water}$ (m/s)	$V_{rel,x,wind}$ (m/s)	$V_{rel,y,wind}$ (m/s)	F_{xc} (kN)	F_{yc} (kN)	F_{xw} (kN)	F_{yw} (kN)	F_{xc}/F_{xw} (kN)	F_{yc}/F_{yw} (kN)	$\sum F_x$ (kN)	$\sum F_y$ (kN)
0.5	16.8	16.6	5	61	8	96	1	1	14	157
1.0	16.8	16.6	21	243	8	96	2	3	29	339
1.5	16.8	16.6	47	547	8	96	6	6	55	643
2.0	16.8	16.6	83	973	8	96	10	10	91	1069
2.5	16.8	16.6	129	1520	8	96	16	16	138	1616
3.0	16.8	16.6	186	2189	8	96	22	23	195	2285
3.5	16.8	16.6	254	2979	8	96	30	31	262	3075
4.0	16.8	16.6	332	3891	8	96	40	41	340	3987
4.5	16.8	16.6	420	4925	8	96	50	51	428	5021
5.0	16.8	16.6	518	6080	8	96	62	63	526	6176

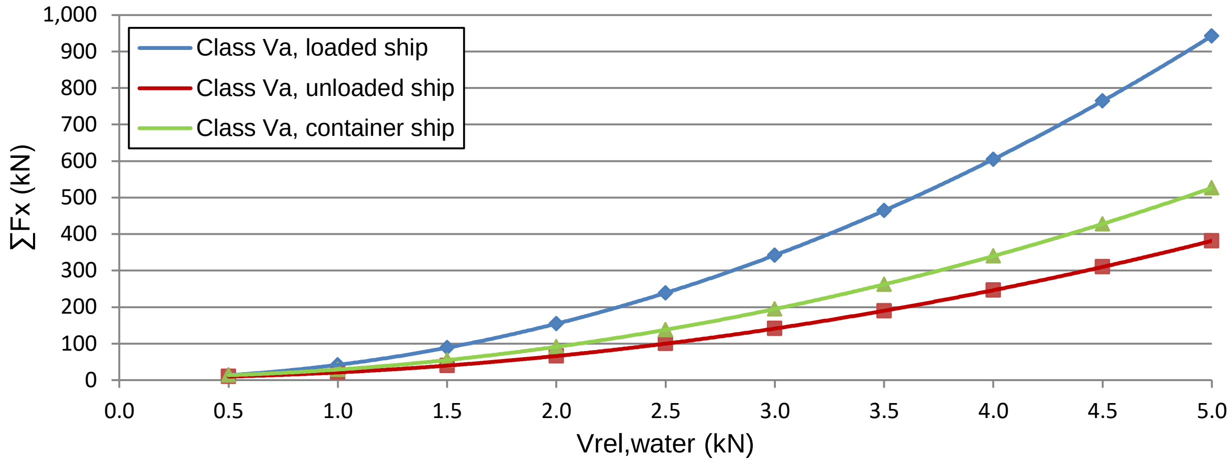

Figure C-2: Total forces (current + wind) on ship in longitudinal direction.

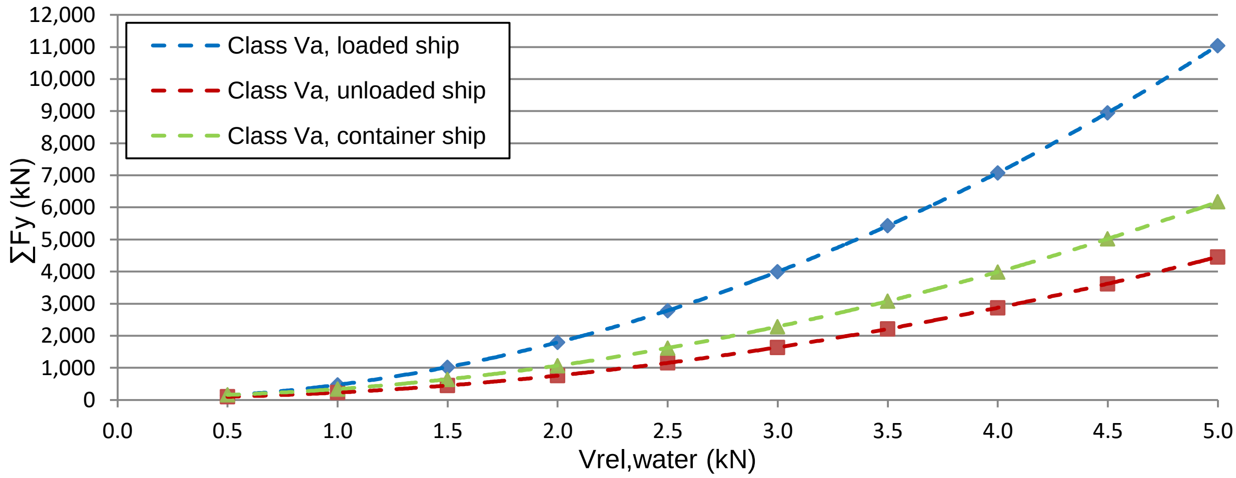

Figure C-3: Total forces (current + wind) on ship in lateral direction.

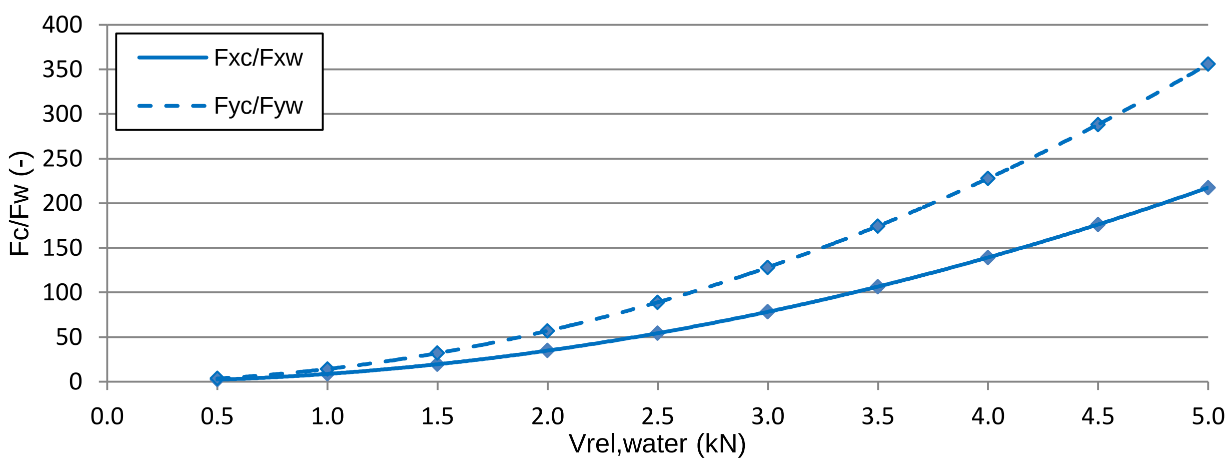

Figure C-4: Influence of the current and wind forces for the loaded ship.

C.4 Conclusions

In this appendix the wind and current forces on ships were calculated in order to answer the following two questions:

- Which ship type is exposed to the largest forces?
- Is it appropriate to neglect the influence of the wind force for the ship that is exposed to the largest forces?

From the calculation results followed that the current and wind forces on the loaded ship were significantly larger than for the unloaded and container ship. Based on these results, it can be concluded that the loaded ship is the decisive ship type.

Furthermore, it appeared that the current forces on the loaded ship are considerably larger than the wind forces. Therefore, it is appropriate to neglect the influence of the wind. However, it should be taken into account that for small relative water velocities the wind force is about 10% of the current force in longitudinal direction and 7% in lateral direction. In such situations, the influence of the wind is important enough to include for a detailed design. However, the results of this research are not suitable for detailed design, because this is one of the limitations of the SHIPMA model. Hence, making a small error by neglecting the wind is not problematic for this research.

In addition, several assumptions were made to calculate the current and wind forces:

- The same current coefficients are used for the unloaded ship and container ship as for the loaded ship. Normally, the coefficients of the unloaded ship and the container ship should be smaller than for the loaded ship. Hence, the calculated forces on the unloaded ship and container ship are larger than correct. However, the calculated forces on the loaded ship are still larger.
- A maximum ground speed of 3.0 m/s was assumed to calculate the relative wind speed on the ship's hull. This ground speed is larger than the ground speeds used in most of the conducted SHIPMA runs for this research. Hence, the calculated wind forces are larger than correct. However, the calculated current forces are significantly larger than the wind forces for the unloaded ship.

Finally, it should be taken into account that it is possible that the current direction and wind direction are not the same. For these situations the wind forces are important to taken into consideration. However, around the port entrance the ship is moving more perpendicular to the current. As a consequence of this cross flow, the ship is exposed to relative water velocities in every direction.

Based on the calculation results and the assumptions made, it can be concluded that the loaded ships is exposed to the largest total forces. Moreover, it is reasonable to neglect the influence of the wind for the loaded ship for the ship manoeuvring simulation study in this research.

D

Modelling of current fields

The flow module of the numerical modelling programme Delft3D 4.00.01 is used to model the input current fields for SHIPMA. Delft3D is developed by Deltares. Delft3D-FLOW is a multidimensional (2D or 3D) hydrodynamic and transport simulation program and can carry out computations for coastal, river and estuarine areas (Deltares, 2014). SHIPMA is only capable of handling 2D current fields; therefore, the current fields are also modelled in 2D with Delft3D-FLOW.

In paragraph D.1 the set-up for the Delft3D computations is described. In paragraph D.2 the modelled current fields, used for the SHIPMA simulations, are discussed.

D.1 Set-up of Delft3D computations

D.1.1 Model domain

All the current fields are modelled over a distance of 2.4 km in x-direction (Δx). The width of the modelled area (Δy) depends on the width of the waterway and the port entrance length. In Figure D-1 Δx and Δy are illustrated. In total, 14 different layouts are used for modelling the current fields. In Table D-1 the different domains, which are used for modelling these layouts, are shown. To provide a clear view of the layout dimensions, the characteristics are included in the table. For the explanation of each symbol is referred to Figure 3-5 and Figure 3-7. Note that Table D-1 is similar to Table 3-2; only Δx and Δy are added to Table D-1.

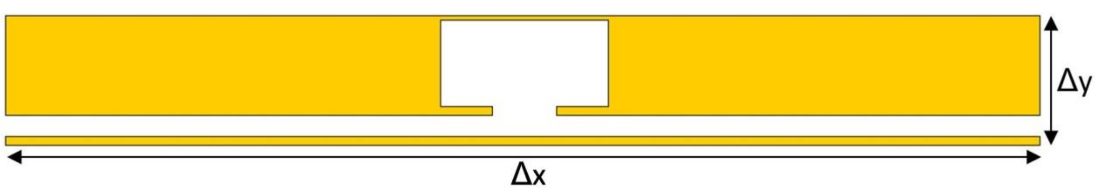

Figure D-1: Top view of modelling domain, Δx and Δy are defined.

Table D-1: Overview of used modelling domain and characteristics of layouts.

Layout nr.	Waterway type	Δx (m)	Δy (m)	W_w (m)	W_d (m)	W_e (m)	L_e (m)	α (deg)	W_b (m)	L_b (m)	d_1 (m)	d_2 (m)
1	Narrow	2400	300	48	24	150	20	90.0	390	200	4.9	3.5
2	Wide	2400	440	148	24	150	60	90.0	390	200	4.9	3.5
3	Wide	2400	440	148	24	150	59	33	390	200	4.9	3.5
4	Wide	2400	440	148	24	150	60	48	390	200	4.9	3.5
5	Wide	2400	440	148	24	150	60	60	390	200	4.9	3.5
6	Wide	2400	440	148	24	150	60	120	390	200	4.9	3.5
7	Wide	2400	440	148	24	150	60	132	390	200	4.9	3.5
8	Wide	2400	440	148	24	150	59	147	390	200	4.9	3.5
9	Wide	2400	600	148	24	150	120	120	390	200	4.9	3.5
10	Wide	2400	472	148	24	150	19	120	390	200	4.9	3.5
11	Wide	2400	440	148	24	90	60	120	390	200	4.9	3.5
12*	Wide	2400	440	148	24	200	8	90	610	200	4.9	3.5
13*	Wide	2400	440	148	24	200	8	90	610	200	4.9	3.5
14**	Wide	2400	440	148	24	150	60	120	390	200	4.9	3.5

*The difference between layouts 12 and 13 is the different orientations of the basins, see figure 3-7.

**The entrance dams of layout 14 are low, as a consequence the dams are flooded, see figure 3-8.

D.1.2 Computational grid

As mentioned before SHIPMA is only capable of handling 2D current fields. Therefore, only a horizontal grid is used for the model domain. A rectangular grid is used to model the current fields, see example in Figure D-2. Each grid cell contains the same dimensions. The dimension of a grid cell in the direction parallel to the waterway axis (x-direction) is 10 meters and 4 meters perpendicular on the waterway axis (y-direction).

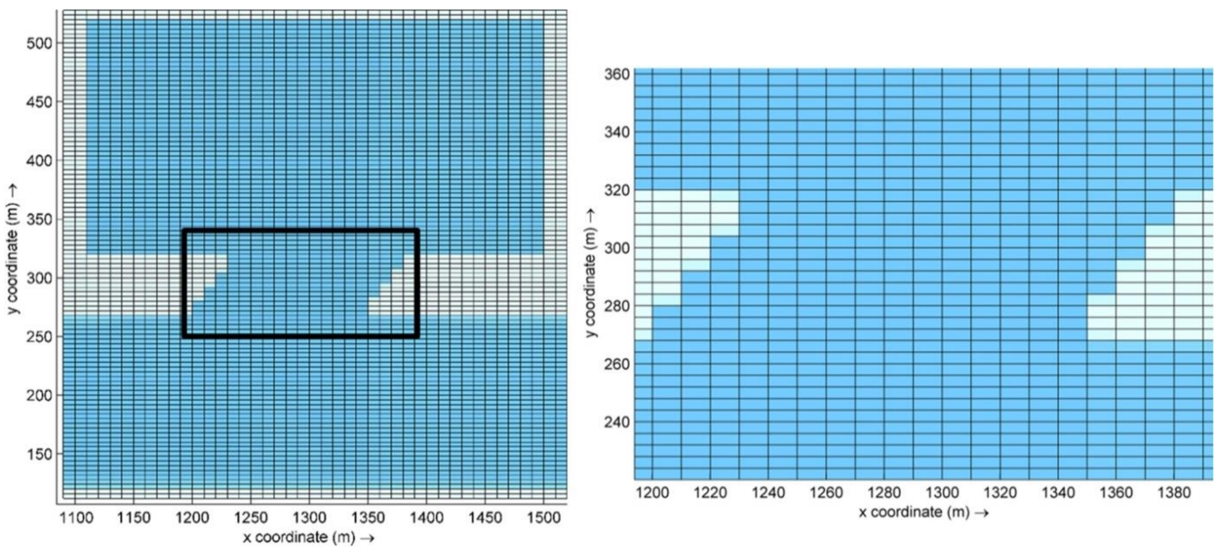

Figure D-2: Example of grid around port (left) and close-up of entrance (right).

D.1.3 Time frame

A time domain of 1 day was used for each computation. For all the computations the solutions are stable after 3 hours or less. So, a domain of 1 day provides a reliable result. A time step of 0.25 minutes was used for calculating a flow field with submerged entrance dams (layout 14). This time step was required to obtain a stable result. For the other calculations a time step of 0.5 minutes was sufficient.

D.1.4 Bathymetry

The bathymetry that is used is for every layout the same. This means the same slopes around the banks and the same bottom level (-4.9 m with respect to the reference level). The layout characteristics are different as described in Table D-1. The bathymetry around the port is shown in Figure D-3. The banks and port dams contain a height of circa +10 m with respect to the reference level. This is done to keep all the water in the waterway and port basin. There is one exception: for layout number 14 the port dams are modelled in such a way that the water can flow over these dams.

For all the layouts a bottom slope along the waterway axis of 10^{-4} is assumed. According to the reports of Van Heel & Verheij (2011) and De Jong et al. (2002b) the differences between the bottom levels for the port of Haaften (located along the Waal river) and Lobith (located along the Rhine river), is circa 10 meters. The distance between these two ports along the river Waal is circa 80 km (source: Google Earth, retrieved on December 7th, 2016). This is in agreement with a bottom slope of circa 10^{-4} for the Waal in the Netherlands.

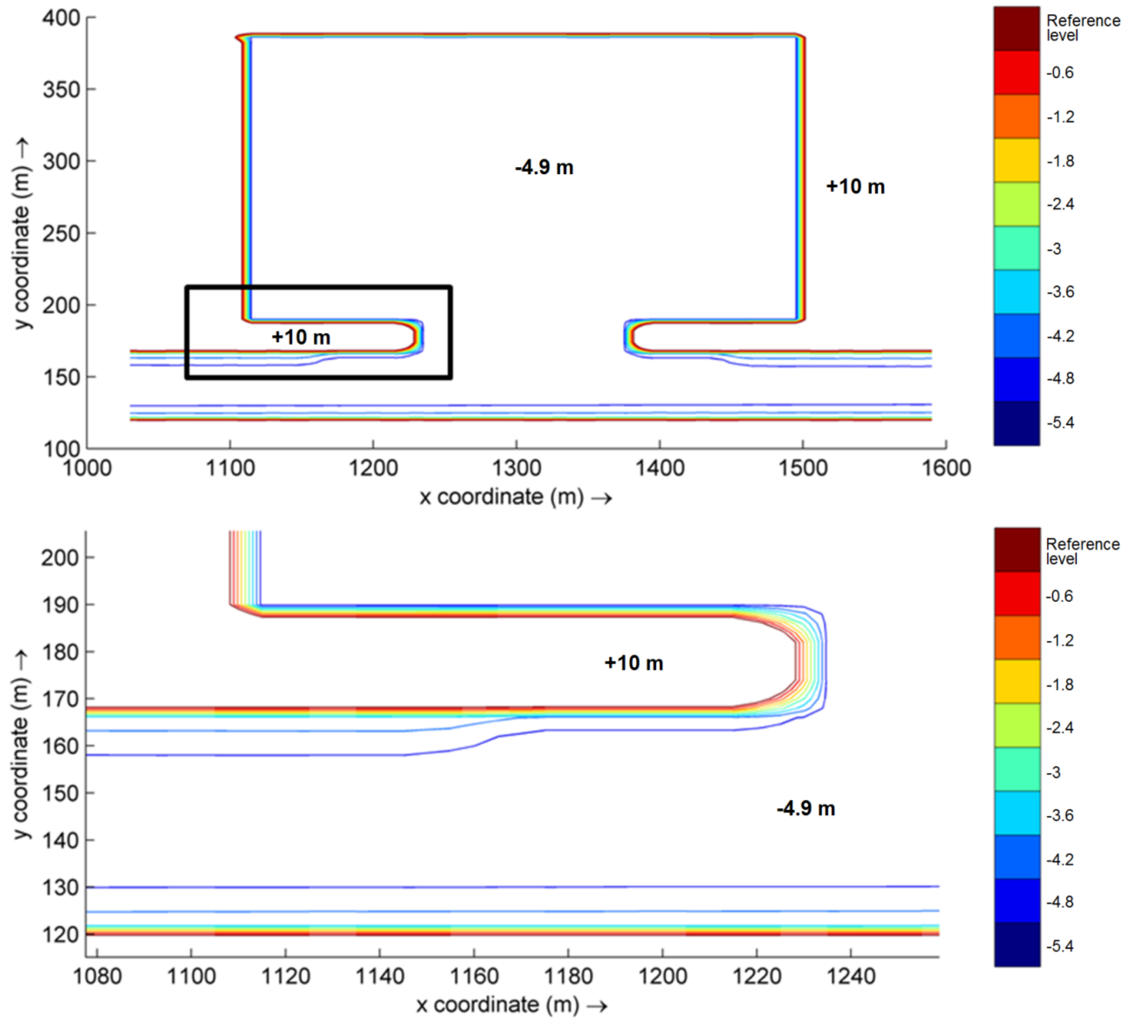

Figure D-3: Example of the bathymetry around the port (top) and close-up around the left entrance bank (bottom).

D.1.5 Initial conditions and boundaries

For all the computations for a current velocity of 1.0 m/s an initial water level of 0 meters, with respect to the reference level, is used and thus a water depth of 4.9 meters. For the computations of 2.5 m/s an initial water level of +2 meters, is used, which results in a water depth of 6.9 meters. The boundary condition on the left side of the domain is a water level boundary. A discharge boundary is chosen at the right side. In Table D-2 an overview is given of the boundary conditions and initial water level for each layout and current.

Table D-2: Overview of boundary conditions and initial water levels for every layout and current.

Layout nr.	Current (m/s)	Left boundary (m)	Right boundary (m^3/s)	Initial water level (m)
1	1.0	-0.239	-215	+ 0
1	**2.5**	**+1.761**	**-795**	**+ 2**
2	1.0	-0.239	-690	+ 0
3	1.0	-0.239	-690	+ 0
4	1.0	-0.239	-690	+ 0
5	1.0	-0.239	-690	+ 0
6	2.5	-0.239	-690	+ 0
6	**2.5**	**+1.761**	**-2493**	**+ 2**
7	1.0	-0.239	-690	+ 0
8	1.0	-0.239	-690	+ 0
9	1.0	-0.239	-690	+ 0
10	1.0	-0.239	-690	+ 0
11	1.0	-0.239	-690	+ 0
12	1.0	-0.239	-690	+ 0
13	1.0	-0.239	-690	+ 0
14	**2.5**	**+1.761**	**-2493**	**+ 2**

D.1.6 Physical parameters

The chosen physical parameters are for all the different simulations the same. The chosen values are displayed in Table D-3.

Table D-3: Overview of physical parameters.

Parameter	Value	Unit
Gravity	9.81	m/s^2
Water density	1000	kg/m^3
Chézy	65	$m^{1/2}/s$
Wall roughness, slip condition	Free	-
Horizontal eddy viscosity	1	m^2/s

The Chézy value is estimated with the following formula:

$C = \frac{1}{n_m} \cdot R^{\frac{1}{6}}$, with:

C : Chézy coefficient ($m^{1/2}/s$)
R: hydraulic radius (m)
n_m: Manning's roughness coefficient; value of 0.02 for smooth earth and no weeds (Henderson, 1966)

For the narrow layout and a water depth of 4.9 meters it results in a Chézy value of 63 $m^{1/2}/s$; in case of a water depth of 6.9 meters, the Chézy value is 66 $m^{1/2}/s$. For the wide layout and a water depth of 4.9 meters, the Chézy value is 69 $m^{1/2}/s$; with a water depth of 6.9 meters this is 71 $m^{1/2}/s$. All the Chézy vales are close to the default setting in Delft3D of 65 $m^{1/2}/s$. Therefore, it is chosen to use a value of 65 $m^{1/2}/s$ for all the Delft3D computations.

D.1.7 Numerical parameters

The numerical parameters are for all the executed computations the same. The chosen values are displayed in Table D-4. In order to export the correct water depths to SHIPMA, the parameter 'depth' at grid cell centres should be set to 'mean' instead of the default setting 'max'. When the value is 'max', a small difference occurs between the Delft3D output and the SHIPMA output for the water depth.

Table D-4: Overview of numerical parameters.

Parameter	Value
Drying and flooding check at	Grid cell centres and faces
Depth specified at:	Grid cell corners
Depth at grid cell centres:	Mean
Depth at grid cell faces	Mean
Threshold depth:	0.1 (m)
Marginal depth:	-999 (m)
Smoothing time:	60 (min)
Advection scheme for momentum	Cyclic

D.2 Modelling results

In Table D-5 an overview is shown of all the different current fields. For every field, it is indicated whether the field is created with Delft3D or with the scaling tool in the SHIPMA input files. The differences between these two methods are discussed in section D.2.1. In addition, other peculiarities of the current pattern around the port entrance and in the port basin are discussed in section D.2.1. Several examples of the current fields are shown in section D.2.2 to give an impression of the current patterns around the port entrance. In section D.2.3 the magnitude differences in front of the port entrance are shown. In Figure A2 of the SHIPMA output plots the current field around the entrance is visible for each run. The SHIPMA output plots are presented in appendix G.

Table D-5: Overview of current fields and indicated whether the field is created with Delft3D or with the scaling tool of SHIPMA.

Current field nr.	Layout nr.	Current (m/s)	Delft3D	Scaled with SHIPMA	Current field nr.	Layout nr.	Current (m/s)	Delft3D	Scaled with SHIPMA
1	1	1.0	✓		19	7	2.5		✓
2	1	2.5	✓		20	8	1.0	✓	
3	2	1.0	✓		21	8	2.0		✓
4	2	2.0		✓	22	8	2.5		✓
5	2	2.5		✓	23	9	1.0	✓	
6	3	1.0	✓		24	9	2.0		✓
7	3	2.5		✓	25	9	2.5		✓
8	4	1.0	✓		26	10	1.0	✓	
9	4	2.5		✓	27	10	2.0		✓
10	5	1.0	✓		28	10	2.5		✓
11	5	2.5		✓	29	11	1.0	✓	
12	6	1.0	✓		30	11	2.0		✓
13	6	1.5		✓	31	11	2.5		✓
14	6	2.0		✓	32	12	1.0	✓	
15	6	2.5		✓	33	12	2.5		✓
16	6	2.5	✓		34	13	1.0	✓	
17	7	1.0	✓		35	13	2.5		✓
18	7	2.0		✓	36	14	2.5	✓	

D.2.1 Evaluation

In section D.2.2 several current fields are shown. The peculiarities of these fields are briefly described in this section. In addition, the differences between the scaled current fields with SHIPMA and the fields modelled with Delft3D are explained in more detail.

Flow pattern in entrance

In all the current fields a flow gradient occurs in the port entrance. The precise pattern around the entrance is influenced by the angle and the length of the entrance. Layouts 9 and 11 contain relatively longer entrances (smaller width/length ratio). As a consequence, for these layouts an eddy arises in the entrance.

Flow pattern in basin

In the port basin a circular flow (eddy) arises, the magnitude of this flow depends on the flow velocity in the waterway. The water exchange between waterway and port basin is further elaborated in section 2.3.1.

Flow pattern in waterway

The current magnitude of the waterway near the entrance is lower than further up- and downstream. This is a consequence of the local widening caused by the port entrance.

Differences between current fields scaled with SHIPMA and modelled with Delft3D

In the current field input files for SHIPMA a scale factor is available to increase or decrease the magnitudes of the current field. In this research only current fields of 1.0 m/s, modelled with Delft3D, are scaled to current fields with larger magnitudes. For example, field number 3 is modelled with Delft3D. By scaling the magnitude of this field with a factor 2.5 in the SHIPMA input file, field number 5 is created. The differences between these methods are discussed by comparing two current fields, with the same current velocity and layout, modelled with the two methods. Fields 15 and 16 are used for this comparison.

The differences between these two current fields are small. This is illustrated in Figure D-4; the magnitudes from the scaled field are subtracted from the modelled field. It was found that the modelled field has larger magnitude at the areas A, C and D and the scaled field has larger magnitudes at the areas B and E. The largest deviations occur in the port entrance, with a maximum of 0.3 m/s.

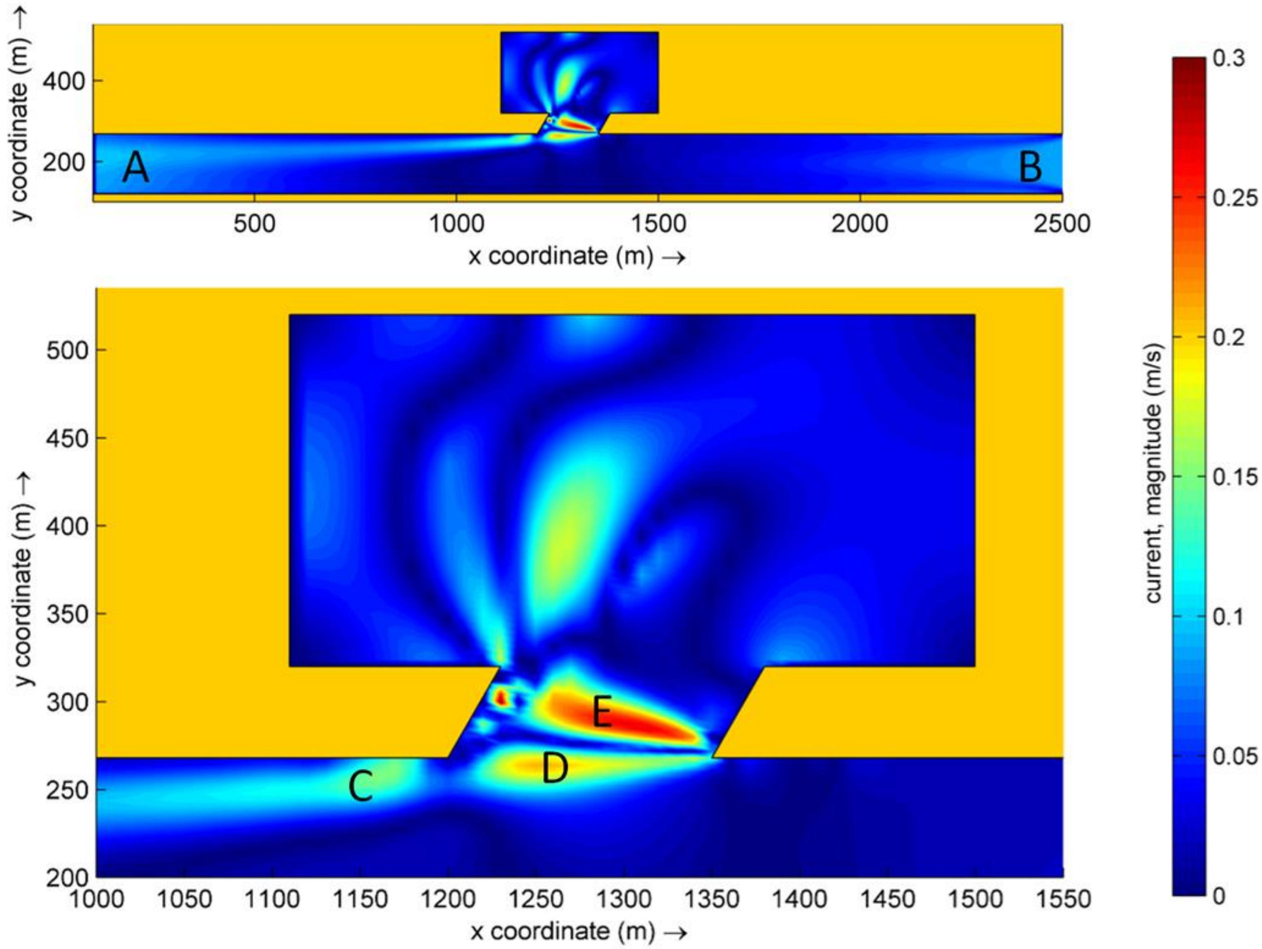

Figure D-4: Differences in magnitude between scaled current field with SHIPMA and modelled current field with Delft3D. Top: overview of waterway. Bottom: close-up around port.

When a ship is sailing through the port entrance, these minor differences can influence the ship behaviour and thus the output of a SHIPMA run. In front of the entrance, the scaled field is more favourable for a sailing ship, because the velocities are smaller. In contrary, in the entrance the modelled field is more favourable. For both fields a SHIPMA run is conducted. The ships start at downstream direction and sailing into the port with a forward manoeuvre. A similar set-up is used for both runs to provide a reliable comparison between the two runs. The output of both runs is shown in Table D-6. The simulation results show that the swept path of the ship is slightly smaller (6%) when using the scaled current field. For the required entrance width the difference is 4%. Note that the required entrance width is the width of the swept path plus safety distance, see section 3.4.2

Table D-6: Differences in SHIPMA output between modelled current field with Delft3D and scaled with SHIPMA.

Run nr.	Current field	Width of swept path in entrance (m)	Required entrance width (m)
Run 37	15 (scaled with SHIPMA)	67	79
Run 65	16 (modelled with Delft3D)	71	82

D.2.2 Current field examples

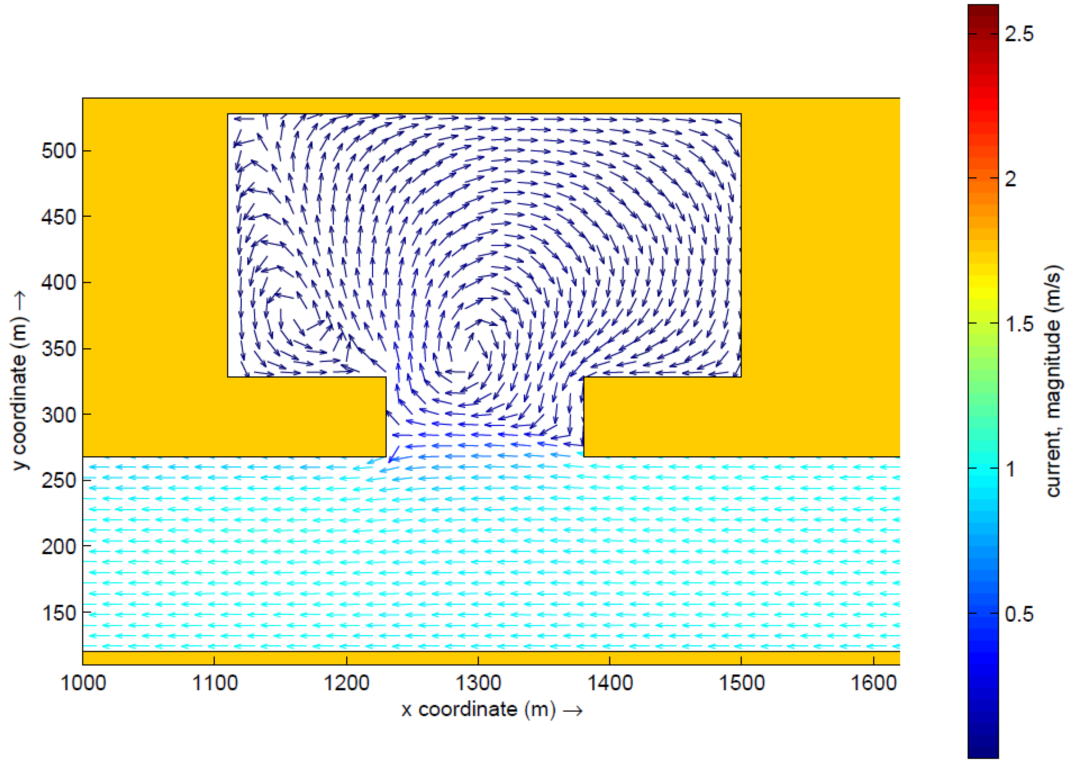

Figure D-5: Overview of current field number 3.

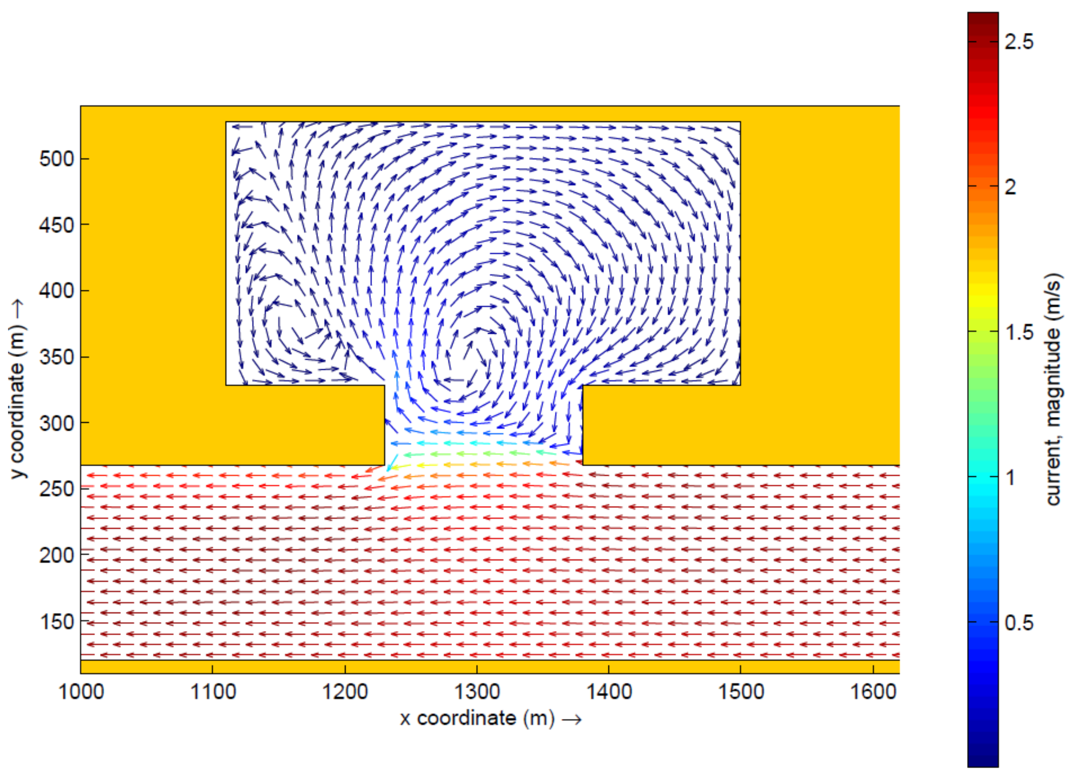

Figure D-6: Overview of current field number 5.

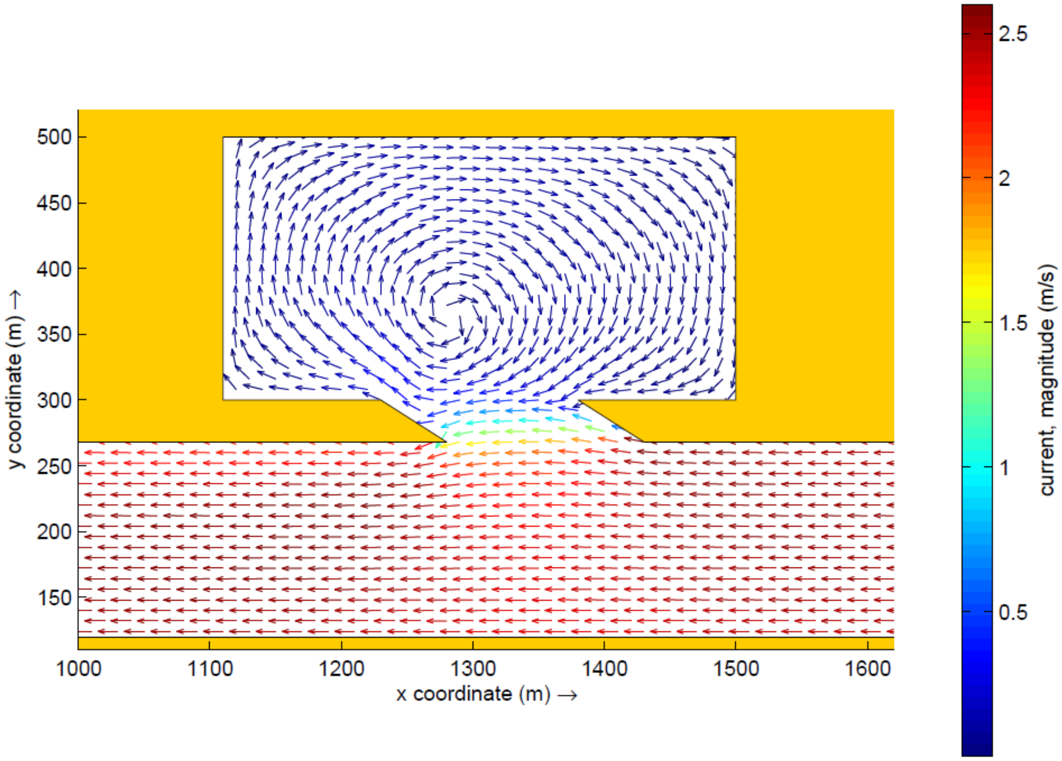

Figure D-7: Overview of current field number 7.

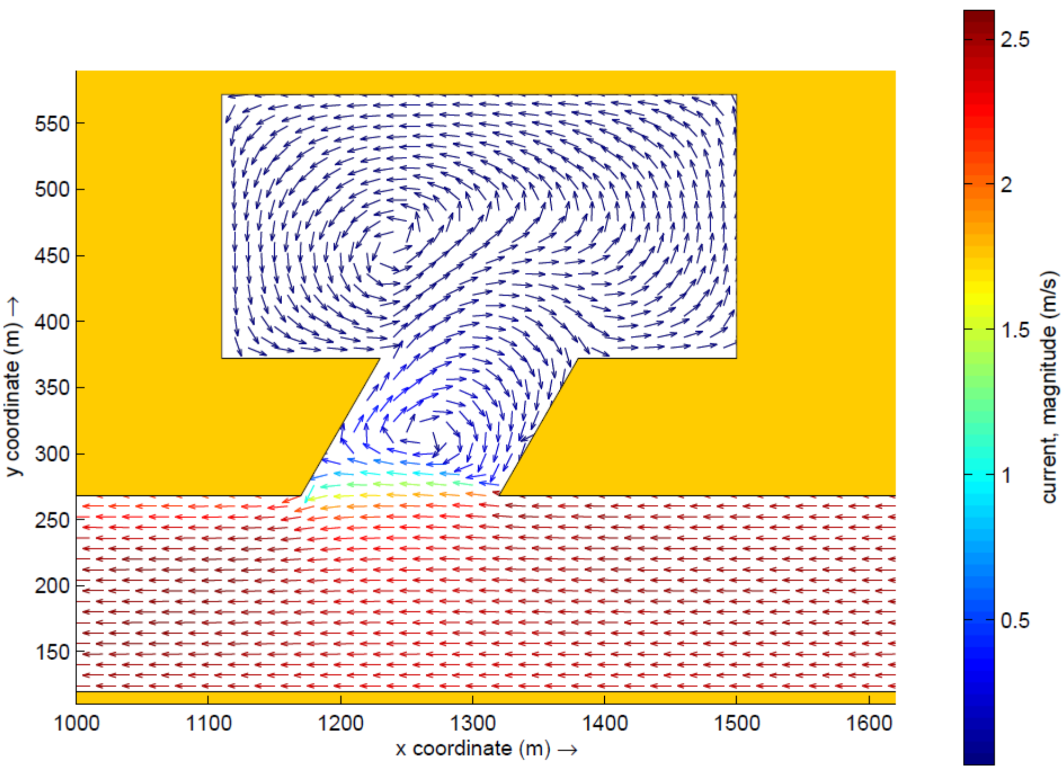

Figure D-8: Overview of current field number 11.

D.2.3 Magnitudes of current fields in front of entrance

In Figure D-9, Figure D-10, Figure D-11 and Figure D-12 the magnitudes of the current fields in front of the port entrance are shown for respectively current fields of 1.0, 1.5, 2.0 and 2.5 m/s. It can be observed that the magnitudes just in front of the entrance (indicated with the colours light blue up to dark red) are 10 to 20% smaller than further down- or upstream of the entrance.

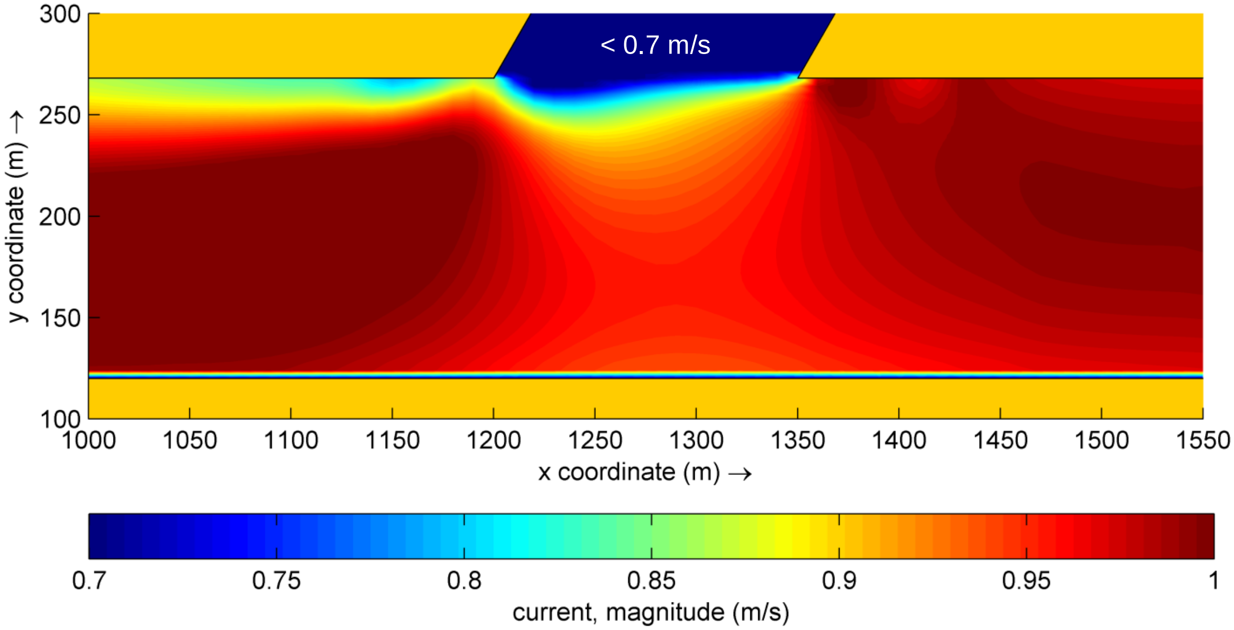

Figure D-9: Overview of flow velocity magnitudes in front of port entrance for current field of 1.0 m/s.

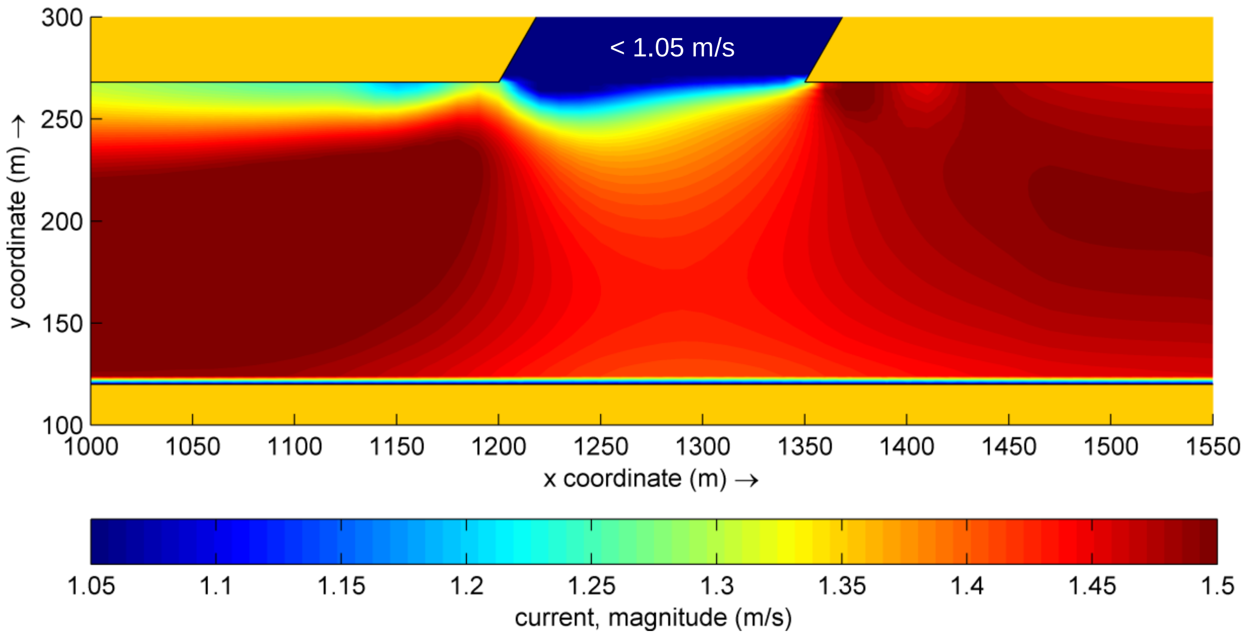

Figure D-10: Overview of flow velocity magnitudes in front of port entrance for current field of 1.5 m/s.

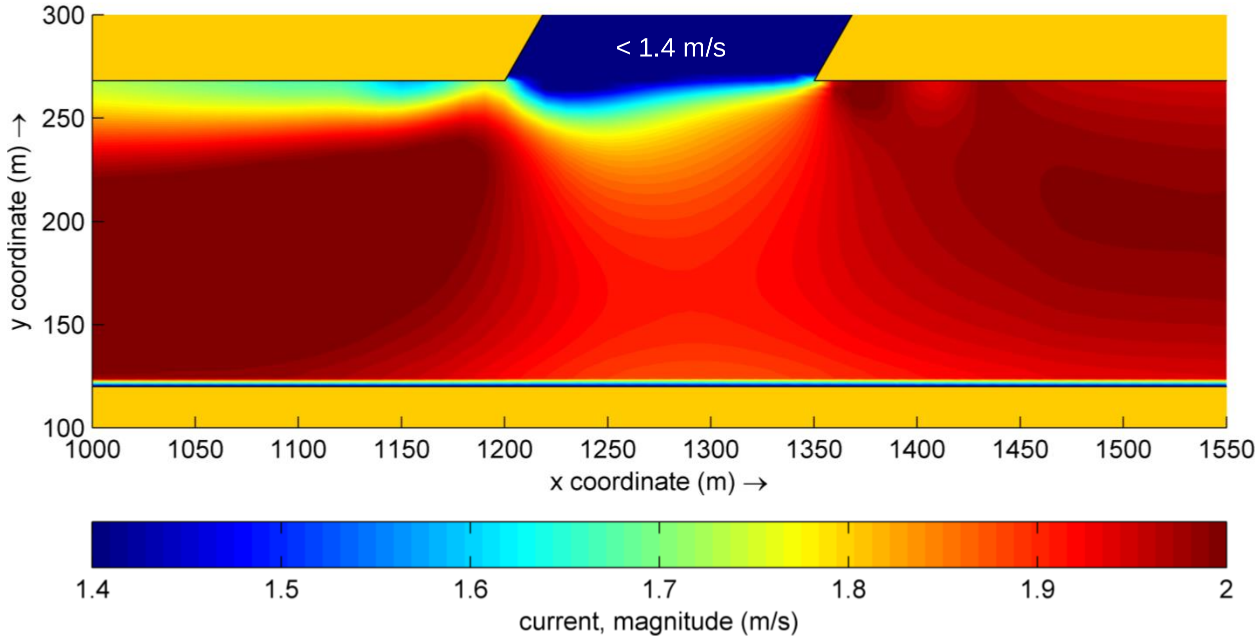

Figure D-11: Overview of flow velocity magnitudes in front of port entrance for current field of 2.0 m/s.

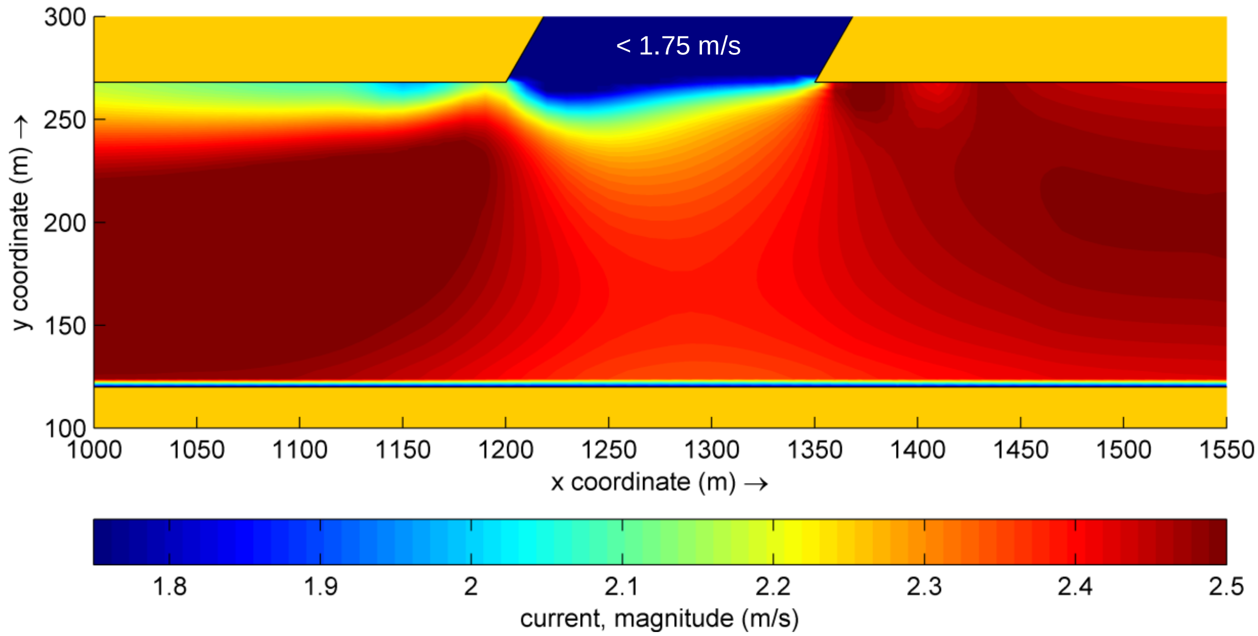

Figure D-12: Overview of flow velocity magnitudes in front of port entrance for current field of 2.5 m/s.

E

Overview of used trend lines for results analysis

In this appendix the used trend lines in chapter 5 are presented. Furthermore, with the value of R^2 is indicated how well the trend lines fit the data points. A R^2 of 1 indicates a perfect fit. Note that the data points are obtained with the simulation study. Each data point corresponds to a run result. Moreover, it should be mentioned that the trend lines are based on a limited amount of data points. As a consequence, the obtained values of R^2 are close to 1. So, most trend lines show an (almost) perfect fit. When more data points are used, it is possible that the fit is less accurate. However, the obtained trends in this research give a good impression of the relation between the entrance angle or flow velocity and required entrance width.

As was described in section 1.5, the results of this research are not useful for detailed design of an inland port entrance. This research gives an insight into the minimum required entrance widths. Hence, the obtained trends are sufficiently accurate for this research.

Relation between entrance angle and required entrance width

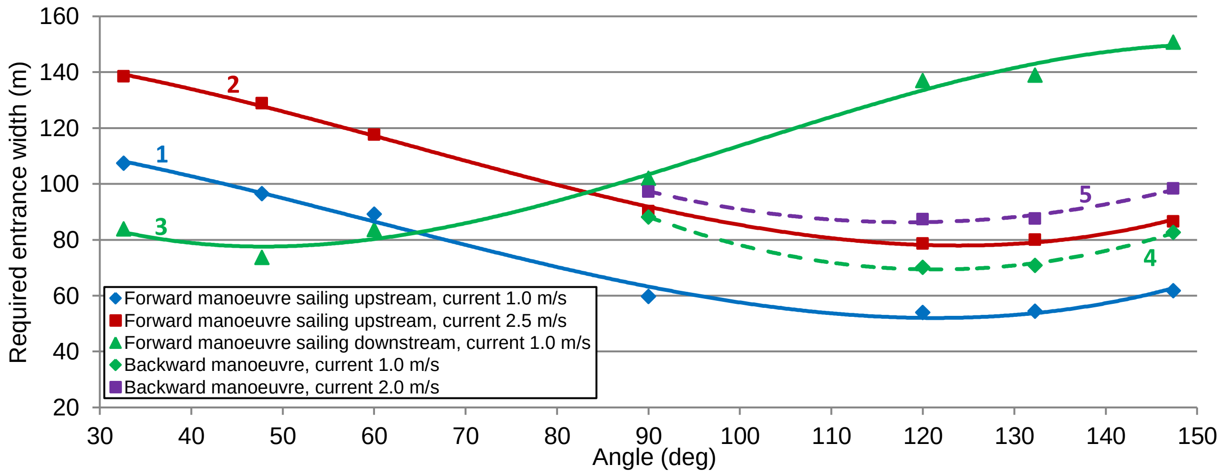

Figure E-1: Overview of plotted trend lines for the relation between the entrance angle and required entrance width. Trend lines from Figure 5-4 and Figure 5-5 from paragraph 5.2 are shown.

Table E-1: Overview of trend line formulas and values of R^2 for Figure E-1.

Trend line nr.	Formula (y = Required entrance width, x = Entrance angle)	R^2(-)
1	$y = 0.0000749585994732904x^3 - 0.0135236451284179x^2 - 0.0293357173130256x + 120.771954480539$	0.992
2	$y = 0.0000828358220684236x^3 - 0.0158774159965593x^2 + 0.11997141315662x + 149.254618399701$	0.998
3	$y = -0.000127532407158751x^3 + 0.0382856670227386x^2 - 2.79027799251455x + 137.399028938956$	0.990
4	$y = 0.0191427982096988x^2 - 4.64605565237297x + 351.280450609728$	0.995
5	$y = 0.0137673096082589x^2 - 3.25956617009455x + 279.205200596048$	0.969

For trend lines 1 to 3 a third order polynomial is used, because based on the shown data points it is expected that one minimum and one maximum point arises. For trend lines 5 and 6 only second order polynomials are used, because the data indicates that only one minimum point arises between angles of 90 and 150 degrees.

Relation between flow velocity and required entrance width

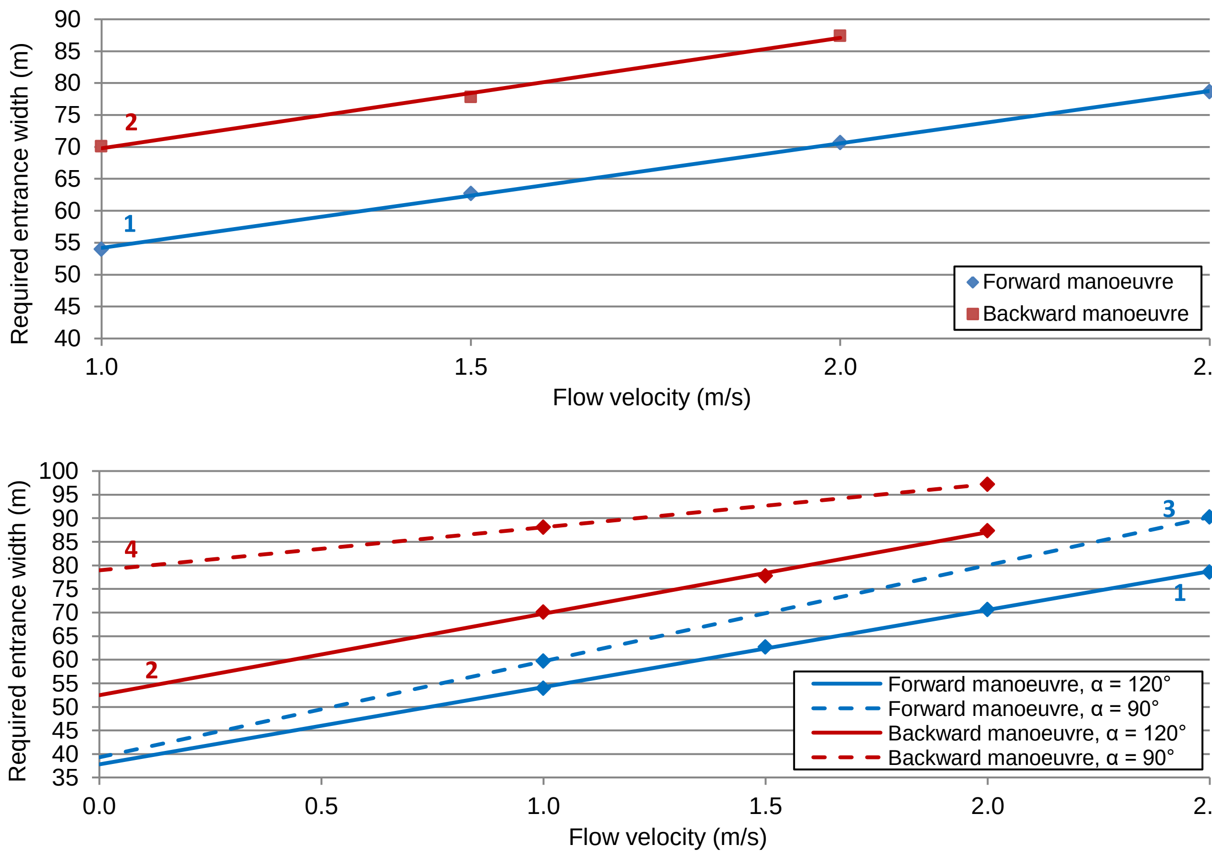

Figure E-1: Overview of the trend lines for the relation between the flow velocity and required entrance width. Figure 5-9 (top) and Figure 5-10 (bottom) from paragraph 5.4 are shown.

Table E-1: Overview of trend line formulas and values of R^2 for Figure E-1.

Trend line nr.	Formula (y = Required entrance width, x = Entrance angle)	R^2(-)
1	y = 16.38974x + 37.8049300000001	0.999
2	y = 17.2897000000001x + 52.4900833333333	0.996
3	y = 20.3736x + 39.324	1 (see explanation below)
4	y = 9.11250000000004x + 78.9856	1 (see explanation below)

For trend lines 3 and 4 the R^2 equals 1. For these lines only two simulation results were obtained. For these points a linear relation was assumed, because for line 1 and 2 also a linear relation was shown. A trend line through two points will always have a perfect fit. Therefore, this value of 1 does not indicate an accurate linear relation. The results on these lines are probably less correct than for lines 1 and 2, because these are based on three data points and thus more reliable.

F

Overview of input characteristics and output of SHIPMA runs

An overview of the conducted runs, with the fast-time simulation program SHIPMA, is given Table F-1.

For each run the following input characteristics are given:

Layout nr.	Layout number that corresponds to the modelled layout with Delft3D.
Dir	Sailing direction of the ship. 'Up' represents a ship that is sailing in upstream direction on the waterway. 'Down' indicates a situation in which the ship is sailing in downstream direction.
Man	Type of manoeuvre. 'In' represents a forward manoeuvre into the port. 'Out' indicates a forward manoeuvre out of the port. 'Stop' indicates a stopping manoeuvre on the waterway, in these runs the ship is sailing in downstream direction and is stopping just downstream of the port entrance. 'Back In' indicates a backward manoeuvre through the port entrance; this manoeuvre starts where the stopping manoeuvre ended.
Lateral approach distance	The lateral distance between the hull of the ship and the port entrance at the starting point of a manoeuvre. This lateral distance is illustrated in figure 3-17.
U_c	Flow velocity in the waterway.
Angle	The angle between the port entrance and the waterway.
W_w	Waterway width.
W_e	Entrance width.

For each run the following output is shown:

L_e	Entrance length.
Speed peak	The maximum speed used during the manoeuvre. * Indicates a speed peak that occurs at the start of the turning manoeuvre in or out of the port. ** Indicates a speed peak at the end of the turning manoeuvre in or out of the port. After this end point the speed increases further.
Time	Time to complete a turning manoeuvre on waterway. The time is given in a range of 1 minute.
$W_{w,req}$	The measured required waterway width.
$W_{e,req}$	The measured required entrance width.
Run assessment	The total assessment of a run. The assessments are discussed in paragraph 4.2.

The following symbolism is used for the total safety assessment of a run:

+	Sufficient
+/-	Critical
-	Insufficient

Table F-1: Overview of run input characteristics and run results.

Run nr.	Layout nr.	Current field nr.	Dir	Man	Lateral approach distance (m)	U_c (m/s)	Angle (deg)	W_w (m)	W_e (m)	L_e (m)	Speed peak (m/s)	Time (min)	$W_{w,req}$ (m)	$W_{e,req}$ (m)	Run assessment
1	1	1	Up	In	12	1.0	90.0	48	150	20.0	1.5	2-3	49	67	+/-
2	1	2	Up	In	14	2.5	90.0	48	150	20.0	<1.4*	1-2	49	91	+/-
3	1	1	Down	In	13	1.0	90.0	48	150	20.0	2.2	2-3	50	140	-
4	1	2	Down	In	12	2.5	90.0	48	150	20.0	3.6	1-2	53	199	-
5	1	1	Up	Out	X	1.0	90.0	48	150	20.0	> 2.0**	3-4	46	84	+
6	1	2	Up	Out	X	2.5	90.0	48	150	20.0	1.0	3-4	44	101	+
7	1	1	Down	Out	X	1.0	90.0	48	150	20.0	2.0	4-5	48	76	+/-
8	1	2	Down	Out	X	2.5	90.0	48	150	20.0	> 3.0**	2-3	54	107	+/-
9	2	3	Up	In	121	1.0	90.0	148	150	60.0	2.0	4-5	148	47	+
10	2	3	Up	In	74	1.0	90.0	148	150	60.0	1.5	3-4	111	48	+
11	2	3	Up	In	12	1.0	90.0	148	150	60.0	1.3	5-6	63	60	+
12	2	3	Up	Out	X	1.0	90.0	148	150	60.0	3.2	4-5	100	50	+
13	2	5	Up	In	124	2.5	90.0	148	150	60.0	< 2.0*	3-4	146	86	+
14	2	5	Up	In	76	2.5	90.0	148	150	60.0	< 2.0*	2-3	99	83	+
15	2	5	Up	In	12	2.5	90.0	148	150	60.0	1.4	3-4	57	90	+
16	2	5	Up	Out	X	2.5	90.0	148	150	60.0	3.6	3-4	88	77	+
17	2	3	Down	In	122	1.0	90.0	148	150	60.0	< 2.2*	6-7	150	52	-
18	2	3	Down	In	74	1.0	90.0	148	150	60.0	2.4	2-3	114	65	+
19	2	3	Down	In	12	1.0	90.0	148	150	60.0	2.1	2-3	65	102	+
20	2	5	Down	In	97	2.5	90.0	148	150	60.0	3.2	4-5	149	157	-
21	2	5	Down	In	22	2.5	90.0	148	150	60.0	3.0	2-3	75	196	-
22	3	6	Down	In	12	1.0	32.6	148	150	59.4	2.7	2-3	53	84	+
23	4	8	Down	In	12	1.0	47.7	148	150	59.5	2.6	2-3	60	74	+
24	5	10	Down	In	12	1.0	60.0	148	150	60.0	2.5	2-3	59	84	+
25	6	12	Down	In	12	1.0	120.0	148	150	60.0	2.2	2-3	65	137	+
26	7	17	Down	In	12	1.0	132.3	148	150	59.5	1.5	2-3	65	139	+
27	8	20	Down	In	12	1.0	147.4	148	150	59.4	1.5	2-3	65	151	+/-
28	3	6	Up	In	12	1.0	32.6	148	150	59.4	1.1	4-5	69	107	+
29	4	8	Up	In	12	1.0	47.7	148	150	59.5	1.2	4-5	68	96	+
30	5	10	Up	In	12	1.0	60.0	148	150	60.0	1.1	4-5	67	89	+
31	6	12	Up	In	12	1.0	120.0	148	150	60.0	2.1	3-4	51	54	+
32	7	17	Up	In	12	1.0	132.3	148	150	59.5	2.2	2-3	49	54	+
33	8	20	Up	In	12	1.0	147.4	148	150	59.4	2.3	2-3	46	62	+
34	3	7	Up	In	12	2.5	32.6	148	150	59.4	< 1.6*	3-4	57	138	+
35	4	9	Up	In	12	2.5	47.7	148	150	59.5	< 1.6*	3-4	57	129	+
36	5	11	Up	In	12	2.5	60.0	148	150	60.0	< 1.6*	3-4	56	118	+
37	6	15	Up	In	12	2.5	120.0	148	150	60.0	1.9	3-4	53	79	+
38	7	19	Up	In	12	2.5	132.3	148	150	59.5	2.0	3-4	53	80	+
39	8	22	Up	In	12	2.5	147.4	148	150	59.4	1.8	3-4	51	87	+

Run nr.	Layout nr.	Current field nr.	Dir	Man	Lateral approach distance (m)	U_c (m/s)	Angle (deg)	W_w (m)	W_e (m)	L_e (m)	Speed peak (m/s)	Time (min)	$W_{w,req}$ (m)	$W_{e,req}$ (m)	Run assessment
40a	2	3	Down	Stop	12	1.0	90.0	148	150	60.0	< 1.6*	2-3	X	X	+/-
40b	2	3	Up	Back In	12	1.0	90.0	148	150	60.0	-0.9	6-7	43	88	
41a	6	12	Down	Stop	12	1.0	120.0	148	150	60.0	< 1.6*	2-3	X	X	+/-
41b	6	12	Up	Back In	12	1.0	120.0	148	150	60.0	-0.9	5-6	41	70	
42a	7	17	Down	Stop	12	1.0	132.3	148	150	59.5	< 1.6*	2-3	X	X	+/-
42b	7	17	Up	Back In	12	1.0	132.3	148	150	59.5	-0.9	5-6	39	71	
43a	8	20	Down	Stop	12	1.0	147.4	148	150	59.4	< 1.6*	2-3	X	X	+/-
43b	8	20	Up	Back In	12	1.0	147.4	148	150	59.4	-0.9	6-7	37	83	
44a	2	4	Down	Stop	12	2.0	90.0	148	150	60.0	< 2.3*	1-2	X	X	+/-
44b	2	4	Up	Back In	12	2.0	90.0	148	150	60.0	-0.9	6-7	44	97	
45a	6	14	Down	Stop	12	2.0	120.0	148	150	60.0	< 2.3*	1-2	X	X	+/-
45b	6	14	Up	Back In	12	2.0	120.0	148	150	60.0	-0.9	5-6	49	87	
46a	7	18	Down	Stop	12	2.0	132.3	148	150	59.5	< 2.3*	1-2	X	X	+/-
46b	7	18	Up	Back In	12	2.0	132.3	148	150	59.5	-0.9	6-7	44	88	
47a	8	21	Down	Stop	12	2.0	147.4	148	150	59.4	< 2.3*	1-2	X	X	+/-
47b	8	21	Up	Back In	12	2.0	147.4	148	150	59.4	-0.9	6-7	42	98	
48a	6	13	Down	Stop	12	1.5	120.0	148	150	60.0	<1.9	1-2	X	X	+/-
48b	6	13	Up	Back In	12	1.5	120.0	148	150	60.0	-1.0	5-6	41	78	
49	6	13	Up	In	12	1.5	120.0	148	150	60.0	2.0	3-4	49	63	+
50	6	14	Up	In	12	2.0	120.0	148	150	60.0	1.9	3-4	54	71	+
51	9	23	Up	In	12	1.0	120.0	148	150	120.1	1.4	3-4	53	54	+
52	9	25	Up	In	12	2.5	120.0	148	150	120.1	1.4	3-4	58	82	+
53a	9	23	Down	Stop	12	1.0	120.0	148	150	120.1	< 1.6*	2-3	X	X	+/-
53b	9	23	Up	Back In	12	1.0	120.0	148	150	120.1	-0.9	5-6	41	70	
54a	9	24	Down	Stop	12	2.0	120.0	148	150	120.1	< 2.3*	1-2	X	X	+/-
54b	9	24	Up	Back In	12	2.0	120.0	148	150	120.1	-0.9	6-7	49	94	
55	10	26	Up	In	12	1.0	122.0	148	150	18.9	1.6	2-3	49	55	+
56	10	28	Up	In	12	2.5	122.0	148	150	18.9	1.6	2-3	53	81	+
57a	10	26	Down	Stop	12	1.0	122.0	148	150	18.9	< 1.6*	1-2	X	X	+/-
57b	10	26	Up	Back In	12	1.0	122.0	148	150	18.9	-0.9	6-7	44	71	
58a	10	27	Down	Stop	12	2.0	122.0	148	150	18.9	< 2.3*	1-2	X	X	+/-
58b	10	27	Up	Back In	12	2.0	122.0	148	150	18.9	-0.9	5-6	41	86	
59	11	31	Up	In	12	2.5	120.0	148	90	60.0	1.9	3-4	53	83	+
60a	11	30	Down	Stop	12	2.0	120.0	148	90	60.0	< 2.3*	1-2	X	X	+/-
60b	11	30	Up	Back In	12	2.0	120.0	148	90	60.0	-0.9	6-7	43	90	
61	12	32	Up	In	12	1.0	90.0	148	200	8.0	< 1.0*	4-5	42	104	+
62	12	33	Up	In	12	2.5	90.0	148	200	8.0	1.7	3-4	46	110	+
63	13	34	Down	In	12	1.0	90.0	148	200	8.0	2.2	2-3	44	161	+
64	13	35	Down	In	12	2.5	90.0	148	150	8.0	3.4	1-2	47	171	+/-
65	14	36	Up	In	12	2.5	120.0	148	150	60.0	1.6	3-4	60	84	+
66	6	16	Up	In	12	2.5	120.0	148	150	60.0	1.9	3-4	54	82	+

G
SHIPMA output plots

In this appendix the output plots of the conducted SHIPMA runs are shown. The complete version of this appendix, with all the output plots, is available at: *http://researchdata.4tu.nl*.

The output of the SHIPMA runs are presented in track plots and data plots. In the track plots every 20 seconds a ships contour is plotted and the distance of the followed path is indicated every 100 meters. The non-water parts of the layouts are covered by a yellow contour. The following plots are provided for each run:

- Figure A1: Track plot overview of entire situation with the water depth, bank suction lines, current, implemented track and ship snapshots. Close-up of the port entrance with the swept path, implemented ship track and ship snapshots.

- Figure A2: Track plot close-up of the port basin, entrance and the waterway in front of the port. In this plot the current, bank suction lines, implemented track and ship snapshots are included.

- Figure B: Data plots with the propeller revolutions (rev/s), rudder angle (deg) and bow thruster force (kN) plotted as a function of the travelled distance (m). The bow thruster force (kN) plotted against the time (min) is also included.

- Figure C: Data plots with the longitudinal ship speed (m/s), transverse ship speed (m/s) and the rate of turn (deg/s) plotted as a function of the travelled distance (m). The track distance plotted against the time (min) is also included.

In every figure the layout number is indicated. An overview of the different layouts used in the simulation study is given in Table 3-2.

The scenarios with a backward manoeuvre are split into two runs:

- Part a: Ship is sailing in downstream direction and stops downstream of the port entrance.

- Part b: Ship is sailing backward into the port. Note that the backward manoeuvres are conducted in upstream direction.

The ship snapshots from part a are coloured red and the snapshots from part b are coloured green. The data plots for both runs are given.

In several runs, wiggles can be observed in the data plots of the propeller revolutions and the rudder angle. An example is illustrated in Figure G-1. These wiggles occur when the SHIPMA model is operating on the edge of using a power burst to increase the steering capacity of the ship. When using the power burst, the rudder angle reduces slightly because not all obtained steering capacity created by the power burst is required. These wiggles can be removed by manually increase the propeller speed along the track where the wiggles occur. The obtained output for the ship manoeuvres used in this research is similar for a situation with wiggles and without wiggles. Hence, these wiggles are not problematic for the output. However, it should be mentioned that the wiggles in the propeller revolutions are not in agreement with the steering behaviour of a human operator.

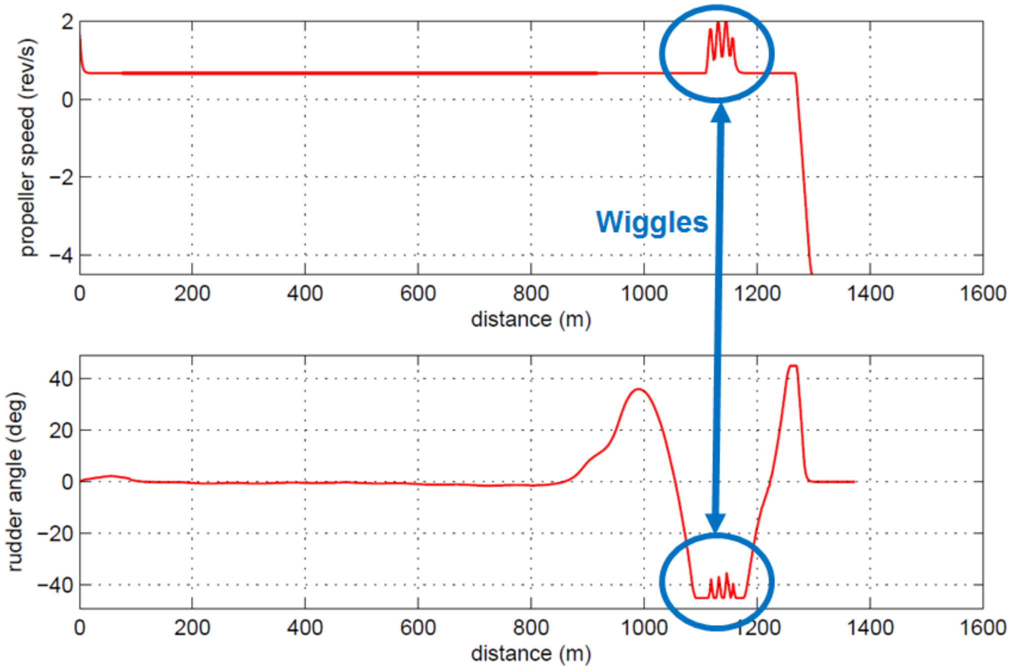

Figure G-1: Example of wiggles in the propeller and rudder angle data plots.