The ship domain in port areas

A case study in the Port of Rotterdam

MSc Thesis

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by

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Preface

Before you lies my Master Thesis about ship domains in port areas, written as a conclusion to my studies at Delft University of Technology. My time in Delft has been both exciting and educational and this thesis was no different. I learned a lot, not only on the subject or on Python coding, but also about myself.

This thesis could not have been written without the help and supervision of my committee. I first would like to thank Mark van Koningsveld for his help in finding this project and for his valuable feedback during the process. Additionally I would also like to thank Winnie Daamen for her consistently sharp, meaningful and scientific feedback. I am also grateful for Solange van der Werff and our weekly meetings. Every time I got stuck she was there to help me further and give me the confidence to continue. Similarly, Harmen van Dorsser helped by keeping me on track, and encouraging me to just put some dots behind the sentences.

Furthermore I would also like to thank Harmen's colleagues, the entire *Nautiek en Scheepvaart* team at Port of Rotterdam, for their interest, ideas and company for the duration of the project. My gratitude also goes out to the VTS Operators in both traffic center Botlek and Hoek van Holland as well as the crew of Trackpilot-ship Alfa Grande for showing me the practical aspects of this research.

And lastly, I would like to thank all the people in my personal life who helped me keep going during the tough times. Many thanks to my fellow musicians in my orchestra and my teammates in field hockey for all the fun activities and memories made this and all previous years. A lot of love to my friends and roommates who were always there with tea, drinks, conversation or food. And finally, to my family for their continuous support and especially my father for reading through this entire thesis despite having a background in history: Thank you.

Jolien Baak
Delft, October 2023

Summary

In the future, the situation on the waterway will become even more complex than it is today. As a consequence of climate change, the amount of different vessel types on the waterway is increasing. The shortage of manpower leads to less experienced people sailing and managing the waterways. Additionally, the combination of climate change, manpower shortage and ever increasing digitization has caused the introduction of (semi-)autonomous vessels. The higher degree of complexity could lead to a decrease in safety, especially in port areas, where the situation is already highly complex due to the combination of sea-going and inland vessels, high traffic density, as well as unusual manoeuvres. Captains and Vessel Traffic Service Operators (VTSO) need to manage this increasingly complex situation on the waterway and know when to take action, intervene or assist.

Multiple concepts that assist in route planning and the safe navigating on the waterway are being developed as part of the transition to autonomous vessels. The first, a Trackpilot, is a system that lets a vessel sail a predetermined route. By using route estimation and collision prediction, future distances between vessels can be estimated and action can be taken if necessary. The second concept is called a Moving Haven, a route-planning concept introduced by Porathe (2016). By claiming an area of the nautical waterway (a Haven) at a certain moment in time for the entirety of its route, a vessel's intentions of route and timing are crystal clear. The Moving Haven would simply follow a vessel's planned route with a certain speed and the vessel only has to stay inside the Moving Haven. The Moving Haven's size, speed and location could be programmed in such a way that there are no overlapping Moving Havens and the vessel arrives at the berth exactly on time. A collision-free voyage would be guaranteed (as long as all vessels stay within their Haven).

The concept of safe navigation is difficult to define. The number of accidents is no measure for the safety, as there may have been many near-misses. What qualifies as a near-miss is also not defined in clear numbers. However, captains do have a certain area around their vessel that they would prefer to keep empty to feel safe. This area is called the ship domain. The size of the ship domain is based on several situation- and ship-specific parameters and is explored in multiple ship domain theories. However, most of these ship domain theories are not applicable to port areas, as they describe a domain that is almost as large as, if not larger than, the the width of the waterway in a port area.

It is vital to analyse and quantify the behaviour of vessels as well as the distance they keep between each other in port areas. From these distances the ship domain can be determined, which can then be applied to assist in safety management and route planning concepts. The main research question answered in this research is: "How can ship domains be defined and applied around vessels in port areas to improve safety management and route planning?" This research has aimed to develop a method that determines the ship domain which can then be used in application. The method should be applicable in all port areas, but has been executed in the Port of Rotterdam.

As the past behaviour of vessels in the port areas needed to be analysed, the Automatic Identification System (AIS) data presented an ideal data set. AIS data provides information on the vessel location, as well as ship-specific parameters like the length, the heading and other voyage related messages. By comparing every vessel to every other vessel at every point in time, an encounter data set was created that contained the distances, the relative positions as well as all information on both vessels. The minimum distances, also referred to as the critical distances, were compared to the corresponding situation- and ship-specific parameters to create a relation. From these critical distances, the ship domain size and shape were defined. The domain was then be applied to the safety management and route planning concepts.

The encounter data set was created for multiple locations in the Port of Rotterdam. Port areas are highly complex but the complexity varies throughout the port. The traffic density, manoeuvres and waterway width varies, which might also have an effect on the vessel behaviour. The sectors included in the analysis were sector Maassluis, a straight forward and simple waterway, sector Botlek, an intersection

with high intensity and various manoeuvrings, and sector Breeddiep, a hotspot with a lot of different vessel types and manoeuvres. The encounter data set was then sorted based on encounter type (head-on and overtake) as well as in four directions (port-side, starboard, fore and aft). The influence of ship-specific parameters was determined per location, encounter type and direction.

Three application scenarios were introduced to select the critical distance parameter. The first scenario was named the regular scenario where no extra conditions apply. It could be used for near-miss analysis as well as alarms in VTSO aid. The second scenario, the OS scenario, was defined by the condition that only the parameters of the considered vessel were selected. The consequence was that the ship domain around the considered vessel is constant in size, regardless of the encountered vessels. It could be used for visual VTSO aid as well as the Moving Haven concept. The third scenario, the same-for-all scenario, was best used to compare the three locations. It required that every combination of encounter type and direction around a vessel used the same parameter, regardless of location. The three different scenarios lead to different choices of parameters, however, there did seem to be a pattern that in the sailing direction, the velocity-related parameters had the largest influence, while in the perpendicular direction the width-related parameters were most influential.

From the chosen parameters, the critical distances were determined and the size of the ship domain followed. It was at all times smallest in sector Botlek, while during overtakes it was largest in sector Breeddiep and during head-on encounters it was largest in sector Maassluis. The size of the domain also showed a large difference in all three locations between the head-on and overtake encounters. The distances were larger in fore and aft direction when compared to port-side and starboard. As the size of the domain was known in four directions, a shape was drawn to connect the distances. Based on the scenarios of application, three different shapes were tested. The first was a diamond, which was minimal and related to the near-miss analysis. The second was an ellipse, which was found in the literature and could be used in Trackpilots and visual VTSO aid. The last shape was a rectangle, which was the shape applied by the Moving Haven concept.

The difference between shapes was tested via the amount of domain breaches. Per scenario, per location, and per shape the amount of unique vessels that enter another vessel's ship domain was counted. The diamond shape always had the lowest amount of breaches, and the rectangle the highest. While the rectangle was twice as large as the diamond, the amount of breaches was at least 2.5 times as high. The lowest amount of breaches occurred for sector Maassluis for the first application scenario and a diamond shape with 158 unique vessels over a time period of two weeks. This resulted in an average of 0.47 breaches per hour. The highest amount of breaches occurred for sector Botlek for the second application scenario and a rectangle shape with 1028 unique vessels over a time period of two weeks. This resulted in an average of 3 breaches per hour. A smaller domain did lead to less breaches, but might not have been an accurate representation of the ship domain. Therefore, the scenarios of application guided the size and shape of the ship domain.

The application of the domain could be used in safety management and route planning. In regards to safety management, the assistance to VTSO could help via alarms if vessels enter each other's domain, or via visual aid on the VTSO screens. The ship domain could also be used in the near-miss analysis, but further research must be done on the correlation between domain breach and near-miss. In regards to the route planning, a Trackpilot would be able to adjust their route automatically in order for the considered vessel to sail around the ship domain of the other vessel. The planned routes could also determine their distances based on the ship domain. As for the Moving Haven concept, the ship domain determined a minimum Moving Haven size of 40m in sector Maassluis, 30m in sector Botlek and more than 60m in sector Breeddiep, for more than 94% of all encounters. However, any form of implementation would need more research into the practicality of the concept.

In conclusion, from the analysis of historical AIS data, a method has been created that is capable of determining the ship domain for every location in a port area considering both situation-specific parameters like encounter type and the relative positioning of the vessels as well as ship-specific parameters like the length, width and velocity. Several applications of the ship domain have also been explored, with the conclusion that it could immediately be used in VTSO aid and for Trackpilots, while near-miss analysis and Moving Havens would need more research before implementation would be possible.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
AIS	Automatic Identification System
CATZOC	Category of Zones of Confidence
COG	Course over Ground
COLREGS	International Regulations for Preventing Collisions at Sea 1972
DQSD	Dynamic Quaternion Ship Domain
ETA	Estimated Time of Arrival
FQSD	Fuzzy Quaternion Ship Domain
GPS	Global Positioning System
HCC	Harbour Coordination Center
IMO	International Marine Organization
MASS	Maritime Autonomous Surface Ships
MMSI	Maritime Mobile Service Identity
MRCC	Maritime Rescue Coordination Centre
OS	Own Ship
PoR	Port of Rotterdam
QSD	Quaternion Ship Domain
RMSE	Root Mean Square Error
ROT	Rate of Turn
RWS	Rijkswaterstaat
SOG	Speed over Ground
STM	Sea Traffic Management
TS	Target Ship
VTS	Vessel Traffic Services
VTSO	Vessel Traffic Service Operator(s)
XTD	Cross Track Distance
XTL	Cross Track Limit

Symbols

Symbol	Definition	Unit
B	Vessel beam/width	[m]
D	Distance between OS and TS	[m]
d_{zoc}	Measure for the accuracy of bathymetric data	[m]
d_b	Vessel beam on each side of the longitudinal axis	[m]
d_{pos}	Positional accuracy of the GPS signal	[m]
d_{NavAlw}	Navigational area safety allowance	[m]
d_{VesAlw}	Vessel's orientation safety allowance	[m]
k_{AD}	Factor for advance	[-]
k_{DT}	Factor for diameter of turn	[-]
L	Vessel length	[m]

Symbol	Definition	Unit
R_{fore}	Distance ship domain fore (N. Wang, 2010)	[m]
R_{aft}	Distance ship domain aft (N. Wang, 2010)	[m]
R_{port}	Distance ship domain port-side (N. Wang, 2010)	[m]
R_{starb}	Distance ship domain starboard (N. Wang, 2010)	[m]
v_{kn}	Velocity	[knots]
v_{ms}	Velocity	[m/s]
α	Angle OS to TS for empirical ship domain	[deg]
α	Drift angle (Kristić et al., 2020)	[deg]
γ	Navigational safety factor	[-]
ϕ	Absolute difference in COG OS and TS	[deg]

Ship domain visual definitions

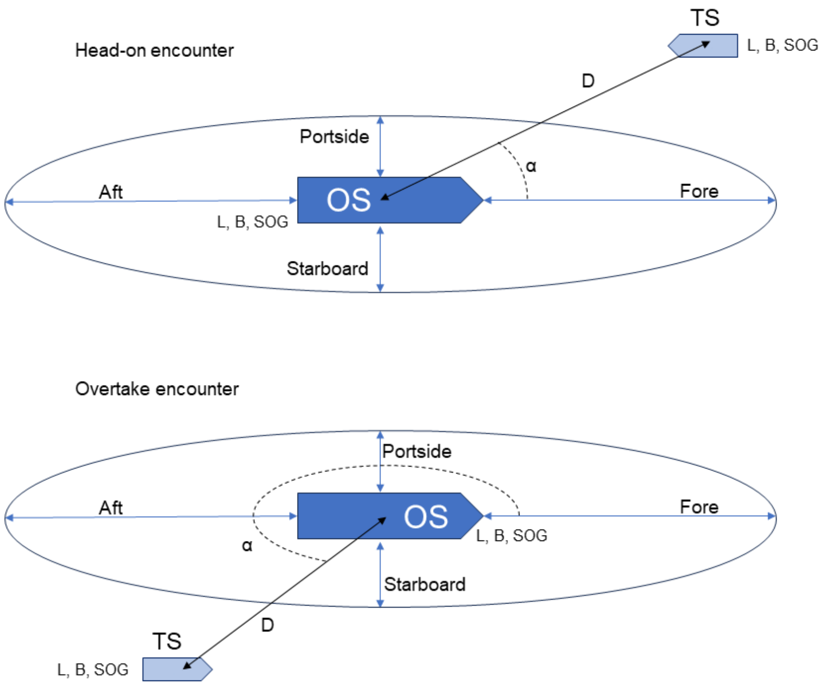

Figure 1: Definitions of the ship domain, head-on and overtake encounter.

1 Introduction

This chapter introduces the subject of this research. Relevant background information shows the knowledge gap which leads into the problem definition. Via the problem definition, the research objective is determined, along with the research questions. Additionally, the approach and scope are discussed, and the chapter is closed with a reading guide.

1.1. Background

Shipping has always been a human enterprise. A captain sails on experience, knowledge and instinct. The water is unpredictable and unforgiving, which means sailors have to be adaptable, yet sure and steady. That is still true to this day. Of course, these days, there is much more information available for captains to base their course on. This increase in information has led to a significant decrease in accidents over the last century (Eliopoulou & Papanikolaou, 2007). However, there remains room for improvement.

To consider safety is especially relevant in light of new challenges in shipping. In the Paris Agreement of 2016, 193 countries and the European Union agreed to limit the production of carbon dioxide. Zero-carbon vessels and vessels sailing on ammonia or hydrogen are being developed. Additionally, more efficient ways of sailing are being investigated. Some vessels can reduce their fuel use by almost 50% by sailing 5 knots slower (Meyer et al., 2012). Combined with just-in-time-arrival, this significantly reduces the carbonated fuel use. However, this does increase the complexity of the fleet present on the waterway, both in vessel types as well as varying sailing speeds. The second challenge concerns the availability of manpower in the shipping industry in particular. The occupation of skipper is declining in popularity (BIMCO & International Chamber of Shipping, 2021). Younger generations do not want to work at sea and spend several months per year away from home, friends and family. Shortage of manpower is also a problem in traffic management divisions on land. Less experienced people need to manage an ever increasing fleet on the waterway.

While shipping automation has long fallen behind when compared to automation on the road, it is now making strides. With the introduction of the Automatic Identification System (AIS) in 2003, traffic is easier to monitor and analyse. It presents not only the vessel location, but also information on the vessel speed, length and voyage related messages. The safety management on land has also become easier as there is much more information available about all vessels on the waterway. The introduction of AIS has also kick-started the automation process to the point where (semi-)autonomous ships are being tested right now.

The International Maritime Organisation (IMO) defines a Maritime Autonomous Surface Ship (MASS) as a ship which, to a varying degree, can operate independent of human interaction. For this 'varying degree', the IMO also defines four degrees of automation (IMO, 2022), while SMASH! (the Dutch Forum for Smart Shipping) distinguishes six degrees (Potgraven & de Lange, 2022). The MASSs are ranked based on three categories, navigation (who/what turns the wheel), monitoring (who/what reacts to the sailing environment), and fallback measures (who/what interferes in case of unusual events like malfunctions). On the lowest degree, the skipper is responsible for all three categories, while on the highest degree, the ship does all three. Automation in shipping would cause the demand for skippers to decrease and smart algorithms and systems can calculate the ideal route, sailing speed and sailing time.

Autonomous ships have advantages but they also bring new challenges. Regulations do not yet allow for a fully autonomous vessel: it is currently still illegal in the Netherlands to sail a ship without a captain onboard. The introduction of yet another vessel type leads to an even higher complexity on the waterway. And, as mentioned in the first paragraph, captains sail on experience, expert knowledge and instinct. An autonomous ship does not have the same experience or the instinct (yet). The combination of autonomy and the shortage of manpower (both on vessels and on land) can have a serious impact on the safety on the waterway, especially as there will be a variation of non-, semi- and fully-autonomous vessels present on the waterways, interacting and sailing alongside each other.

Multiple concepts that assist in route planning and the safe navigating on the waterway are being developed as part of the transition to autonomous vessels. The first, a Trackpilot, falling in the first (and lowest) degree of automation, is a system that lets a vessel sail a predetermined route. The captain determines the track and the vessel starts sailing. By using route estimation and collision prediction future, distances between vessels can be estimated and action can be taken if necessary. The second concept is called a Moving Haven, a route-planning concept introduced by Porathe (2016). By claiming an area of the nautical waterway (a Haven) at a certain moment in time for the entirety of its route, a vessel's intentions of route and timing are crystal clear. The Moving Haven would simply follow a vessel's planned route with a certain speed and the vessel only has to stay inside the Moving Haven. The Moving Haven's size, speed and location could be programmed in such a way that there are no overlapping Moving Havens and the vessel arrives at the berth exactly on time. A collision-free voyage would be guaranteed (as long as all vessels stay within their Haven).

1.2. Problem definition

The concepts explained in the previous paragraph prompt the question of when a particular situation can be deemed as "safe". "Safe" would determine the moment a captain or operator needs to take action as well as the size of the Moving Haven. Based on a limited number of accidents, it is difficult to determine how safe a waterway actually is. Accidents are recorded and analysed, but near-misses can easily go under the radar. A near-miss is defined by IMO (2008) as "A sequence of events and/or conditions that could have resulted in loss. This loss was prevented only by a fortuitous break in the chain of events and/or conditions. The potential loss could be human injury, environmental damage, or negative business impact (e.g., repair or replacement costs, scheduling delays, contract violations, loss of reputation)." This definition still makes it difficult to quantify the concept of safety. However, most captains do have a certain distance that they prefer to keep to other ships in order for them to feel safe. These distances are explored in ship domain theories. These theories determine the distance based on several (ship and circumstance specific) parameters. Unfortunately, most of these are applicable to vessels in open waters (Goodwin (1975), N. Wang (2010)) and they are not applicable in port areas as the determined domains are larger than an average waterway in a port area.

The increased complexity on the waterway due to the introduction of zero-carbon vessels, increasing autonomy of vessels and shortage of manpower in combination with the existing complexity of port ares due to limited space, a large variation in fleet composition and various unusual manoeuvres presents an interesting challenge. It is vital to analyse and quantify the behaviour of vessels as well as the distance they keep between each other in port areas. The ship domain in port areas can provide a good indication of what captains experience as safe. This ship domain can then be applied and used to assist in safety management and route planning.

1.3. Research objective

The main objective of this research is to define the ship domain in a port area, in order for it to be used for the improvement of safety management in the form of near-miss analysis and traffic management assistance as well as the implementation of route planning concepts like Moving Havens and Trackpilots. The aim is to create a method that can be executed in all port areas.

To reach the objective, the main research question is defined as follows:

How can ship domains be defined and applied around vessels in port areas to improve safety management and route planning?

To answer the main research question, four sub-questions are composed.

Question 1 - Theoretical orientation: What are the most commonly used parameters to describe the ship domain?

Question 2 - Historical AIS data analysis: Based on historical AIS data, how are critical distances between vessels, that are key inputs to ship domain definition, related to situation- and ship-specific parameters?

Question 3 - Formation ship domain: What shape and size can best be used to describe the ship domain as observed in historical AIS data?

Question 4 - Application: How can the AIS-based ship domain be used to improve safety management and route planning in port areas?

1.4. Approach

The sub-questions give a clear route for this report. First, a literature study will explore the similarities and differences in existing ship domain theories. The purpose is to understand what parameters determine the various ship domain theories. Based on the theory, a list of relevant parameters will emerge, which will be used in the historical data analysis. AIS data contains the sailing of vessels in port areas, therefore a historical data analysis based on AIS data on behaviour in port areas is done. The distances during an encounter between vessels will be determined and related to the list of parameters. The influence of the parameters on the distance will be compared and the most influential parameter will determine the size and shape of the ship domain. The last part of the research will focus on the implementation in regard to safety management and route planning. A schematic overview can be found in Figure 1.1. The bold text indicates an analysis step, while the italic text indicates the output.

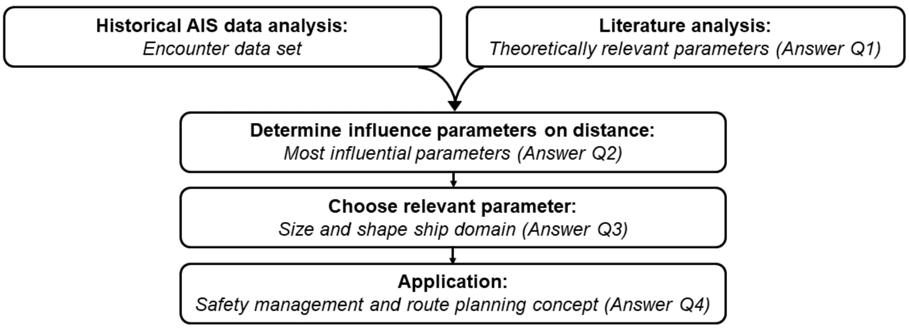

Figure 1.1: Schematic overview of approach

1.5. Scope

A case study is performed for vessels inside the Port of Rotterdam. As mentioned, port areas are highly complex but the complexity varies throughout the port. Therefore, sailing behaviour is not the same in every part of the port. To analyse this difference, the analysis will be carried out in three different sections in the port. Furthermore, not all vessels in the port will be included in the analysis. Only sailing vessels and vessels relevant to the shipping process will be included. Smaller vessels often do not ship anything themselves, occupy a lower position in the hierarchy or have a lot more adaptive ability. These will therefore not be included in the analysis.

1.6. Reading guide

This thesis will have the following structure; after this introduction, Chapter 2 elaborates on the relevant literature. Chapter 3 explains the methodology and Chapter 4 gives more information on the case study in the Port of Rotterdam. Chapter 5 discusses the historical AIS data analysis which results in the creation of the encounter data set. The influence of the parameters is discussed in Chapter 6 after which the shape and size of the ship domain is determined in Chapter 7. Chapter 8 explores the possible applications of the ship domain. And finally, Chapter 9 contains the discussion, followed by the conclusions and recommendations in Chapter 10.

2
Literature

This chapter aims to answer the first research question, which is formed based on the demand for theoretical orientation. The existing ship domain theories are explored, as well as the parameters that determine the domains. The concept of Moving Havens is also further elaborated on after which all ship domain theories and Moving Havens are compared to each other. Finally, AIS data is further explained to determine how the relevant parameters are available.

2.1. Ship domain theory

A ship domain is a term widely used to define the area around a vessel in which other vessels should not enter. The three most common definitions are as follows:

- ”A two-dimensional area surrounding a ship which other ships must avoid – it may be considered as the area of evasion” by Fujii and Tanaka (1971).
- ”The effective area around a ship which a navigator would like to keep free with respect to other ships and stationary obstacles” by Goodwin (1975).
- ”The effective area around a ship which a typical navigator actually keeps free with respect to other ships” by Coldwell (1983).

Each of the theories explored in this chapter cite one of these definitions as the definition they use. The difference in definition is very minimal but it leads to slightly different interpretations and therefore different domains. The interpretations can be summed up into four different safety criteria, as discerned by Szlapczynski and Szlapczynska (2017). The four criteria can be found in Figure 2.1. The figure shows two vessels; the Own Ship (OS) and the Target Ship (TS), each with their own size, as well as the minimum distance d between them. Each vessel has its own ship domain, represented by an ellipse around it. The size of the domain is different for OS and TS as they have different sizes. The minimum distance between OS and TS is determined by one of the four safety criteria:

(a) The OS domain should not be violated by the TS, the minimum distance is therefore equal to the OS domain size.
(b) The TS domain should not be violated by the OS, the minimum distance is therefore equal to the TS domain size.
(c) Both the OS and TS domains should not be violated by the TS and OS respectively, the minimum distance is therefore equal to the largest domain size.
(d) Ship domains should not overlap, the minimum distance is therefore equal to sum of the OS and TS domain sizes.

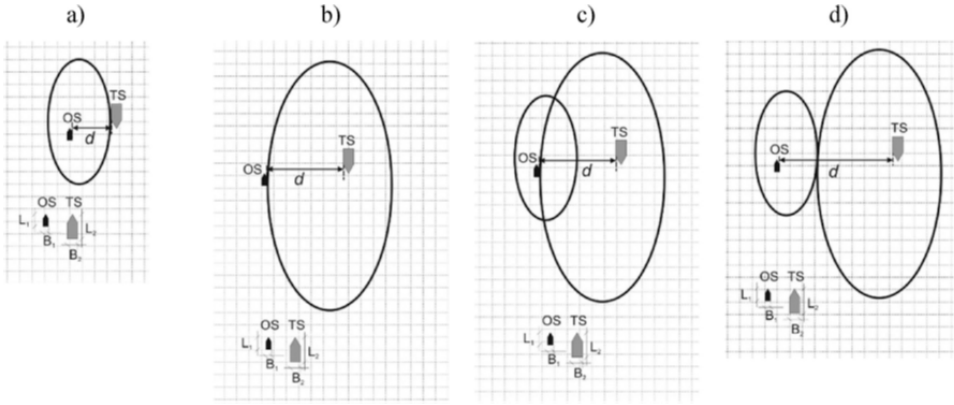

Figure 2.1: Ship domain safety criteria (Szlapczynski & Szlapczynska, 2017).

All ship domain theories discuss which parameters are included when determining the size of the domain. Some even discuss influential parameters that are then not included in determining the ship domain. In combination with the various safety criteria, this leads to a lot of different theories. This paragraph aims to explain the similarities and differences between several the existing theories.

Fujii and Tanaka (1971) is the first to define some sort of ship domain by looking at the capacity of a waterway. They state the parameters relevant to the ship domain are the vessel's length, speed, environmental conditions like weather, visibility and tidal currents, as well as route conditions like depth, width and obstacles. The domain is determined empirically via radar data. By looking at radar photographs they are able to show the distances between OS and all other vessels during the observation period. Figure 2.2 shows the result. In the upper left corner the OS is pictured, while all the other dots are TS. The assumption is made that the domain is symmetrical which is why only a quarter of the domain is pictured. However, there is a clear area around the vessel where no other ships were present during the entire period of observation.

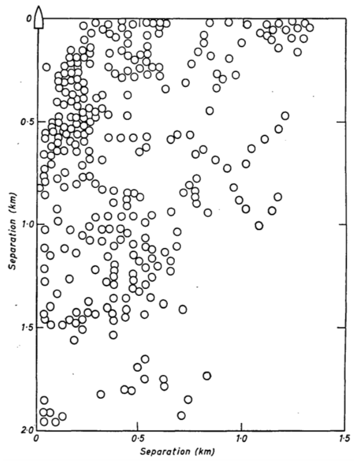

Figure 2.2: Empirically determined ship domain (Fujii & Tanaka, 1971).

Despite naming multiple relevant parameters, Fujii and Tanaka (1971) then relates the domain size only to the length of the OS, as well as the combined length in case of varying vessel lengths. This is of course all done by observations and radar footage from almost 50 years ago. The method was reproduced by Hansen et al. (2013) but with a few changes. The introduction of AIS data and faster computers allow for a more detailed and elaborate analysis. Every vessel is compared to every other vessel, instead of just one vessel to all other vessels. The distance can then be compared to each vessel's length resulting in the distance being expressed in the OS vessel's length. The result is an intensity map that shows the distance expressed in vessel length, as shown in Figure 2.3. Despite the changes the result remains very similar, with a domain that is roughly the same size. However, Fujii and Tanaka (1971) assumes that the domain on port is equal to the domain on starboard, as well as an equality between front and aft. The results by Hansen et al. (2013) show that there is in fact a small difference between them, as the distance on port-side is slightly larger than the distance on starboard.

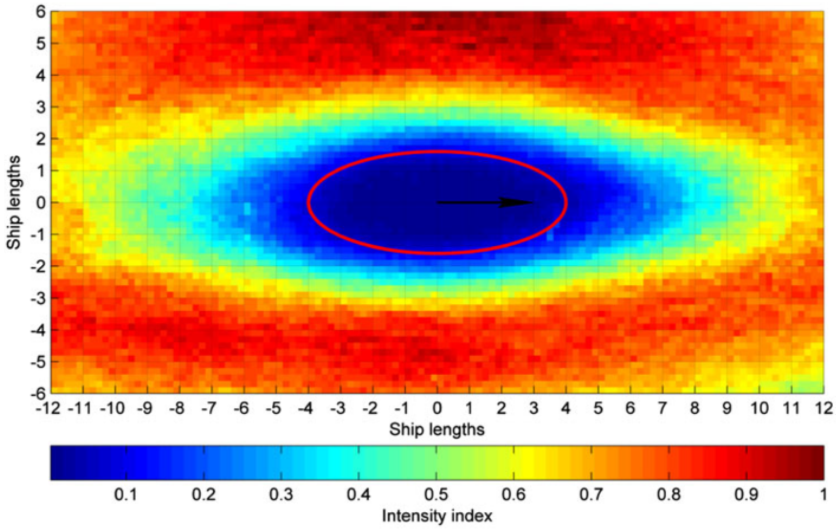

Figure 2.3: Empirically determined ship domain (Hansen et al., 2013)

2.1.1. Differences between encounter types

Multiple ship domain theories highlight the influence of the encounter type on the size of the ship domain. Hydraulic factors play a large role in the distance between ships, as shown in Figure 2.4. During an overtake, the water pushes the vessels closer to each other. The vessels reinforce the water level depression caused by them sailing through water. The water level between the ships is now lower than the water level near the bank. This leads to higher forces near the bank, pushing the ships together. As a result vessels will start an overtaking manoeuvre with as much distance as possible. For head-on encounters it is the other way around. The opposing return currents will cause a higher water level between the two vessels, which would push them apart. As a result vessels will start a head-on encounter as close to each other as possible.

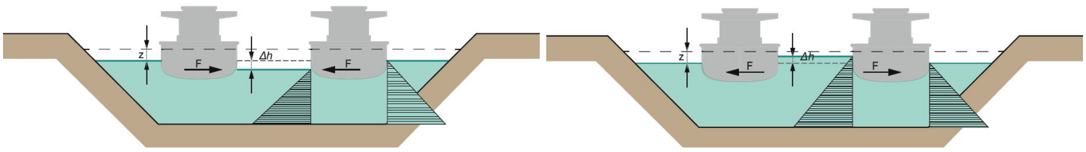

Figure 2.4: Hydraulic forces during overtaking (left) and head-on encounters (right) (Van Koningsveld et al., 2021).

However, the consequences of an accident are much more severe in case of a head-on encounter when compared to an overtake encounter. The difference in velocity is higher and therefore damages are likely to be higher. Therefore, if there is enough space on the waterway, vessels might actually keep a larger distance during head-on encounters than during overtake encounters.

The distinction between encounter types is made via the value for ϕ, which is defined as the absolute difference between the COG of both vessels. IMO (2018) makes a distinction between three encounter types: head-on, overtake and crossing encounters. An overtake encounter is defined as approaching a vessel from an angle 67.5° above or below the vessel's direction. ϕ then ranges from 292.5° to 67.5°. A head-on encounter is defined as "when two vessels are meeting on reciprocal or nearly reciprocal courses". What a reciprocal course is, is not defined as clearly as for the overtake encounters. All encounters with values for ϕ that are not in the overtake or head-on encounter ranges can be defined as crossings. Van Iperen (2015) classifies encounters on the North Sea using AIS data. A distribution of the values for ϕ shows peaks around 0°, 180° and 360° which are then attributed to head-on and overtake encounters. Head-on encounters are defined as 165° < ϕ < 195°, and overtake encounters as ϕ ranging from 335° to 25°. The empirical approach to this determination is not replicated by other publications. Zhang et al. (2015) and He et al. (2021) both investigate collision prevention based on different encounters types. For overtake encounters, the definition by IMO is kept, while IMO (2018) is used, while for head-on encounters the definition is interpreted as ϕ ranging from 175° to 185°. Ahmed et al. (2021) also looks at collision avoidance and discerns 7 different encounter types: head-on, crossing (give-way and stand-on), overtaking, overtaken, quarter lee (give-way and stand-on). The overtake encounter definition is in line with the IMO definition, while for head-on encounters they use 168.75° < ϕ < 191.25°.

Besides the encounter types, there are more reasons for captains to change the distance they keep to other vessels at certain points. These reasons are mostly due to what is the norm and regulations. It is common for ships to pass each other on port and overtaking happens also on port. However, in some situations encounters on starboard happen. These starboard-starboard encounters are quite uncommon and make navigators uneasy. The International Regulations for Preventing Collisions at Sea 1972 (IMO, 2018) (COLREGs) state that the skipper is responsible for their own actions, which is what causes them to retain a larger distance to the other vessel, just in case.

One theory that really makes this distinction is Goodwin (1975). Three sectors around a ship are distinguished (starboard, port and astern), each with their own safety distance. The domain is determined using both simulations and survey data. The relevant parameters are divided into three categories: psychological factors (navigator's sea experience), physical factors of the ship (length, relative speed) and physical factors for all ships (weather, traffic density). Most of these are then also included in the analysis: Goodwin (1975) looks at the influence of types of sea area, relative velocity, gross tonnage, length of ship, maximum speed of ship, navigator's experience, traffic density, restricted channels and even more. Per simulation there are 3 values found for the ship domain, one for each sector. An example of this ship domain can be seen in Figure 2.5 (left). Most of Goodwin's research is carried out on open sea. It is noted that in a channel navigation is severely restricted by the width of the channel and it would affect the size of the domain. Additionally, Goodwin (1975) expresses the amount of representative data in channels is very low.

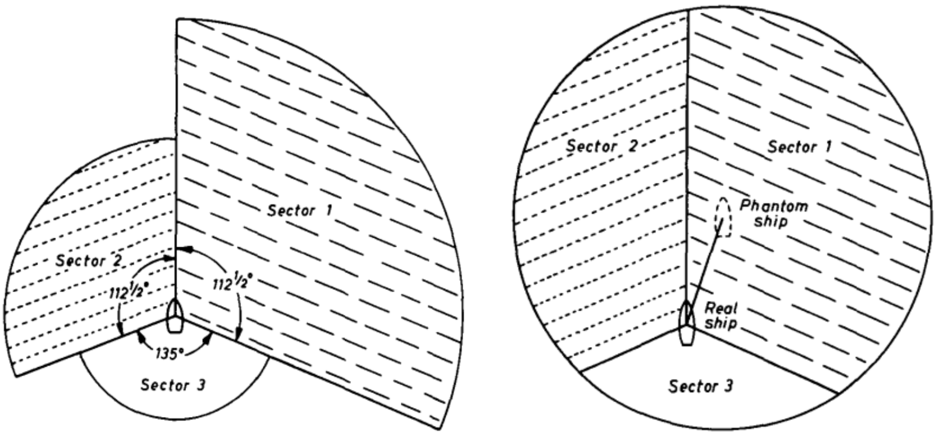

Figure 2.5: Examples of ship domain theory. Left: Goodwin (1975), right: Davis et al. (1980).

Coldwell (1983) states that Goodwin's theory is appropriate to determine the critical danger factor, while an approach like Fujii and Tanaka (1971) is better suited to define the distances at which navigators feel more comfortable. Davis et al. (1980) modifies the domain as defined by Goodwin (1975) to be a normal circle, as can be seen in Figure 2.5 (right). This circle has the same area as the sum of the segments from Goodwin, and the ship's position is not exactly in the middle of this circle to compensate for the lack of segments. This is done to make the domain smoother which makes computer modelling easier.

2.1.2. Fuzzy ship domain

So far, the theories and their resulting domains have all been different in size and circumstances. But all theories have in common that they do not vary within themselves. That is not the case for the ship domain theory by Zhao et al. (1993) and later Pietrzykowski (2008).

The concept initially introduced by Zhao et al. (1993) comes from a theory on personal space. As a human there are zones around you of distance held between another person. When in a location were it is very busy, these zones become smaller. Suddenly people will be in each other's personal space which is acceptable but only because of a high density. Pietrzykowski (2008) builds on this concept and develops what he calls a fuzzy domain. He defines the fuzzy domain as "an area around a ship which the navigator of the ship should maintain clear of other vessels and objects, the shape and size of which depend on an adopted level of navigational safety, understood as a degree of membership of a navigational situation to the fuzzy set 'dangerous navigation'." The navigational safety is represented by a factor γ between 0 and 1. If γ = 0 the situation is very safe, while if γ = 1, there is a very dangerous situation. The impact of this safety factor on the size of the ship domain is clearly visible in Figure 2.6.

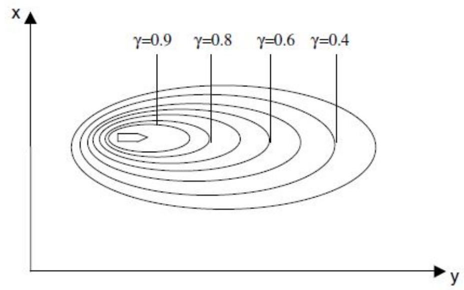

Figure 2.6: Schematic representation of the fuzzy ship domain (Pietrzykowski, 2008).

2.1.3. Quaternion Ship Domain

N. Wang (2010) introduces a new model to determine the ship domain: the Quaternion Ship Domain (QSD). The model is designed to give 4 parameters of distance ($R_{fore}, R_{aft}, R_{port-side}$ and $R_{starboard}$) as well as a factor k that determines the shape of the domain. This shape can for example be a quadrangular or a combined elliptical, as shown in Figure 2.7. The values for R are determined by the vessel's length and maneuverability (which is in turn determined by the vessel speed). The formulae are much more complicated than those determined by Fujii and Tanaka (1971). The formula below describes a quadrangular domain.

$$f_q(x,y;Q) = (\frac{2x}{(1+sgnx)R_{fore} - (1-sgnx)R_{aft}})^k + (\frac{2y}{(1+sgny)R_{starb} - (1-sgny)R_{port}})^k$$

Where:

$$sngx = \begin{cases} 1, & x \geq 0 \\ -1, & x < 0 \end{cases}$$
$$R_{fore} = (1 + 1.34\sqrt{k_{AD}^2 + (k_{DT}/2)^2}L$$
$$R_{aft} = (1 + 0.67\sqrt{k_{AD}^2 + (k_{DT}/2)^2}L$$
$$R_{starb} = (0.2 + k_{DT})L$$
$$R_{port} = (0.2 + 0.75k_{DT})L$$
$$k_{AD} = 10^{(0.3591 \cdot log(v_{kn}) + 0.0952)}$$
$$k_{DT} = 10^{(0.5441 \cdot log(v_{kn}) - 0.0795)}$$

While the formula determines the exact shape of the domain, the real interesting values are the parameters of distance. These are determined by the vessel length as well as the time to 90° heading. This 90° heading time is determined by the advance k_{AD} and the tactical diameter k_{DT}, which in turn depend on the velocity. The formulas have been estimated by Arimura et al. (1994) and are then further developed by Kijima and Furukawa (2003) and N. Wang (2010).

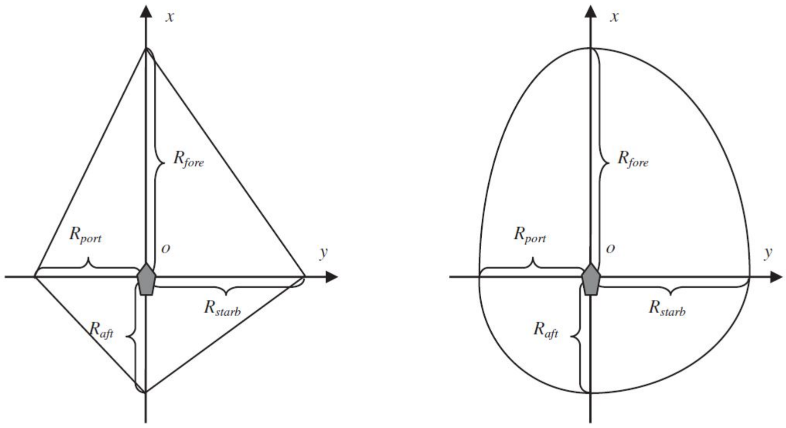

Figure 2.7: QSD for quadrangular (left) and combined elliptical (right) shape (N. Wang, 2010).

This model is expanded on by N. Wang (2013). A Fuzzy Quaternion Ship Domain (FQSD) is already defined to look at the uncertainty and collision risk by N. Wang (2010). He then also introduces a Dynamic Quaternion Ship Domain (DQSD) which in principle works the same as the QSD and FQSD, but is able to account for more factors than just the vessel length and manoeuvrability. N. Wang (2010) does not look at human or environmental factors, which is exactly what was added for the DQSD. Sub-models for the ship, human factor and the circumstances are added. From multiple simulations it is concluded that DQSD is more detailed and accurate than most other models for ship domain. And finally, as all sub-models are time-dependent, DQSD is able to collaborate in collision risk, path planning and other similar calculations.

2.1.4. Ship domain in port areas

The ship domain theories so far have been tested or determined in open waters, slightly constricted waters or channels, but none are tested in port areas. Rawson et al. (2014) looks at ship domains on the Thames in the center of London, where there are a lot of mooring areas, lots of high speed ferries as well as towed barges and pleasure crafts without AIS signal. The domain is simulated as ”a fixed seven metre buffer around each vessel with a dynamic ‘nose’ that extends forward dependent upon a reaction distance”, with 7 meters being the average beam of the vessels in the area. After normalising the AIS data the amount of contraventions, defined as when the domains touch each other, is observed. For each encounter certain information was inventoried: the name and type of the vessels, the distance between the vessels, the speeds, the encounter type and whether or not it was a prolonged encounter. This is used to create an overview of high intensity and (thus) high risk areas in the Port of London. While the vessels in this analysis are on average much smaller than in most industrial ports, it does give an interesting perspective and a much smaller ship domain.

2.2. Moving Havens

The concept of Moving Havens in shipping was first introduced in 2016 by Porathe (2016). He wrote about it in earlier papers (Porathe et al., 2014), but under the name of ”safety haven”. Since the initial introduction he has published multiple papers and congress proceedings on the subject. He presents an idea/concept derived from submarines. Submarines cannot see or hear each other under water. However, by sharing their voyage plans in three dimensions, they are assigned to a cube underwater inside which they need to stay (Figure 2.8). This cube can also be called a Moving Haven.

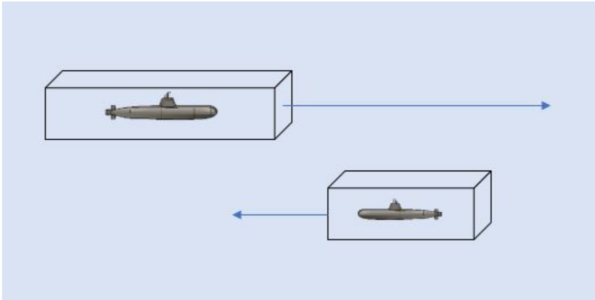

Figure 2.8: Moving Havens for submarines.

Porathe (2016) argues that Moving Havens could also be applied to a 2D situation, where the Moving Haven would not be a cube, but a rectangle. In 1999, the IMO has made guidelines for voyage planning (IMO, 1999) which state "On the basis of the fullest possible appraisal, a detailed voyage or passage plan should be prepared which should cover the entire voyage or passage from berth to berth, including those areas where the services of a pilot will be used." By also sharing an ETA, the planned position of a vessel can be determined.

The Moving Haven should show a captain and a VTS operator if the ship is on time. If all Moving Havens get programmed in such a way that they do not overlap and all vessels stay inside their Moving Havens, the amount of collisions will decrease significantly (and maybe even become zero).

But there are more advantages. Other vessels can easily see if a vessel is on course or not via the color of the Moving Haven (Figure 2.9). When a vessel is located nicely inside the Moving Haven, it is colored green. When moving towards the edge, the Moving Haven turns yellow and a warning signal goes off. If the vessel moves outside of the Moving Haven, it turns red and an alarm goes off. Porathe (2020a) argues this concept could also assist MASS. If an autonomous vessel moves out of its Moving Haven, an signal goes off that activates an adjustment in course. Thus the automated vessel stays on track.

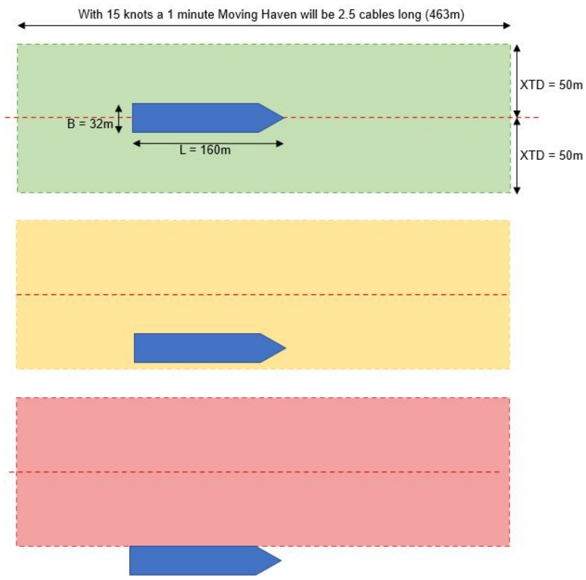

Figure 2.9: Moving Haven and it's functionality.

Another big advantage is that it can help during the transitional period of manual to autonomous ships. Human captains can easily see where an autonomous vessel is headed and anticipate their own course based on this. But even more: a Moving Haven is automatically calculated and if all vessels (manual and autonomous) stay inside of it, no communication between them is necessary. On top of that the

Moving Havens could also be programmed to be as cost effective or environmentally friendly as possible, via the required sailing speed and just-in-time arrivals.

A Moving Haven in a 2D-setting has the form a rectangle. The length of the Moving Haven is defined as the distance the vessel can travel in the required temporal precision period. In high density areas, a higher temporal precision is required than somewhere offshore. As shown in Porathe (2020b), a vessel travelling with a speed of 15 knots with a 1-minute precision Moving Haven will be 2.5 cables (or 463m) long. It should also be noted that there seems to be no direct relation to the ship's length for the determination of the length of the Moving Haven. Table 2.1 shows that almost all ship domain theories determine their domain partly based on the OS or TS length.

The width of the Moving Haven is determined by the Cross Track Distance (XTD). In the example case by Porathe this is 50m, which is added on both sides of the longitudinal axis of the vessel. The width of the Moving Haven can be adjusted based on the waterway, obstacles or insufficient depth. Porathe does not elaborate on the exact reasoning for XTD being equal to 50m unfortunately. The XTD is a parameter that captains currently determine themselves during the making of their voyage plan.

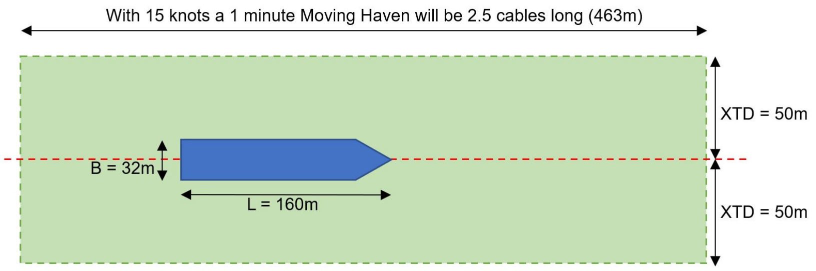

Figure 2.10: Example of a Moving Haven (Porathe, 2020b).

Yoo and Kim (2022) describes the XTD as the distance to the Cross Track Limit (XTL) on port and starboard. XTL is then defined by Kristić et al. (2020) as "the minimum safety corridor along the navigational route which is defined by end user". After interviews with shipping companies, minimum XTL values were found. In port areas this is determined to be 0.03 to 0.1 nautical miles on both port and starboard. Kristić et al. (2020) also defines it using the following formula:

$$XTL_{Kristic} = d_{zoc} + d_b + d_{pos} + d_{NavAlw} + d_{VesAlw}$$

Where d_{zoc} is determined by the Category of Zones of Confidence (CATZOC) which is a measure for the accuracy of bathymetric data. d_b is the vessel's beam on each side of the longitudinal axis. d_{pos} is the positional accuracy of the GPS signal. d_{NavAlw} is the navigational area safety allowance, determined based on the guidance of shipping companies involved in the research. In port areas this is determined to be 50m. d_{VesAlw} is the vessel's orientation safety allowance, which is determined by the vessel length and the drift angle: $L \cdot sin(\alpha)/2$.

This formula for XTL also depends on the vessel's length and beam, which is similar to the ship domain theories. It should be noted that the values found by Kristić et al. (2020) are much higher than the 50 meters suggested by Porathe. The shipping company determines 0.03 to 0.1 nautical miles on both port and starboard, which is equal to 55.6 to 185.2 meters on both sides. The formula can of course differ per situation but d_{NavAlw} is already equal to 50 meters in port areas. So while the Moving Haven's width by Porathe might not be totally based on scientific literature, Section 2.3 will show that the values found by Kristić et al. (2020) are still smaller than most ship domain theories.

Finally, Porathe (2020a) emphasizes the main difference between a Moving Haven and ship domains as described in the previous section. A ship domain is a result of the movements of the ship, whereas a Moving Haven behaves independently from the ship. The ship must always locate itself within the Moving Haven while by definition the ship is always inside the ship domain. However, he also states that there is nothing preventing Moving Havens and ship domain from being used together to enhance nautical safety.

2.3. Comparison of the ship domains and Moving Haven concept

The theories elaborated on in the previous sections can be compared to each other, both visually and based on the exact methods and parameters included. Figure 2.11 compares several ship domain theories as well as the Moving Haven concept by Porathe in a visual manner. Not all of the theories elaborated on above have been plotted. Not all ship domains can easily be plotted for the same set of parameters. Some don't have an equation to calculate it with, which means they are only valid for ships of a certain length or in a certain situation. The domains and Moving Haven plotted in the figure are valid for the following conditions:

- This is a standard head-on encounter.
- Length OS = 95.5 [m]
- Length TS = 156.68 [m]
- Beam OS = 18.2 [m]
- Beam TS = 24 [m]
- Speed OS = 7 [kn]
- Speed TS = 10 [kn]
- Time accuracy = 60 [seconds]

The average width of a waterway in a port area is taken to be 400m and shown by two black vertical lines. The image shows a variety of different shapes and sizes. The shapes range between circles, ellipses, diamonds as well as rectangles. Not all of them are symmetrical and the vessel is not always located in the center of the domain. Furthermore, a lot of these ship domains are clearly too large as they do not even fit inside the waterway. This can be explained by the experiment location. Most of the domains are determined in open waters, where vessels have more space which means they also take more space. The theories that are determined in restricted waters (Rawson et al. (2014), Pietrzykowski (2008)) are often much smaller. This leads to the conclusion that even though traffic density and route conditions are not often included, they are very relevant to the size of the ship domain. To determine the impact of these parameters within the restricted waters of a port area, the chosen locations must deviate from each other in regards to traffic density and route conditions.

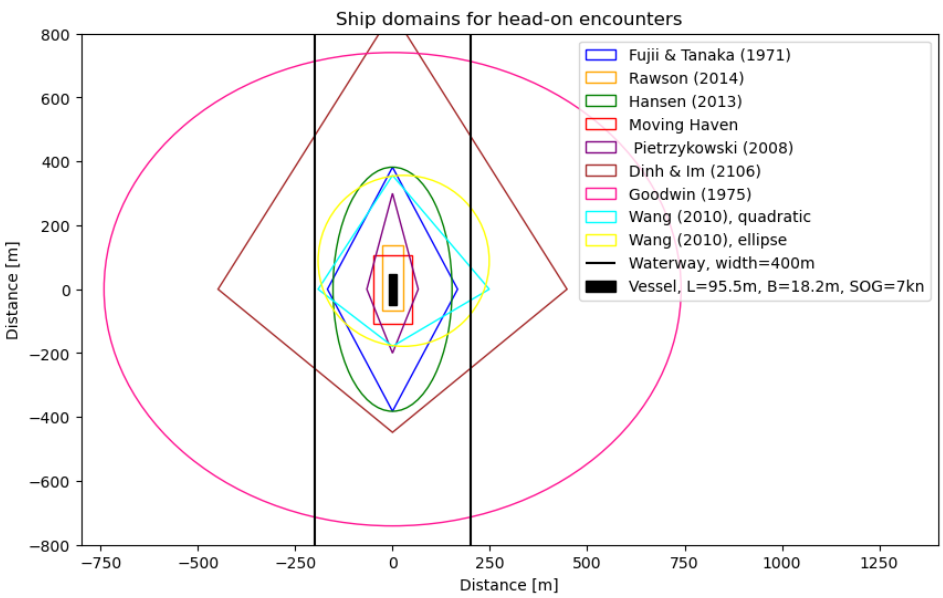

Figure 2.11: Overview of various ship domain theories compared to the waterway

The Moving Haven concept can also be compared to the ship domains. It is clearly much smaller than most ship domains and it would fit inside most port areas. However, this does not indicate that the concept is applicable. An area too small leads to dangerous situations. The opposite could also be valid: an even smaller Moving Haven might also still be regarded as safe by a captain and therefore be applicable.

After the visual comparison, the theories can also be compared based on the methods used and the parameters included. Szlapczynski and Szlapczynska (2017) gives a detailed overview of existing theories and distinguishes them based on the safety criteria mentioned in Figure 2.1, the type of method used as well as which of the parameters above are included. This overview is presented in Table 2.1. For a larger, more readable version of the table, see Appendix A. Some parameters are combined into one for the table. For example, visibility and tidal currents are combined into the weather conditions and the route parameters are combined with the traffic density. The Moving Haven as defined by Porathe is included as well. By Porathe's definition, the vessel's speed and the human factor are the only parameters it depends on. However, when using the XTL as defined by Kristić et al. (2020), the vessel length, beam and other conditions also apply.

Table 2.1: Overview of ship domain theories (Szlapczynski & Szlapczynska, 2017).

Domain by	Safety criterion	Method	OS Length	OS Speed	OS Manoeuvrability	TS Length	TS Speed	Encounter type	Weather conditions	Traffic conditions	COLREGS	Human Factor
Fujii and Tanaka, 1971	(b)	Empirical: statistical processing of radar data	Yes	No	No	Yes	No	No	Yes	No	No	No
Goodwin, 1975	N/A	Empirical: statistical processing of radar data	Yes	No	No	N/A	No	No	Yes	No	Yes	Yes (minimal)
Davis et al., 1982	(a)	Computer simulation	Yes	No	No	No	No	No	No	No	Yes	No
Coldwell, 1983	(a)	Empirical: statistical processing of radar data	Yes	No	No	No	No	Yes	No	No	Yes	No
Zhu et al., 2001	(a)	Expert's knowledge / neural networks	Yes	No	Yes	Yes	No	No	Yes	No	Yes	No
Pietrzykowski, 2008	(a)	Expert's knowledge / fuzzy neural networks	Yes	Yes	Yes	N/A	N/A	No	Yes	Yes	N/A	No
Pietrzykowski and Uriasz, 2009	(a)	Expert's knowledge / fuzzy neural networks	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
N. Wang, 2010 & N. Wang, 2013	(a)	Safety analysis	Yes	Yes	Yes	N/A	N/A	No	Yes (2013)	Yes (2013)	No	Yes (2013)
Hansen et al., 2013	(c)	Empirical: statistical processing of AIS data	Yes	No	No	N/A	N/A	No	No	No	N/A	No
Rawson et al., 2014	(d)	Safety analysis local traffic	No (ship type used instead)	Yes	No (ship type used instead)	N/A	N/A	No	No	No	N/A	No
Y. Wang and Chin, 2016	(d)	Empirical: statistical processing of data	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No
Liu et al., 2016	(a)	Analytical safety of local traffic	Yes	Yes	No	No	No	No	No	Yes	N/A	No
Dinh and Im, 2016	(b)	Expert's knowledge / analytical	No	Yes (for action area only)	No (target's manoeuvrability)	Yes	Yes (for action area only)	Yes	No	No	Yes	No
Porathe, 2020b	(d)	Expert's knowledge	Yes	Yes	No	No	No	No	No	No	No	Yes

The safety criterion used in the theory has a large influence on the used parameters. For example, safety criterion (a) only looks at the OS, which means all TS parameters are not considered. The method is also influential as some parameters are much easier analysed with different methods. This includes the weather and traffic conditions, but also the human factor.

Generally, the OS length is used in the most amount of domain theories. The human factor is included the least amount of times. It is a difficult parameter to determine as most methods do not easily allow for any human input, for example, AIS data does not show the experience of the captain. Additionally, equally experienced captains may act in unequal ways, which makes it difficult to put a number or influence on the human factor.

As a final note, Shu et al. (2013) shows that (specifically in the Botlek area of the Port of Rotterdam) some of the mentioned factors above also influence each other. For example, vessel speed is influenced by vessel type and vessel size as well as the route. Smaller vessels sail faster than larger vessels and incoming vessels have a lower SOG than outgoing vessels. Furthermore, wind and visibility also have an effect on the vessel's speed; less visibility and higher wind speeds lead to lower vessel speeds. The vessel's manoeuvring characteristics are also influenced by the speed.

2.4. Automatic Identification System

Safety on the waterway is aided by Vessel Traffic Services (VTS). They are defined by IMO (2021) as: "Services implemented by a Government with the capability to interact with vessel traffic and respond to developing situations within a VTS area to improve safety and efficiency of navigation, contribute to the safety of life at sea and support the protection of the environment." As technology further developed, VTS also evolved and the Automatic Identification System (AIS) was introduced. Vessels transmit a signal via AIS that contains a multitude of information on the vessel's size, route and more.

Since 2003 every seagoing vessel needs to have AIS installed on board (IMO, 2003). Furthermore, as regulated in the Binnenvaartpolitiereglement, AIS has also been mandatory for all vessels longer than 20 meters in Dutch inland waters since 2017 (Infrastructuur en Milieu, 2017). Vessels have to transmit a signal every 2 seconds to 3 minutes. This temporal interval is determined by the vessel's speed. When docked, AIS data is transmitted every 3 minutes, while every 2 seconds when a vessel sails 23 knots or faster (IALA, 2016). The data can be sorted into three categories, based on the update rate of the datatype: static data, dynamic data and voyage related messages.

Static data remains constant (or *static*) during the vessel's lifetime. In this category the vessel size, type and MMSI are included. Dynamic data describes information that is variable during the voyage. This includes the time, vessel speed, heading and more. Voyage related messages are constant during the voyage, but not constant during the vessel's lifetime. Table 2.2 shows the categories and what information is included in these categories. Information on the draught are sorted into either static information (Tu et al., 2017) or voyage related messages (Last et al., 2015), which is why it is included in the table twice. Furthermore, there are 27 standard messages, ranging from a special position report to interrogation (IALA, 2016).

Table 2.2: AIS data categories and messages (IALA, 2016), (Tu et al., 2017).

Static data	**Dynamic data**	**Voyage related messages**
MMSI	Time	Destination
Ship name	GPS Location	ETA
Ship type	SOG	Safety messages
Ship length	COG	Cargo information
Ship beam	Heading	Draught
Draught	ROT	
Callsign	Status	

MMSI = Maritime Mobile Service Identity, GPS = Global Positioning System, SOG = Speed over Ground, COG = Course over Ground, ROT = Rate of Turn, ETA = Estimated Time of Arrival

The main purpose and advantage of AIS data can be found in improved safety. Vessels emit signals to other vessels in the (near) vicinity as well as to satellites and stations on land. AIS and radar cover each other's weaknesses (Harre, 2000), allowing for more detailed identification and tracking of vessels. Lin et al. (2008) elaborates on the benefits of AIS, specifically in port areas. AIS data assists radar in the form of more information, better identification, better tracking, higher accuracy and a wider operational range. All these lead to a better anticipation of the vessel's position and planning. This then leads to an increase in the traffic safety. Furthermore, not only the harbour master uses AIS, but also various other groups on land like VTSO, Maritime Rescue Co-ordination Centre (MRCC) and shipping companies. Multiple other processes, such as loading management and customs, therefore also operate more efficiently and the entire port benefits.

The arrival of AIS data has allowed for new (and more detailed) approaches to old issues, as was done by Hansen et al. (2013). Tu et al. (2017) elaborates on four main possibilities:

- Anomaly detection: Via AIS data analysis it quickly becomes clear if a vessel deviates from the standard routine. The anomaly can be either in position, speed or time.
- Route estimation: Using AIS data the future position of a vessel can be estimated.
- Collision prediction: By estimating all routes and future positions, a collision chance can be predicted. If two vessels are predicted to be in the same position at the same time, an intervention can be made.
- Path planning: The planning of a safer, collision-free path can also be done based on AIS data. Furthermore, the most efficient path can also be planned, whether it is efficient in time, environmental impact or for financial reasons.

While AIS has brought the maritime industry a lot of benefits, it is also important to be aware of its problems and imperfections. AIS is not infallible. Its quality is sometimes found lacking and various errors or ”noise” can occur. Mao et al. (2018) explains the process of constructing an AIS database, including the filtering of errors like a loose, discontinuous or tangled trajectory, as well as the interpolation of missing data. Furthermore, not all AIS data providers have the same precision, resolution or validity. Not all of them include the same information. A complete overview of various AIS data providers can be found in Tu et al. (2017).

And finally, AIS transponders can be turned off in its entirety. This has been a more recent development during the war between Russia and Ukraine. Several Russian yachts and oil tankers have ”gone dark” to avoid sharing their locations and activities, and to avoid the sanctions imposed on Russia for the initiation of the war (Oanh Ha, 2022). The practice is highly illegal and the United States Treasury has previously issued a statement on what they call ”Deceptive Shipping Practices” (Department of the Treasury, 2022). While the purposeful turning off of transponders is unlikely to happen, it is important to remember that AIS transponders can also malfunction, which can have the same result as a vessel ”going dark”.

2.5. Conclusions

The parameters mentioned in the various ship domain theories explored in this chapter can be ranked based on the frequency of usage in ship domain theories. This is done via Table 2.1 and shown in Figure 2.12. The bar plot shows the influential parameter and the amount of times they are used in the ship domain theories. The color of the bar indicates the parameter’s availability via AIS data, green equals available and red indicates the parameter is otherwise available. The orange color indicates it is possible, but quite complicated to determine the parameter via AIS data.

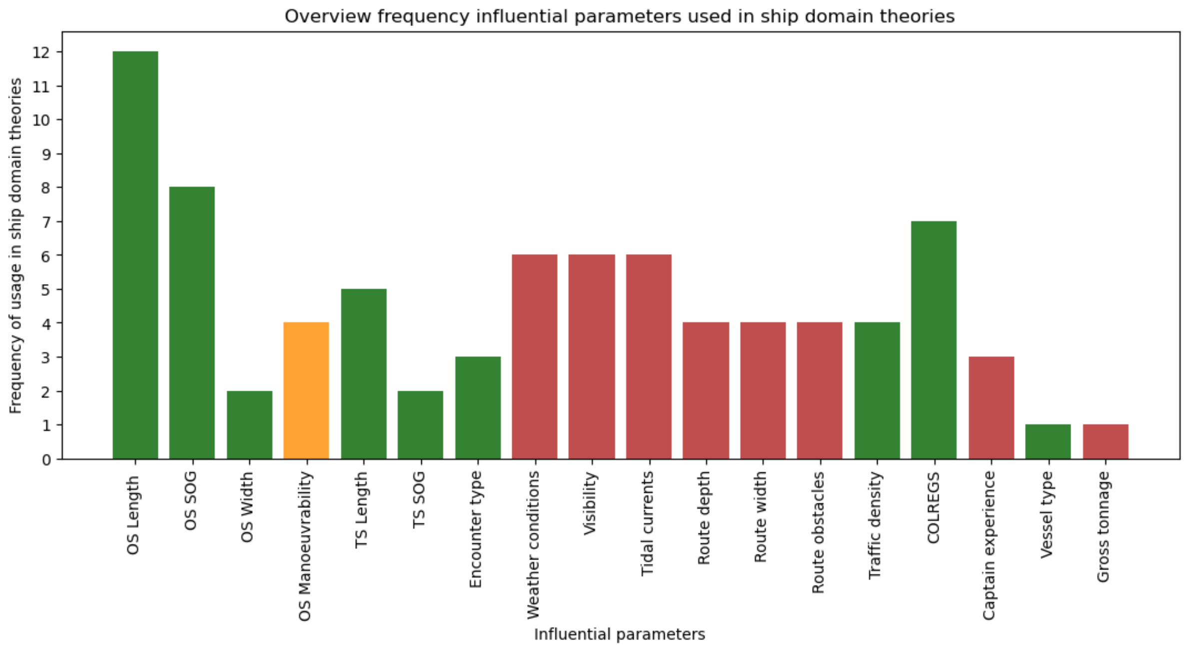

Figure 2.12: Overview influential parameters and their frequency used in ship domain theories. The color of the bar indicates the parameter’s availability in AIS data.

The most used parameter is the OS length, used in 12 of the 14 theories explored. The OS SOG and the COLREGS are used in 8 and 7 of the theories respectively. They are closely followed by the weather conditions (in which visibility and tidal currents are also included). Five theories use the TS length, while the traffic conditions and the OS manoeuvrability are used in 4 theories. All others are used 3 times or less.

A lot of the parameters mentioned in Table 2.1 are available via AIS data (as shown in Table 2.2), but not all of them. The manoeuvrability is vessel specific but not directly included in the AIS data. There are studies done to determine the manoeuvrability based on AIS data, but a clear value per vessel cannot easily be determined. The weather conditions including visibility and tidal currents are obviously not included in AIS data as they are not related to the vessel in any way. Any data on this can be found in weather measurement records as well as tidal and climate models. The route conditions including depth, width and obstacles are voyage related but they are not included in AIS data. Instead, they can be found on geological and bathymetry maps. Furthermore, the captain's experience is of course also not included in any AIS data.

All other parameters in the list above are available in AIS data, or easily determined via the AIS data and will therefore be considered in this study. Obviously the OS length, width, SOG and vessel type are directly included. The encounter type can be determined via the difference in COG between the two vessels and the COLREGS can be included by considering the different sides around a vessel (port-side, starboard, fore and aft).

3
Methodology

This chapter discusses the methodology used to determine the answer to research questions 2 and 3. First, the creation of the encounter data set is discussed, then the influence of parameters on the critical distance, after which the formation of the ship domain is explained.

3.1. Schematic overview

The overall methodology can be put into a schematic overview as presented in Figure 3.1. The figure shows rectangles, which represent actions and analyses, while the ellipses represent information and results. If a particular result is an answer to one of the research questions, this is indicated in red.

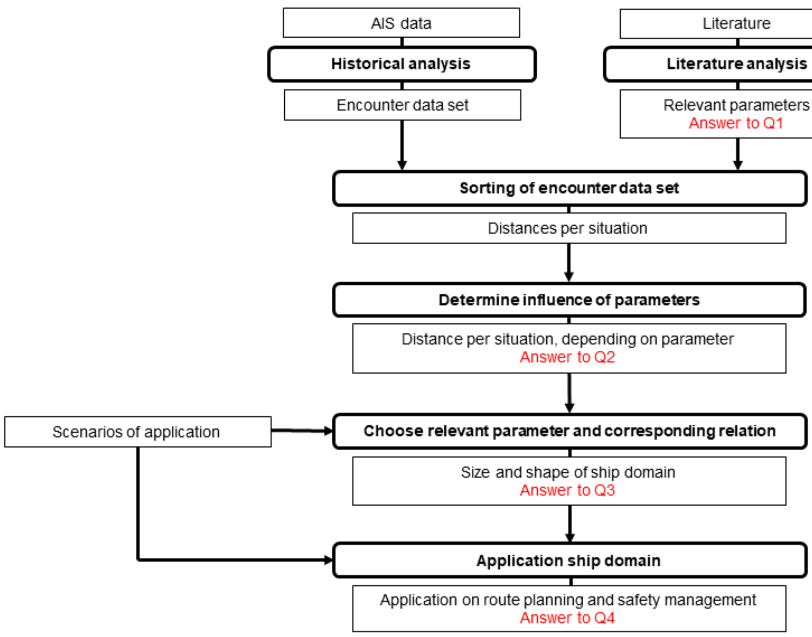

Figure 3.1: Schematic overview of the methodology

The literature analysis in Chapter 2 presents the answers to research question 1. Via a historical analysis of AIS data an encounter data set is created. Combined with the relevant parameters, the data set is sorted and the distances per situation are determined. The influence of the parameters is determined, which presents the answer to research question 2. The scenarios of application assist in determining the size of the ship domain, from which the shape follows. Both form the answer to research question 3. This is then implemented to answer research question 4. This chapter discusses the methodology to finding the answers to research questions 2 and 3. Chapter 8 further elaborates on the application of the ship domain.

3.2. Encounter data set

The purpose of the historical analysis is to analyse the past behaviour of vessels and determine the distances between vessels during encounters. These distances will form the ship domain which is an indication of what captains experience as safe.

The definition of the ship domain used in this research is the definition by Fujii and Tanaka (1971): "A two-dimensional area surrounding a ship which other ships must avoid – it may be considered as the area of evasion". This definition is chosen as the purpose of the research is to determine the safe navigation ship domain, not the "critical danger factor" by Goodwin (1975). The safety criterion used is criterion (c), which means the OS domain should not be violated by the TS and the TS domain should not be violated by the OS. The minimum distance between vessels is therefore equal to the largest domain size of the two. A port area is complex and there are a lot of different vessels present and it is therefore illogical that only the OS parameters would determine the distance to another vessel.

As the definition by Fujii and Tanaka (1971) is used, a similar method for determining the ship domain can also be used. Furthermore, the historical behaviour of vessels in port areas can most easily be analysed using AIS data. Hansen et al. (2013) reproduces the method by Fujii and Tanaka (1971), but uses AIS data instead of radar photographs. Therefore, the historical analysis will be based on the empirical method for ship domain by Hansen et al. (2013).

The principle of the method is to compare the position of every vessel to every other vessel, at every moment in time. An example where two vessels (ship A and ship B) are sailing alongside each other is discussed and shown in Figure 3.2. At time T=1, ship A is defined as OS and ship B is TS. The relative position of TS (ship B) to OS (ship A) is determined. The relative position can be determined by the distance as well as angle α. Figure 3.2 shows a visual representation of the distance and the angle α.

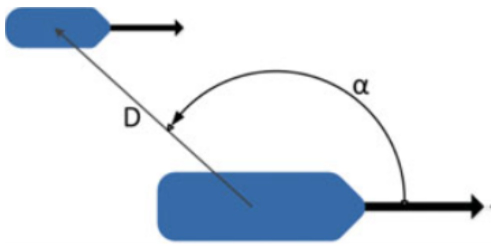

Figure 3.2: Visual representation of angle α and distance D (Hansen et al., 2013).

Additionally, all information on the encounter is registered. The time, distance D and angle α are joined by the ship specific parameters of both OS and TS. Then, ship B is defined as OS and ship A is TS. Again, the relative position of TS (ship A) to OS (ship B) is determined, along with all information on the encounter. Therefore, for every encounter between two vessels, there are 2 entries. One where ship A is defined as OS as well as one where ship B is defined as OS. The distance is the same, but angle α differs per entry. At time T=2 both ships have moved closer to each other and the process is repeated. This continues until the ships leave the area of interest. The entries are registered into a data set, from now referred to as the encounter data set.

An example of the data set can be found in Table 3.1. For every entry the distance D and angle are determined, as well as the date and time of the encounter. Furthermore, the MMSI, length, width, SOG, COG and vessel type of both OS and TS are included. For privacy reasons, the actual MMSI numbers are replaced by dummy values. Immediately noticeable are the first two rows, which are from the same encounter. The vessel with MMSI 123456789 is the OS in the first row, but TS in the second row. The only difference between the two entries is the angle.

Table 3.1: Example of encounter data set

	D	α	Date & time	OS_MMSI	OS_length	OS_width	OS_SOG	OS_COG	OS_type	TS_MMSI	TS_length	TS_width	TS_SOG	TS_COG	TS_type
0	975.860491	0.176291	2023-03-13 00:32:36	123456789	110.0	11.4	3.7	118.3	80.0	987654321	135.0	15.0	6.5	299.9	80.0
1	975.860491	0.204031	2023-03-13 00:32:36	987654321	135.0	15.0	6.5	299.9	80.0	123456789	110.0	11.4	3.7	118.3	80.0
2	945.878549	0.206211	2023-03-13 00:32:39	987654321	135.0	15.0	6.5	299.7	80.0	123456789	110.0	11.4	3.7	118.2	80.0
3	945.878549	0.180211	2023-03-13 00:32:39	123456789	110.0	11.4	3.7	118.2	80.0	987654321	135.0	15.0	6.5	299.7	80.0
4	914.617803	0.184049	2023-03-13 00:32:42	123456789	110.0	11.4	3.7	118.1	80.0	987654321	135.0	15.0	6.5	299.5	80.0

The encounter data set now contains all relevant information to determine what parameters are actually influential on the distance between vessels, as well as the ship domain. More in detail analysis of the encounter data set should lead to the answer to sub-research question 2 as well as question 3. The next paragraphs will elaborate further on that.

3.3. Parameter influence

The encounter data set is sorted by encounter type and direction around the vessel, after which the influence of the ship-specific parameters is determined. The parameters are normalised and plotted to the distance. Then, a trend line is fitted to the minimum values of the normalised parameters to determine the influence.

The considered ship-specific parameters are the length, width and SOG of the OS. Furthermore, to include the TS, combined parameters are also included. The combined length and width, are included via the formulas presented below. Based on the formula by Fujii and Tanaka (1971), the larger vessels have more weight as they are more likely to be the decisive vessel.

$$L_{combined} = 0.5 \cdot \sqrt{L_{OS}^2 + L_{TS}^2}$$
$$B_{combined} = 0.5 \cdot \sqrt{B_{OS}^2 + B_{TS}^2}$$

The velocity of the TS is also included via the relative SOG, which for overtake encounters is equal to the absolute difference between OS and TS SOG. For head-on encounters the relative SOG equals the sum of OS SOG and TS SOG.

Overtake encounter: $SOG_{relative} = |SOG_{OS} - SOG_{TS}|$

Head-on encounter: $SOG_{relative} = SOG_{OS} + SOG_{TS}$

Ship specific parameters can easily be numerically related to the distances between vessels, but that is not true for parameters like encounter type and COLREGs. Therefore, the encounter data set must be sorted into categories for these non-numerical parameters. This does mean that the influence of the encounter type is not necessarily comparable in numbers, but a ship domain will be determined specifically per encounter type. The combination of specific encounter type and COLREGs-direction will now be referred to as a situation. So, for every situation, there will be a unique relation.

The distinction in encounter type is between head-on encounters, overtake encounters and crossing encounters. This is done via the absolute difference between OS COG and TS COG, also referred to as ϕ. For overtake encounters the definition by IMO (2018) is used. The overtake is defined as an approaching vessel from an angle 67.5° above or below the vessel's direction. The head-on encounter definition is taken from Van Iperen (2015). Van Iperen (2015) uses this definition for research on the North Sea and not in some sort of constricted water area but it is empirically determined based on AIS data instead of simulations. The crossing encounters are all encounters that do not fall into the range of either head-on or overtake. Figure 3.3 shows the full overview of all values for ϕ.

The inclusion of the COLREGs are inspired by the theory by N. Wang (2010). The Quaternion Ship Domain determines the size of the domain via 4 values of distance (R_{port}, R_{starb}, R_{fore} and R_{aft}), after which a shape is added. For each of the four directions (port-side, starboard, fore and aft) an individual relation is determined. This is done analysing only the data in that direction. For head-on encounters only three directions are analysed. The aft direction is irrelevant as the vessels have already passed each other and are sailing away. As starboard-starboard encounters are rare, a larger interval is taken to ensure all data is included. For the other directions, an interval of 10 degrees is chosen. A visual representation of these ranges around a vessel is shown in Figure 3.3.

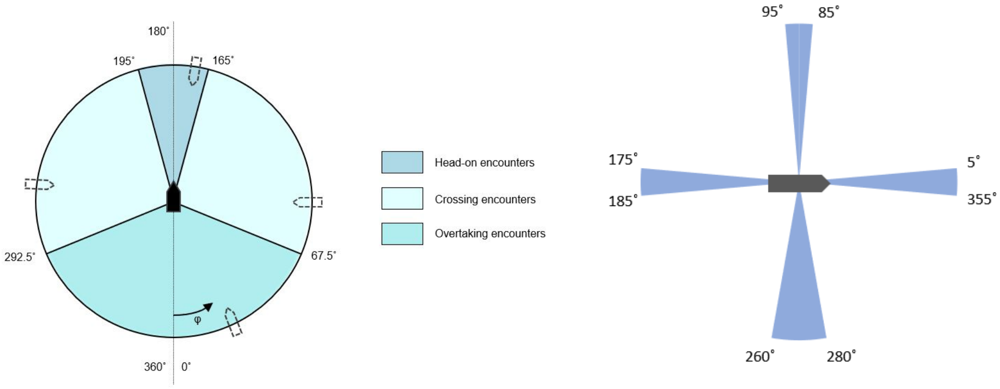

Figure 3.3: Left: Encounter definitions via values for ϕ. Right: Inclusion of COLREGs, inspired by N. Wang (2010).

The unique relation per situation will be determined by the most influential ship-specific parameter. However, the ship-specific parameters vary a lot in size, which makes their influence difficult to compare via a formula. For example, OS length varies from 50 to 400m, while the SOG only varies from 0 to 10m/s. The distance between vessels might be equal to 1 time the length, but 50 times the SOG. That does not mean the SOG has more influence. The ship-specific parameters are normalised to ensure them being in the same range. The parameters should rank between the same values to be able to compare them properly. Therefore, all parameters are scaled to a range of 0 to 1, where the maximum value is equal to 1, and the minimum value is equal to 0. For every parameter, Equation (3.1) is used.

$$x_{normalised} = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{3.1}$$

Other normalisation formulas have been tested, but were found inapplicable in the comparison between parameters. This can be found in Appendix B.

Additionally, the relation between the distance and the ship-specific parameter should not depend on one outlier. Simultaneously, the closest distances are the most relevant for the analysis. Vessels can often keep larger distances when there is unlimited space. The interest lies in when they do not have this unlimited space. Therefore, only the shortest distance per encounter is considered and used to determine the relations. These will be referred to as the critical distance. The influence of the normalised parameters on the critical distances is then compared.

Figure 3.4 shows a visual representation of this comparison. The first plot shows critical distances plotted against the normalised parameters. The purpose of normalisation was to compare the parameters to each other, which is why all of them are plotted together. The interest is on the minimum distances of these critical distances. The parameters are divided up into bins of size 0.05 and the minimum distance per bin is determined. This is shown in the second plot with the dashed-dot lines. A clear upward trend can be observed, indicating that vessels keep larger distance for higher values of the parameters. The trend is quantified by fitting a trend line through the minima, as done in the third plot.

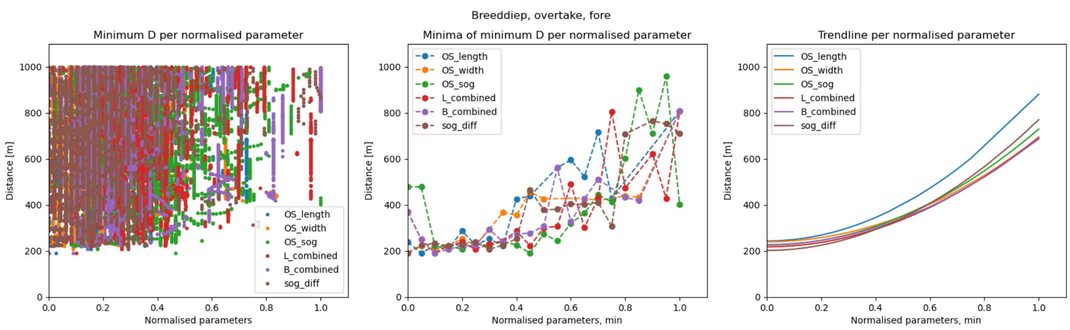

Figure 3.4: Example of plots used to determine the relation between the normalised parameters and the critical distances. The example shows direction fore during an overtake encounter in sector Breeddiep.

By fitting a simple trend line over the normalised critical distances, a clear comparison can be made. A simple trend-line with only two variables is chosen. One variable being a_{norm}, which determines the influence of the parameter and the slope of the trend-line and on one variable b_{norm} which determines the absolute minimum distance and the interception point. If a is high, the influence of the parameter is also high. The trend line is fitted to the form of Equation (3.2). Other fits were also tested, but found to be inaccurate. This can be found in Appendix B.

$$D_{min} = a_{norm} \cdot x_{norm}^2 + b_{norm} \tag{3.2}$$

The quality of the fit is checked via the Root Mean Square Error (RMSE). A high value for the RMSE$_{norm}$ indicates that the fit is not great and there are quite some outliers.

The combination of the values for a_{norm}, b_{norm} and the RMSE$_{norm}$ will give a representation of the influence of the ship-specific parameters and therefore give an answer to the second sub-question. The highest value for a_{norm} represents the highest influence, the lowest value for RMSE$_{norm}$ represents the best fit and the value for b_{norm} is a measure of the minimum distance.

3.4. Size and shape of the ship domain

The most influential parameter will determine the size of the ship domain. The choice is made for only one parameter for two reasons. First, this is also what Fujii and Tanaka (1971) and Hansen et al. (2013) did to determine their domains. While they do not experiment with parameters other than the vessel length, it is the only parameter used. The empirical domain lends itself well to one parameter. It leads to a simple relation with a straight-forward application. Secondly, as stated in Chapter 2, some of the parameters are loosely related, like the length and width which means including both is unnecessary.

As seen in the third plot of Figure 3.4, the trend lines are often very similar. This indicates that there might indeed be some relation between some of the ship-specific parameters. It results in a difficult choice for the most influential parameter, as the differences between values for a_{norm} are very minimal. To assist in this, scenarios of application are considered. These give extra conditions to assist in the choice for influential parameter. There are three scenarios. The first scenario is the condition-free scenario, where there are no extra conditions, the second scenario is the OS scenario, where only OS parameters are considered, and the final scenario is the same-for-all scenario, where the same parameter is chosen for each location. The scenarios will be further elaborated on in the next section.

To determine the actual relation, the non-normalised parameter is used and again compared to the critical distance. The same fit is used to determine a, b and RMSE as is done for a_{norm}, b_{norm} and RMSE$_{norm}$. The equation gives the relation between the size of the ship domain and the influential parameter, specific for each direction, encounter type and location. If the influential parameter varies, so will the size of the ship domain. If the ship-specific parameter is the relative SOG for example, the SOG of both OS and TS determine the distance and both are not constant like the length. Furthermore, there can be multiple TS at the same time, and therefore the ship domain would be varying per encounter between OS and each specific TS.

As the domain varies in size for every encounter, any comparison or assessment is difficult. Normalisation presents an ideal solution as it will lead to a domain size of 1 for all encounters. By dividing all distances between vessels by the relevant determined ship domain distance, the distances will be normalised and the impact of the domain can more easily be determined.

The shape of the ship domain is also much more easily determined via the normalisation, especially in a visual aspect. The literature discusses various shapes: diamonds, circles, ellipses, rectangles and more. Three shapes are tested in this research: a diamond, ellipse and rectangle. The choice is made in regards to the scenarios of application. For near-miss analyses, a minimal shape is required, which is why the diamond is chosen. The ellipse is chosen as this is the shape that Hansen et al. (2013) and Fujii and Tanaka (1971) found in their research and the rectangle was chosen as that is the shape of the Moving Haven. Figure 3.5 shows the normalisation process per shape.

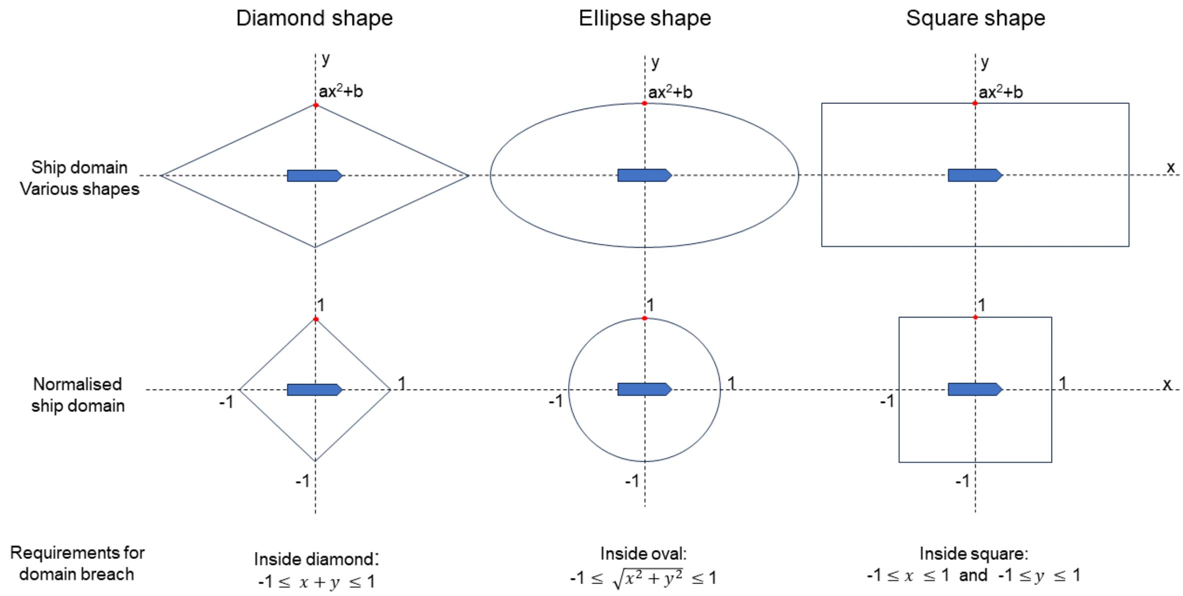

Figure 3.5: Schematic overview of normalisation per shape

The result of this section is the answer to research question 3. It describes a ship domain specific to each vessel's situation and ship-specific parameters. The ship domain can then be used in the implementation of Moving Havens and to improve safety management. Chapter 8 will go further into this.

3.5. Scenarios of application

This section will further elaborate on the three application scenarios. These give an extra condition for the choice of most influential parameter and can therefore give more guidance in the decision and analysis process. The scenarios are named in the list below:

- Scenario 1: The condition-free scenario
- Scenario 2: The OS scenario
- Scenario 3: The same-for-all scenario

Scenario 1: The condition-free scenario
In this scenario, the parameter choice is purely determined by the values of a_{norm}, b_{norm} as well as $RMSE_{norm}$, without further conditions. The result is probably the most accurate, purely determined on the data. This scenario can be best used for applications that look at the behaviour of vessel after it has already happened. The domain size would change constantly and this cost quite some computing time if this is done in real-time. It will also not result in any visual aid, due to these constant changes.

Scenario 2: The OS scenario
For safety management it could be desirable for the ship domain around the OS to remain of similar size, regardless of the various TS. This kind of domain could also be used to support VTSO in a visual manner. By displaying the domain around a vessel, any breach is easily spotted and warnings can be issued. This is especially true for busy areas where there might be multiple TS at the same time. If TS parameters are also included, the ship domain would have multiple different sizes and this is not workable for visual aid. Of course, the computers can still give warnings, but it would probably lead to a more complicated situation. The Moving Havens concept also remains of the same size, regardless of the TS and would therefore also be applicable in this scenario.

Scenario 3: The same-for-all scenario
In this scenario, it is assumed that the parameter per encounter and direction should be the same in

all locations of the port. So for example, for all overtakes on port-side, the same parameter determines the distance. In this scenario, per encounter type and region, the sum of the normalised variables of all locations will be compared. An important note: only the chosen parameter is the same in every sector. The corresponding variables still vary, which means the size of the ship domain also varies. The big advantage of this scenario is that it allows for better comparison between the locations. The comparison can lead to new insights in regards of excluded parameters like traffic density or route conditions. It also gives a standard influential parameter for every situation, which might be convenient for analyses in other parts of the port.

4

Case study Port of Rotterdam

A case study is performed for vessels inside the Port of Rotterdam. This chapter elaborates on the Port of Rotterdam itself, as well as the data used in this research. Furthermore the exact research locations are explored and compared based on data processing and fleet distribution.

4.1. Background Port of Rotterdam

The Port of Rotterdam (PoR) stretches from the center of Rotterdam to the reclaimed area of Maasvlakte II and consists of 105 km^2. It is managed by the port authority which is also called Port of Rotterdam. The port authority is responsible for the management, operation and support of the continuous development of the PoR. The key values for the port are smart, sustainable, safe and accessible. PoR also has a Harbour Master's Division. The Harbour Master is responsible for the safe and efficient handling of shipping (Port of Rotterdam, 2023a). The Harbour Master is assisted in this task by the following subdivisions:

- Harbour Coordination Center (HCC)
- Vessel Traffic Service Operators (VTSO)
- Harbour Patrol Boats
- Inspection
- Port Health Authority
- Port Security

In 2022, a total amount of 29,029 seagoing vessels visited the PoR, as well as 97,459 inland vessels (Port of Rotterdam, 2023c). A port call starts with vessels registering at the HCC to make their presence and plans known. The HCC will register the vessel and inform them of circumstances like tide, weather etc. After gaining approval, the vessel sails into the PoR. In this they get assistance from pilots, tugboats and boatmen.

PoR is closely involved with the International Task-force for Port Call Optimization (ITPCO). This task-force aims to reduce the time vessels spend at berths in the port. By more relevant data exchange, the port can be used more efficiently. This is done with a framework of three road-maps: Avanti, Basta and Pronto (ITPCO, 2015). Of these three, both Avanti and Pronto (implemented under the name PortXchange) have been introduced. Avanti assists the registration at the HCC by providing data like vertical clearance and depth. This significantly reduces the workload for the HCC. PortXchange ensures the sharing of berth planning and real-time status of berth occupation. This allows for just-in-time arrivals and it reduces the waiting time significantly (Port of Rotterdam, 2020).

4.1.1. Safety management

VTSO supervise the traffic from two traffic centers, one located in Hoek van Holland, and one located in the Botlek. There are 11 VTS areas in the PoR, as visible in Figure 4.1. Via Very High Frequency (VHF) channels, the vessels are able to communicate with each other as well as the VTSO.

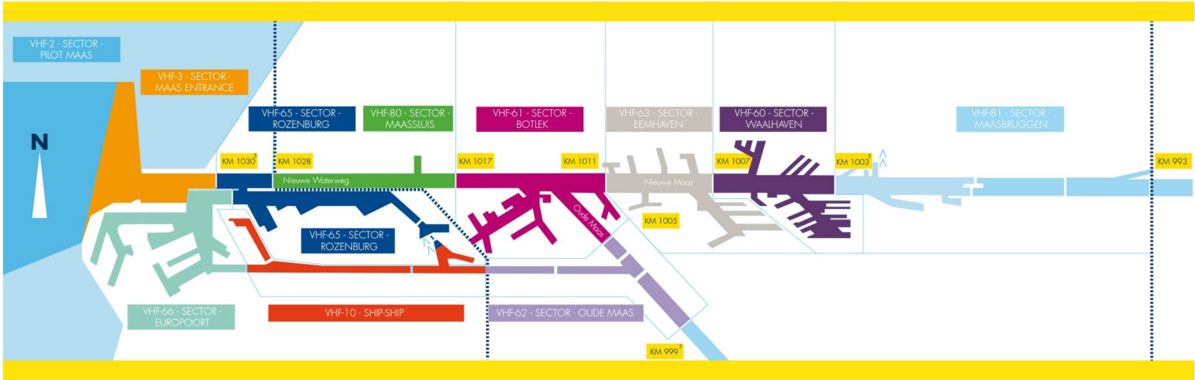

Figure 4.1: VTS sections (Port of Rotterdam, 2023b)

VTSO in PoR are not allowed to force vessels to adjust their route, they are purely there for communication, information and assistance. Of course, (most) vessels do listen to the VTSO as they are the ones with the overview and specific knowledge of the area. Most of the information on vessels is provided by a combination of radar and AIS data. The two types of data complement each other very well and reduce the inaccuracy as also elaborated on in section 2.4.

4.2. Data

As mentioned, data obtained from PoR combines radar and AIS data, which increases the accuracy. However, not all vessels send their AIS data at the exact same moment. A consequence of this is that if vessel A sends their location at T=0s and vessel B sends their location at T=1s, vessel A will of course be at a different location at T=1s. The PoR data has therefore been interpolated to a point where all vessels are updated every 3 seconds. So for all ships there is a location at T=0s, T=3s, T=6s. However, even with that interpolation there is still some missing data. More interpolation seems the logical solution but it is possible that one wrong entry leads to several extra error entries. In the assumption that the amount of errors is low as the data comes from a radar and AIS combination, interpolation is carefully applied.

For every vessel, the gaps between AIS entries larger than 3 seconds are interpolated, up to and including gaps of 15 seconds. After 15 seconds any bend in the path or non-linear effects will not be represented in a correct way which leads to presumably incorrect entries. As for the values that get interpolated, the location, SOG, COG and heading get interpolated. All other values like length, width and MMSI stay constant.

In the analysis not all vessels will be taken into account and filtering is necessary for relevant results. There are a lot of vessels in the port that are quite small. These are relevant for the shipping process, but do not ship anything themselves. This includes vessels like tugboats, patrol vessels, water-taxis, dredgers (while dredging), boatman vessels, pilot vessels, etcetera. AIS provider VT Explorer has made list with codes for different vessel types (VT Explorer, 2023). The codes range from 0 to 99 and indicates the vessel type, from pleasure craft to tanker. The default code is equal to zero, but all vessels relevant to this research have a code of 60 or higher. This means that vessels with a code between 1 and 59 can be excluded from analysis. To further ensure that all irrelevant vessels are still taken out, a length minimum is set. All vessels with a length lower than 50 meters will also be excluded. Furthermore, the ship domain is only applicable in the case of a sailing vessel. Therefore all vessels with a speed over ground lower than 2.0 knots will not be included in the analysis. This value is derived from Silveira et al. (2022), where they assume any vessel going slower than 2.0 knots is "adrift, anchored or not under command".

4.3. Locations

The VTS sections in the port each have their own characteristics. As mentioned, port areas are highly complex but the complexity varies throughout the port and is different per VTS section. The fleet composition of vessels sailing in these different areas is also different per section. For example, the really large seagoing vessels have a large draught and can therefore not sail at all locations in the port. These different characteristics lead to different sailing behaviour in different sections of the port. To characterise this difference, the analysis will be carried out in three different sections in the port. The locations should vary in their situations and increase in intensity and complexity. The following characteristics are determined:

- A straight waterway without crossings: This is the simplest form of waterway in a port area and it presents a baseline case.
- An intersection with various manoeuvrings: Port areas differ from regular waterways by the amount of (irregular) movements. An intersection will allow for analysis of these irregular movements.
- A hotspot with a lot of different vessels: Port areas also differ from regular waterways by the large variation of vessels. Seagoing and inland vessels sail alongside each other.

The chosen locations in the PoR are elaborated on below, along with all relevant information on the differences between the chosen sectors. The choice for each location is made based on expert advice from the Port of Rotterdam based on the characteristics. Figure 4.2 shows the chosen locations on the map.

A straight waterway without crossings
The VTS section Maassluis is chosen. This is the green area in Figure 4.1 and the blue area in the center of Figure 4.2. Both schematically and in reality this is a simple straight-forward waterway. Vessels simply have head-on encounters and there is the occasional overtake. It makes for an ideal first location.

An intersection with various manoeuvrings
The VTS section Botlek is chosen. This is the purple area in Figure 4.1 and the blue area on the lower right corner of Figure 4.2. The Botlek is the sector with the highest VTS intensity and a sector where a lot of different manoeuvres occur. There is ongoing traffic in both directions sailing along the Nieuwe Maas and there are vessels going in and out of the Botlek as well as the Oude Maas. Starboard-starboard passes often occur between vessels from the Botlek van Oude Maas. On top of that, the Oude Maas occasionally has a high flow rate, causing vessels to be pushed off course.

A hotspot with a lot of different vessels
The Breeddiep area in sector Rozenburg is chosen. This is the left part of the dark blue area in Figure 4.1 and the blue area in the upper left corner of Figure 4.2. The two previous sections are further inland, which means the variation in vessels is not very large. While inland vessels can vary a lot, they often do not need a pilot or tug boats. That is not the case for seagoing vessels. They are larger and have special requirements. An area where both come together is at Breeddiep, in VTS section Rozenburg. This area has many different vessels as well as interesting manoeuvres: a true hot-spot.

Figure 4.2: Locations of the three sectors analysed in this thesis.

For all three locations, two weeks of data is analysed: March 13 2023 to March 26 2023. After the interpolation and data filtering the sectors can be compared based on AIS entries, unique vessels, as well as on their fleet distribution. Table 4.1 shows a numerical comparison, while Figure 4.3 shows the different fleet distributions.

Table 4.1: Data processing

	Maassluis	Botlek	Breeddiep
Total AIS entries	3,142,285	2,862,703	1,165,716
After filtering	815,214	1,094,338	549,127
After interpolation	881,026	1,194,757	595,296
% data via interpolation	7.47%	8.40%	7.76%
Unique vessels	508	1433	746
Percentage vessels L>135m	56 (11%)	221 (15%)	140 (18%)

Immediately, it is clear that sector Maassluis has the largest amount of AIS entries and Breeddiep the lowest. This not necessarily an indication of the amount of traffic: the Maassluis sector is largest so one vessel sailing through simply results in more AIS data. This becomes even clearer when comparing the amount of unique vessels. That is almost 3 times as high in sector Botlek compared to Maassluis, but the amount of AIS entries is a factor 1.3 higher. Therefore, vessels spend a longer time in sector Maassluis compared to the other two, most likely due to the size of the sector. The amount of unique vessels in the Botlek sectors highlights the traffic density: the sector is quite small but twice as many vessels pass through compared to sector Breeddiep.

Filtering causes the most amount of exclusions in sectors Maassluis and Botlek and lowest in sector Breeddiep. This indicates there is quite some traffic that is irrelevant for this analysis located in the former two sectors. The missing data from the relevant vessels is interpolated and the percentage of interpolated data is quite similar in all three sectors. Missing data is therefore independent of location in the PoR. Vessel sizes, traffic density and other factors do not have an influence on the inaccuracies of the data.

The final row of the table shows the amount of sea-going vessels in the different sectors. In general, sea-going vessels are used to more space and would therefore prefer to keep more space. As there is no good way to distinguish sea-going vessels from inland vessels due to AVG rules, the distinction is made by looking at the vessel length. Vessels larger than 135m will be classified as sea-going vessels. Sector Botlek has the most sea-going vessels but also the largest amount of vessels in general. The percentage is therefore also given. This shows that sector Breeddiep has the highest percentage of sea-going vessels.

As visible in Table 4.1, the sectors each have a different character. To visualize more of the differences, Figure 4.3 shows the distribution of the vessel length, width and SOG per location. The ship types are also presented. The AIS data gives a number, and via VT Explorer (2023), these numbers indicate the following ship types:

- 60 - Passenger, all ships of this type
- 70 - Cargo, all ships of this type
- 80 - Tanker, all ships of this type
- 90 - Other Type, all ships of this type

It quickly becomes clear that the Botlek has the highest amount of AIS entries, as the bin for sector Botlek is almost always highest. This starts to change when increasing the vessel sizes, when sector Breeddiep often has the most entries. As for the SOG, that is lowest on average in sector Botlek and highest in sector Breeddiep. The vessel type distribution actually shows a similar image regardless of location. The only exception is the amount of tanker vessel entries in the Botlek which is relatively high compared to the other locations and vessel types.

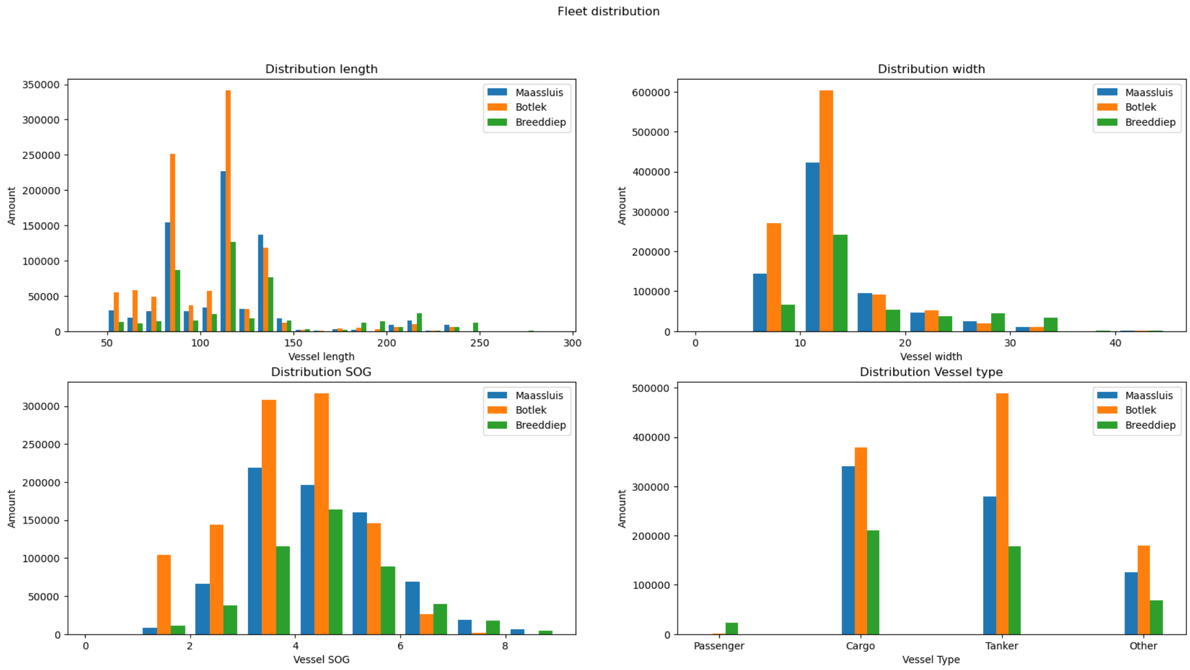

Figure 4.3: Fleet distribution per location

5
Encounter data set

The encounter data set is created via a historical AIS data analysis. The encounter data set is discussed by composing a visual representation of the ship domain. The three locations are compared, based on initial domain size, traffic intensity and the amount of encounters. Additionally, the differences between encounter types are analysed. Some preliminary observations are made, based on the visual comparison and numerical comparisons.

5.1. Historical AIS data analysis

For each of the locations the method by Hansen et al. (2013) is applied and an encounter data set is created. Shu et al. (2017) states that in the PoR vessels are influenced by each other when the distance between them is 1000m or lower. Therefore, only encounters with a distance of 1000m or less will be included in the encounter data set. The encounters can be plotted for an initial visual analysis. OS is positioned at (0,0) and the relative position of TS is plotted as a point. This is done for all entries of the encounter data set. To properly represent the frequency of TS locations, a density map is created. This is done in Figure 5.1. For each of the locations (Maassluis, Botlek and Breeddiep) an intensity plot is created. The scale on the right side of each plot indicates the amount of points per pixel. Note that these color scales have different values for each plot. If there are no points located in a particular pixel, the pixel is white. Another aspect of note is that of the clear horizontal lines at -250m and 500m. This is done to exclude any encounters with vessels in different waterways. A vessel in another waterway might be closer than 1000m but both vessels do not impact each other.

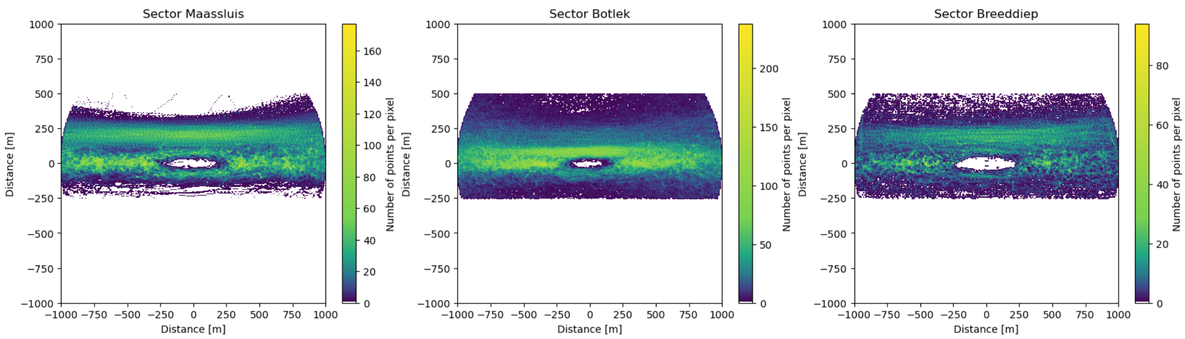

Figure 5.1: Ship domain as defined by Hansen for sector Maassluis, Botlek and Breeddiep

The intensity plots clearly show a white area around the (0,0) coordinate. This implies that there is an area around a vessel where no other vessels are present, also defined as the ship domain. What influences the size of the area and the actual area itself will be further explored in Chapter 6 and Chapter 7. The difference in size between the three locations is particularly interesting. When zooming in on the white oval area as done in Figure 5.2, the differences becomes much more clear. The white area is largest in sector Breeddiep, while it is smallest in sector Botlek. The edge of the white area is also the least irregular in the Breeddiep sector and the most irregular in the Botlek sector.

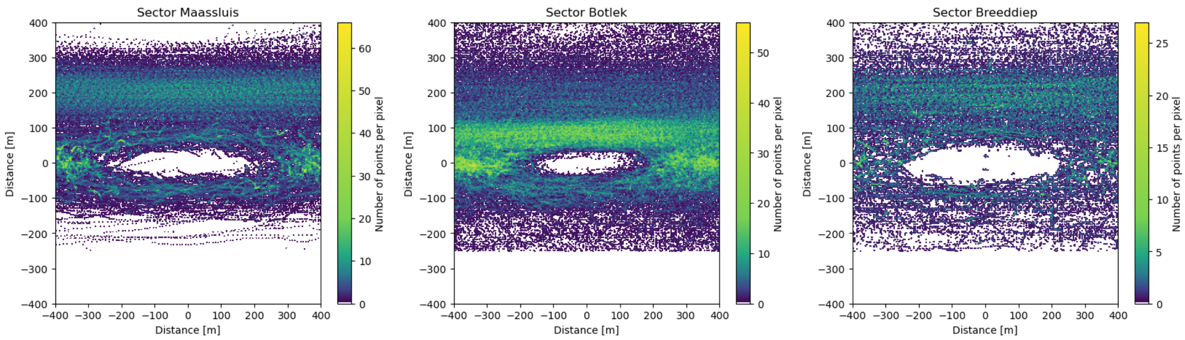

Figure 5.2: Ship domain as defined by Hansen for sector Maassluis, Botlek and Breeddiep, zoomed in.

The comparison between the three is not limited to the size of the white area. The color scales show that there is a large difference in intensity and the amount of entries. Sector Botlek has the highest amount of points per pixel with the maximum amount of points per pixel being around 230, while sector Breeddiep definitely has the lowest intensity with a maximum of about 90 points per pixel.

The encounter data sets of each of the locations can also be compared numerically. This is done in Table 5.1. The total amount of entries confirms the observation based on the visual analysis: the Botlek has the highest amount of entries, while sector Breeddiep has the least amount of entries. To assess the exact intensity of the waterway, it is relevant to determine the amount of unique encounters. Every time two vessels pass each other there will be multiple entries in the data set, but it will be counted as one unique (vessel) encounter. That parameter is by far largest in the Botlek and it indicates that the traffic density is highest there.

Table 5.1: Information on encounter data set in all sectors

	Maassluis	**Botlek**	**Breeddiep**
Total entries	328,570	468,482	129,137
Unique encounters	4,354	13,636	3,317

5.2. Encounter type

The encounters can also sorted by encounter type. Figure 5.3 shows three pie-charts with the distribution of encounter type per location. The blue part represents the head-on encounters, the orange part represents the overtake encounters and the green part represents the crossing encounters.

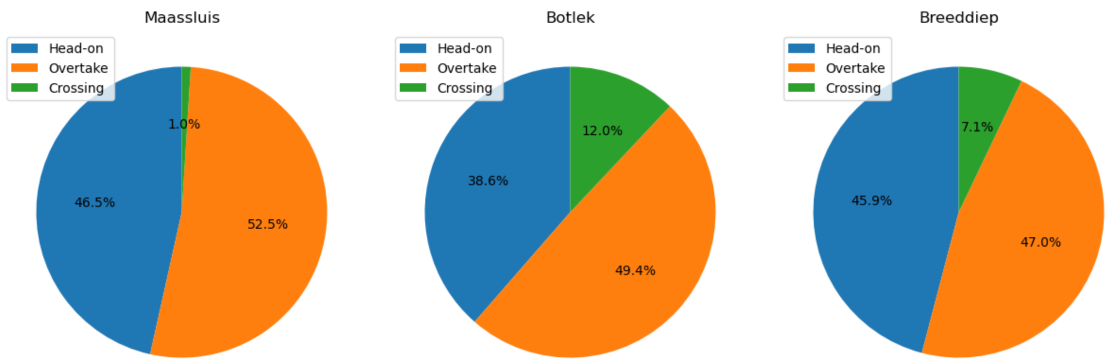

Figure 5.3: Distribution of encounters types in the three sectors.

Figure 5.3 shows for all locations that the most common encounter is the overtake, followed by the head-on encounter. The crossings occur by far the least, with it being near zero in the sector Maassluis. This is of course to be expected in a straight waterway. The crossings that do occur are likely due to a bend in the waterway which causes a large difference in COG. The choice is made to not include crossings in the analysis. The irregular nature of the various crossings makes it difficult to analyse into one specific domain or situation. Furthermore, they make up a very small percentage of the encounter types and in case of a crossing the domain of an overtake should also suffice.

The sorting based on encounters can also be done visually, as done in Figure 5.4. The upper row shows all head-on encounters per location, while the lower row shows the overtake encounters. The red triangle indicates the OS vessel, located at the (0,0) coordinate.

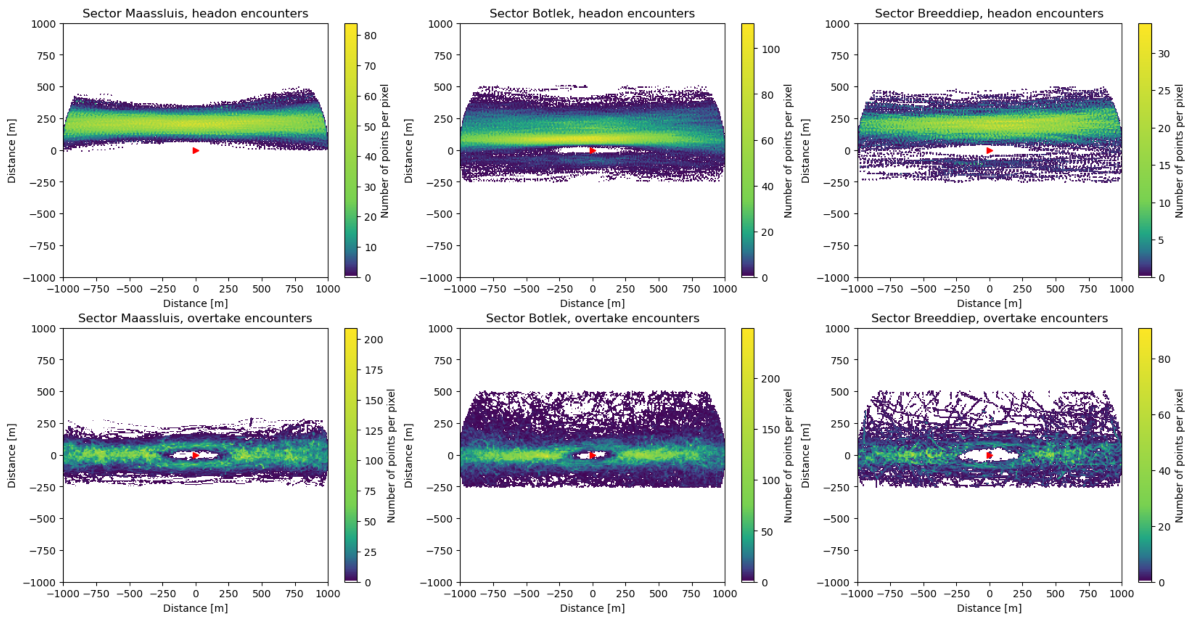

Figure 5.4: Head-on and overtake encounters, per sector

Sector Maassluis is a straight-forward waterway, which means all head-on encounters are on port side. This is also visible in the image, all points are located above the OS vessel. The highest intensity can be found just in a wide bandwidth above the OS, indicating that most vessels just pass each other in a straight line, with the distance between them ranging from 100 to 250 meters. There are some outliers, but they are likely due to bends in the waterway. Another interesting aspect is the moment that vessels start to re-adjust their course in order to avoid collision. At a distance of about 500m there are still some vessels directly in front of OS, while there are no vessels in the direct sailing line at a distance closer than 500m.

The head-on encounters for both sector Botlek and Breeddiep show that not all head-on encounters occur on port-side. In both sectors, there are points located below the OS vessel, which represent the vessels passing each other on starboard side. These 'starboard-starboard' encounters are quite rare, but they do occur occasionally in sector Breeddiep and more often in sector Botlek. As they are so rare, they often occur only via a lot of communication between both vessels and the VTSO. The amount of communication or the irregularity of the encounter can have an effect on the distance between vessels. However, visually, this effect does not seem to be that large as distances on port-side and starboard of OS look quite equal.

The overtakes for all locations show quite a similar story. Both the overtaking and the overtaken vessel are represented, causing TS to be located on both port-side and starboard of the OS. A clear area around the vessel emerges, which represents the distance the vessels keep between them during an overtake. The separation of encounter types also shows that the ship domain visible in Figure 5.1 is mostly caused by overtake encounters. The distances between vessels during a head-on encounter are much larger, particularly on the direct sailing line. It is evident that there is a large difference between the two encounter types, and separation is necessary for an accurate analysis.

5.3. Conclusions

The encounter data set obtained from the historical AIS data analysis has been analysed on a superficial level. Based on the visual comparisons as well as initial information, two main observations can be made. First, there is a clear difference between the three locations. This shows that the ship domain would not be the same everywhere in the port. The sector with the smallest empty area around the vessel is sector Botlek, followed by sector Maassluis, while the largest domain is found in sector Breeddiep. The intensity of the sector Botlek is also highest, with it being lowest in sector Breeddiep. Secondly, the encounter types clearly have different domains. The two most common (head-on and overtake encounters) are very different and should definitely be separately analysed. The crossings are excluded from analysis, due to their rare occurrence and irregular nature that is not well analysed with the chosen method.

6 Parameter influence

This chapter aims to provide an answer to research question 2 which aims to determine the relation between the critical distances and the situation- and ship-specific parameters. It shows the influence of the different parameters on the critical distances per situation and location. The differences and similarities in influence are analysed and the relevant parameters are chosen via the scenarios of application.

6.1. Results

Chapter 3 shows how the influence of the parameters on the critical distances is determined. This paragraph will discuss the resulting trend lines and the differences between locations, encounters and directions around a vessel. First, the trend lines and the different parameters will be explored. It varies per situation what the trend lines look like and whether they are in any way similar. Figure 6.1 shows the entirety of the spectrum. All three plots show the critical distance in fore direction for an overtake encounter in all three locations. The first plot, sector Maassluis, shows large differences between trend lines, both in initial value, as well as the slopes. The second plot, sector Botlek, shows similar initial values but varying slopes and the third plot, sector Breeddiep shows both similar initial values as well as similar slopes. The influence of the parameters is much more easily determined and ranked for sector Maassluis than it is for sector Breeddiep.

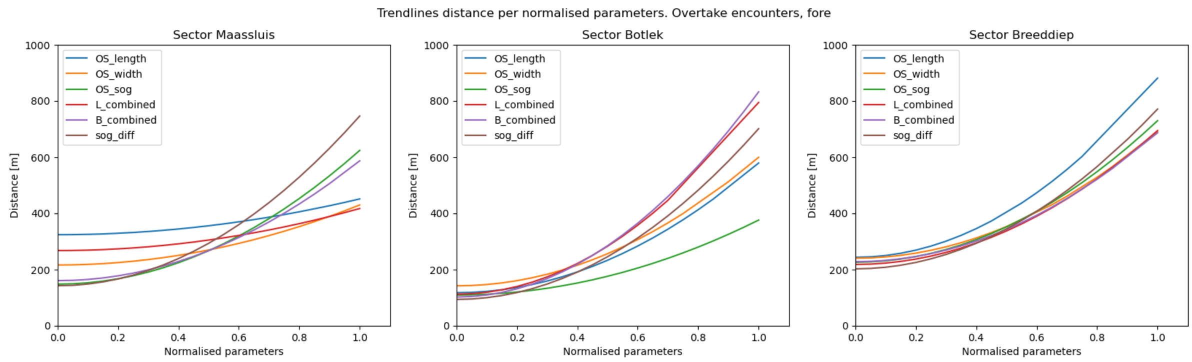

Figure 6.1: Critical distances in fore direction in an overtake encounter in sectors Maassluis, Botlek and Breeddiep.

This difference between sectors is also visible in the critical distances. Figure 6.2 shows the port-side direction during a head-on encounter for all three locations. It confirms that in sector Botlek the distances are lower by default when compared to the other two sectors. The maximum distances in the Botlek is about as high as the minimum distance in sectors Maassluis and Breeddiep. The largest distances between vessels can be found in sector Breeddiep. This all confirms the visual observations and comparisons made between the locations in Chapter 5.

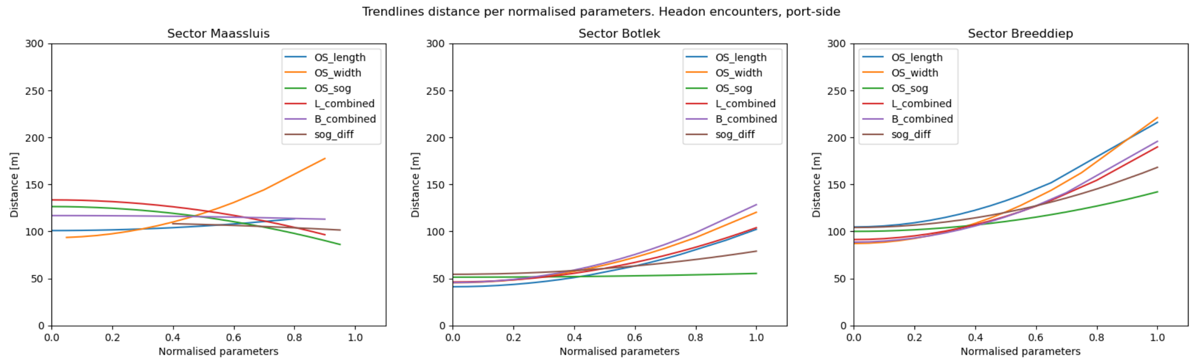

Figure 6.2: Critical distances in port-side direction during head-on encounters in sectors Maassluis, Botlek and Breeddiep.

Besides comparisons between locations, the comparison can also be made between the encounter types. Figure 6.3 shows both the head-on and the overtake encounters in fore direction in sector Breeddiep. It is clearly visible that the distances between vessels are much smaller during an overtake. The overtake distances range from 200m to 800m, where the head-on distances start between 400m and 600m and range to 1000m. This indicates that differentiating between the encounter types is vital to determine the critical distances and therefore the ship domain.

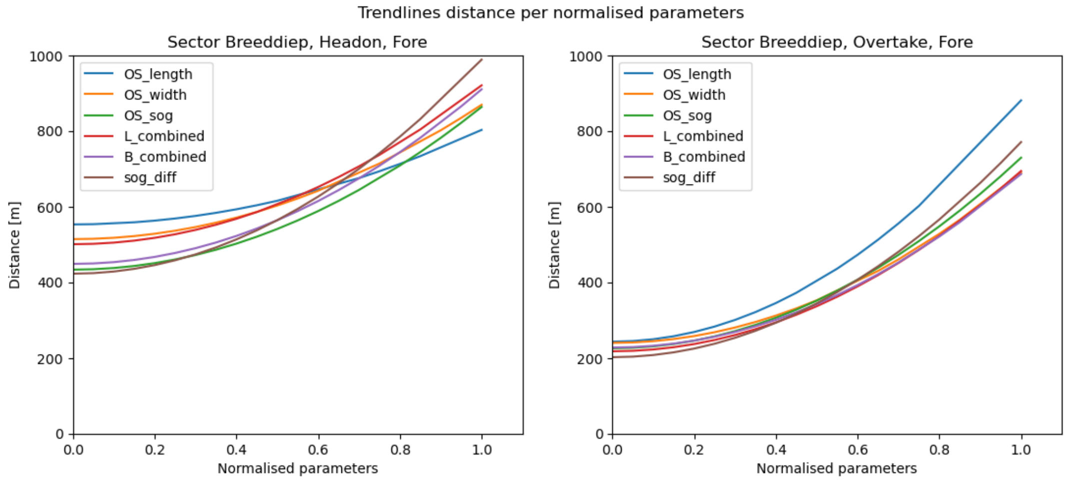

Figure 6.3: Critical distances in fore direction in sector Breeddiep
Left: Head-on encounter. Right: Overtake encounter.

The COLREGs are also included in the sorting of the encounter data set. Figure 6.4 shows a comparison between distances on port-side and starboard. The figure considers the head-on encounters in the Botlek sectors. The plots seems very similar and the range of critical distances is fairly equal: ranging from 50m to 140m. However, the lines for the individual parameters are different. For example, the trend line for parameter L_combined ranges between 50m to 100m in the first plot, but from 50m to 140m in the right plot. The choice of parameter can therefore really impact the size of the domain.

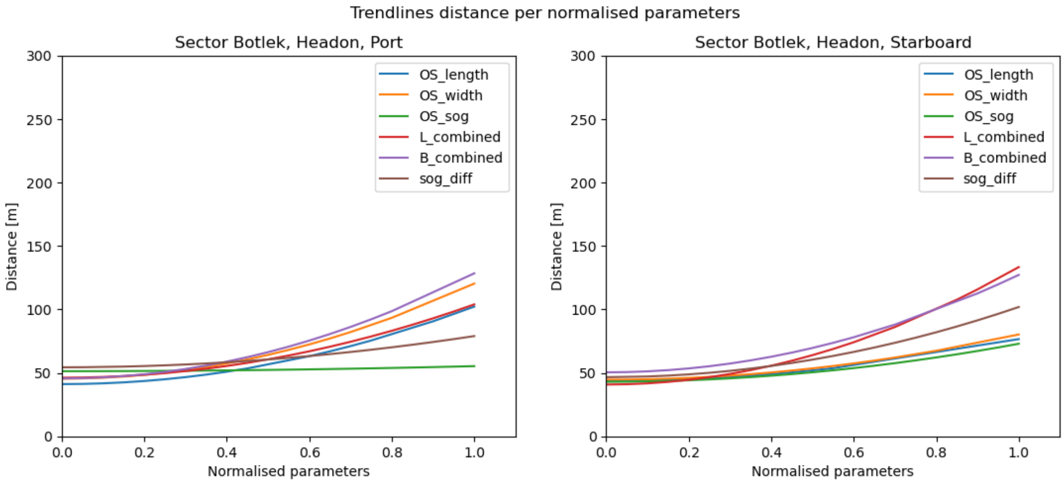

Figure 6.4: Critical distances during head-on encounters in sector Botlek
Left: Port-side direction. Right: Starboard direction.

6.2. Scenarios of application

At the basis of the choice for most relevant parameter is the equation with the normalised variables. Based on a high value for a_{norm}, a regular value for b_{norm} and not the highest value for RMSE$_{norm}$, the choice for relevant parameter is made. As visible, different parameters lead to very similar trend lines. The values therefore are very similar and there is not always a clearly dominant parameter. This also means that different parameters could be chosen which would lead to similar results.

An extra condition for the choice of parameter can therefore give more guidance in the choice and also be used in practice as it looks at possible usage scenarios. Three scenarios have been analysed to show the difference in parameters chosen. The scenarios are named in the list below:

- Scenario 1: The condition-free scenario
- Scenario 2: The OS scenario
- Scenario 3: The same-for-all scenario

As explained in Chapter 3, the encounter data set for each location has been sorted based on encounter type and direction around the vessel. There are three locations, two encounter types and four directions around a vessel. For head-on encounters the aft direction is not included as it is irrelevant in safety analysis. Additionally, the starboard direction in sector Maassluis is non-existent. In summary, the result for one scenario results in 20 equations. This section only shows the chosen parameters, the normalised values on which the choice is based can be found in Appendix B.

6.2.1. Scenario 1: The condition-free scenario

The condition-free scenario has no conditions. The choice for parameter is made via the normalised variables as well as the quality of the fit. Table 6.1 shows the corresponding parameters.

Table 6.1: Relevant parameters for scenario 1

Situation		Maassluis	Botlek	Breeddiep
Head-on	**Port side**	OS_width	B_combined	OS_width
	Starboard	N/A	L_combined	B_combined
	Fore	OS_SOG	OS_length	SOG_relative
Overtake	**Port side**	B_combined	OS_SOG	L_combined
	Starboard	SOG_relative	OS_width	OS_width
	Fore	SOG_relative	SOG_relative	OS_length
	Aft	B_combined	L_combined	SOG_relative

Purely looking at the data leads to a large variation in the most influential parameter. All parameters are most influential at least twice, with the OS width and SOG relative occurring the most. There is barely any similarity between locations, as they often have a different parameter for the same direction and encounter type. However, it seems that the parameter in the sailing direction is often SOG related, while the parameter in the perpendicular direction is more often related to the vessel size. The reason for the large variation in influential parameter is unclear. It further emphasizes the small differences between these parameters and the usefulness of the scenarios of application.

6.2.2. Scenario 2: The OS scenario

The OS scenario only considers the OS parameters, as it would allow the ship domain to remain constant in size, regardless of the TS variations. This leaves only OS_{length}, OS_{width} and OS_{SOG} to consider as the most influential parameter. Table 6.2 shows the corresponding parameters.

Table 6.2: Relevant parameters for scenario 2

Situation		Maassluis	Botlek	Breeddiep
Head-on	**Port side**	OS_width	OS_width	OS_width
	Starboard	N/A	OS_width	OS_length
	Fore	OS_SOG	OS_length	OS_SOG
Overtake	**Port side**	OS_width	OS_SOG	OS_SOG
	Starboard	OS_width	OS_width	OS_width
	Fore	OS_SOG	OS_length	OS_length
	Aft	OS_width	OS_length	OS_SOG

The limitation in choices for most influential parameter have lead to some more consistency. The OS width is the most influential parameter for head-on encounters on port-side as well as overtake encounters on starboard. The OS width is by far the most chosen parameter, chosen 10 times, with OS SOG occurring 6 times, and the OS length only 5. This means that the ship domain is mostly constant in size except where the OS SOG is the most influential. However, this does not occur often.

6.2.3. Scenario 3: The same-for-all scenario

The same-for-all scenario chooses a the parameter based on results for all three locations combined. It allows for better comparison between the locations. The impact of the variables a and b on the ship domain is the same for all locations, as the chosen parameter is also the same. Table 6.3 shows the corresponding parameters. An important note: only the chosen parameter is the same in every sector. The corresponding variables still vary, which means the size of the ship domain also varies.

Table 6.3: Relevant parameters for scenario 3

Situation		Maassluis, Botlek and Breeddiep
Head-on	**Port side**	OS_width
	Starboard	B_combined
	Fore	OS_SOG
Overtake	**Port side**	B_combined
	Starboard	OS_width
	Fore	SOG_relative
	Aft	SOG_relative

The resulting relevant parameters for this scenario seem quite logical. All distances in the sailing axis (fore and aft) are determined by the SOG, whether it be relative or OS. All distances on the perpendicular axis (port side and starboard) are determined by the width. For regular head-on encounters it only depends on the OS width but for starboard both widths are taken into account. The starboard-starboard encounters are quite rare and only occur with quite a lot of communication between both vessels and the VTSO. The combined width is a logical choice. In the overtakes, the overtaking vessel determines the distance to the overtaken vessel (on starboard) based on its own width. The overtaken vessel has little say and experiences the distance to the overtaking vessel (located on port side) as determined by both widths, but mostly TS width.

When comparing the parameters chosen for the three scenarios, it is clear that there is a lot of variation, especially when comparing scenario 1 and 3. In scenario 1 there is not one situation where in all sectors the same parameter is chosen. There are even sectors where all three parameters in scenario 1 are different and the chosen parameter in scenario 3 is again different. The difference in results and the impact of the extra conditions will be further explored in the next chapter.

6.3. Conclusions

This chapter discussed the influence of the situation- and ship-specific parameters on the critical distances. These critical distances are key inputs in the formation of the ship domain. The influence of the situation-specific parameters is determined via sorting based on location, encounter type and direction around a vessel. The influence of these can not be expressed in numerical values. However, the results show clearly that the observations made from the encounter data set are correct. The differences in critical distances between the three locations are very clear. The differences between head-on and overtake encounters are also clearly visible. This justifies the sorting of the data set and individual analysis per situation.

The ship-specific parameters can be very similar in their influence, or very different. The choice for a ship-specific parameter is made based on the scenarios of application. These scenarios lead to different choices and therefore a different ship domain. However, on average it seems that in the sailing direction the velocity-related parameters are influential, while the perpendicular direction is influenced by the width-related parameters. The same-for-all scenario must be mentioned specifically, as it chooses the same parameter for every location. This could allow for a better numerical comparison between the locations.

7

Size and shape of the ship domain

This chapter aims to answer research question 3, which involves the formation of the ship domain. The size of the domain results from the parameter choices in the previous chapter and it is placed back into the encounter data set. The shape of the domain is then tested based on the amount of domain breaches. These are counted, as well as placed on a timeline.

7.1. Size

For each of the scenarios, the influential parameter is chosen and the actual relations are determined. This is shown in Table 7.1 for scenario 1 in sector Maassluis. The table shows the chosen parameter with the corresponding values for the variables.

Table 7.1: Relations for chosen parameters in scenario 1, sector Maassluis

Encounter	Direction	Parameter	a	b
Head-on	Port-side	OS_width	0.045	99.432
Head-on	Starboard	OS_width	0.045	99.432
Head-on	Fore	OS_SOG	2.064	576.897
Overtake	Port-side	B_combined	0.189	21.683
Overtake	Starboard	SOG_diff	3.707	30.057
Overtake	Fore	SOG_diff	19.593	151.122
Overtake	Aft	B_combined	0.886	80.659

Appendix C shows all relations per scenario via a table with the variables per relation. A visual representation of the relations can be found in Figure 7.1. The upper image shows a head-on encounter, while the lower image shows an overtake encounter. Around the blue OS there are 4 red dots indicating the relations determined. These determine the size of the domain. The dashed lines indicate possible shapes, which will be discussed in the next section. The green and red vessels surrounding the blue vessels are TS. The color of the TS indicates if they have entered the ship domain. This will now be referred to as a domain breach.

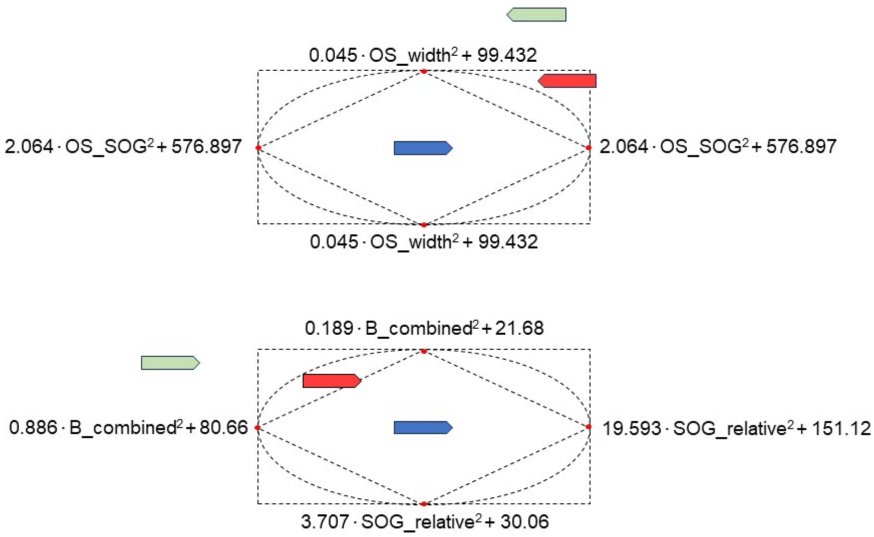

Figure 7.1: Size ship domain sector Maassluis, head-on and overtake encounter, scenario 1

To put the ship domain further in perspective, Figure 7.2 shows the domain plotted for the average values of the parameters over the visual analysis images as shown in Chapter 5. Again, multiple shapes are drawn over it in order for the size being easier to discern. The size of the domain for a head-on encounter is almost 3 times as large as for the overtake encounters, especially in sailing direction.

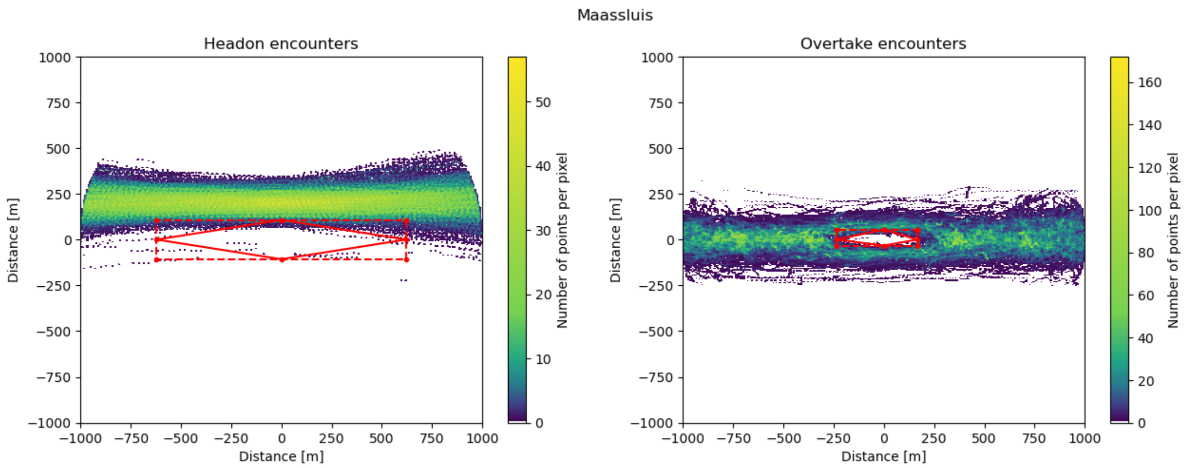

Figure 7.2: Ship domain in sector Maassluis, via scenario 1

Furthermore, the difference between the diamond and rectangle shape of the domain also becomes quite evident. The rectangle clearly has more domain breaches than the diamond. This is logical as that shape is twice as big as the diamond. However, there is a difference between the amount of points inside the domain and the amount of vessels. For example, for the head-on encounters, there is a clear trail of around six points inside the diamond shape. This is most likely caused by 1 vessel, but it has 6 entries in the encounter data set. This one vessel would result in 1 warning message, even though there are six entries.

A special mention must be made for the size of the domain in scenario 3. As the chosen parameter is the same in all three locations, the differences in size between the three locations can be plotted and analysed. Figure 7.3 shows the relation for every situation in all three locations. Note that the y-axis is different per plot. The first row consists of the head-on encounters (port-side, starboard and fore), while the second row consists of the overtake encounters (port-side, starboard, fore and aft). The red, green and blue lines represent the sectors Maassluis, Botlek and Breeddiep, respectively. For each of the entries in the encounter data set, the critical distance is plotted. The higher, or more extreme, values values occur less and are therefore only represented by a dot.

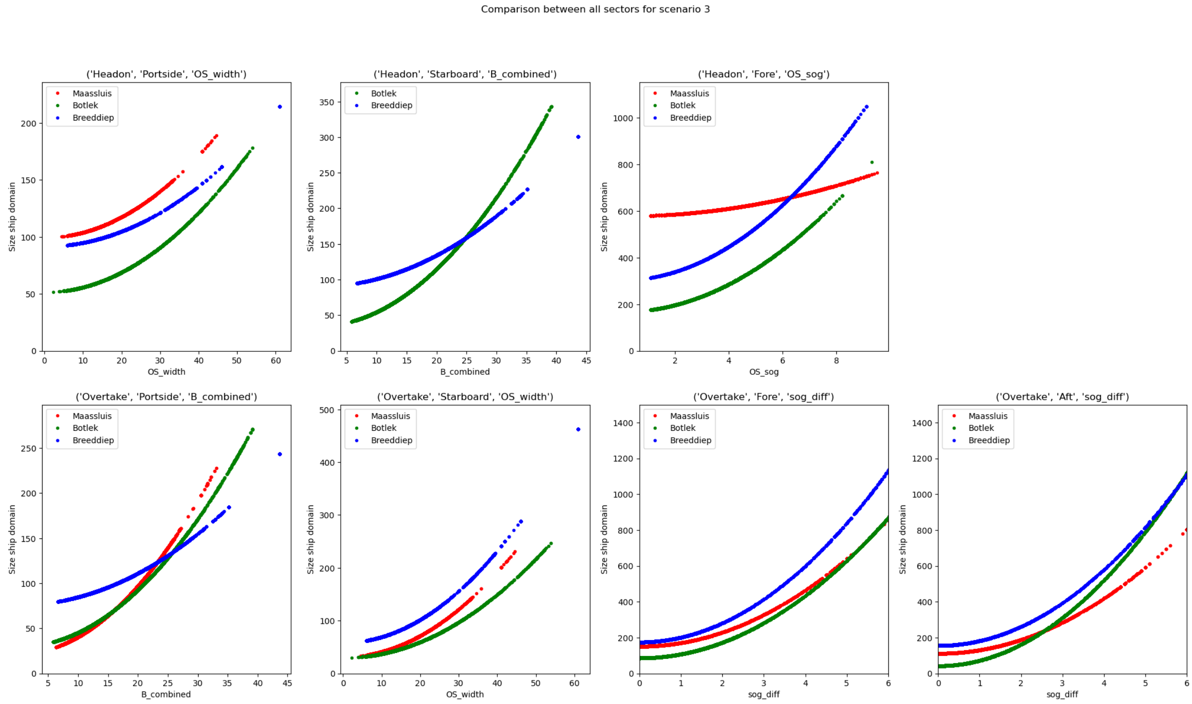

Figure 7.3: Comparison ship domain size for scenario 3

Generally, the domain size is smallest in sector Botlek. The largest domain in head-on encounters is found in sector Maassluis, while in overtake encounters the largest domain is found in sector Breeddiep. It is possible therefore that head-on encounters are also partly influenced by the complexity of the sector, and overtake encounters are more influenced by the amount of encounters.

The next section will test different shapes and count the amount of domain breaches, both in actual entries as well as in unique vessels.

7.2. Shape

The shape of the ship domain varies throughout the literature and therefore multiple shapes are analysed. As the size of the domain is different for every encounter, any form of comparison is difficult. The solution is normalisation where every distance of an encounter is related to the size of the ship domain for that encounter. This is especially helpful for the testing of the ellipse shape, as a normalised ellipse is just a circle with a radius of 1. For sector Maassluis in scenario 1, Figure 7.4 shows the normalised domains.

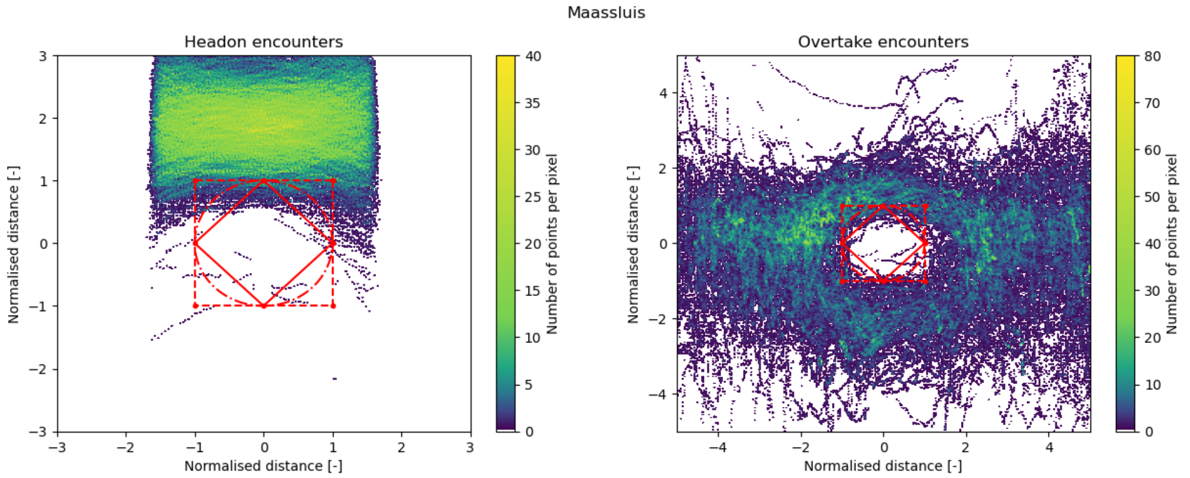

Figure 7.4: Normalised domain in sector Maassluis, scenario 1, for head-on and overtake encounters.

For the testing of each of the scenarios, multiple values and percentages will be determined. First, a distinction will be made between the total amount of breaches and the amount of unique ships that breach. As mentioned in the previous section, there is a clear difference between the two. Furthermore, as the Botlek area has a much higher traffic intensity compared to Breeddiep, only giving the percentage value will tell a distorted story when comparing the sectors to each other. The total amount of breaches is a very useful indicator for VTS operations and how often VTSO might have to intervene. Therefore, the total amount of breaches will also be given. And lastly, there are the three possible domain shapes. The rectangle, ellipse and diamond. The expectation is that the rectangle will see the highest amount of breaches as it is largest, and the diamond will yield the lowest amount of breaches.

The testing of the shapes for all sectors in scenario 1 is given in Table 7.2. The table paints a logical picture. The amount of domain breaches is for all sectors lowest for the diamond shape, and highest for the rectangle. For the total amount of data points, the difference between the diamond and the rectangle is a factor of about 6 in both sectors Maassluis and Botlek, while a factor of 4 in sector Breeddiep. For unique vessel breaches this factor ranges between 2.4 and 3.2. It indicates that the choice of domain shape can really impact the amount of domain breaches. A shape twice the size leads to 4-6 times the amount of breaches.

Table 7.2: Testing of shapes in scenario 1

		Maassluis		**Botlek**		**Breeddiep**	
		Amount	**Percentage**	**Amount**	**Percentage**	**Amount**	**Percentage**
Diamond	**Data points**	1305	0.40	1718	0.37	2989	2.31
	Unique vessels	152	3.49	301	2.21	229	6.90
Ellipse	**Data points**	4041	1.23	4873	1.04	7427	5.75
	Unique vessels	234	5.37	490	3.59	350	10.55
Rectangle	**Data points**	8146	2.48	9381	2.00	11428	8.85
	Unique vessels	438	10.06	879	6.45	531	16.01

Between the three sectors, sector Maassluis always has the least data point breaches and also the lowest amount of unique vessel breaches. Furthermore, sector Breeddiep always has the highest amount of data breaches, but sector Botlek has the most unique vessel breaches. This indicates that in the Botlek various vessels get very close to each other and "accidentally" enter the ship domain for a short period of time. Vessel in sector Breeddiep stay inside the domain much longer.

And finally, the amount of unique vessel breaches must be further elaborated and put into context. If there is one unique vessel breach per hour, the total amount of breaches for a period of two weeks is $1 \cdot 14 \cdot 24 = 336$ unique domain breaches. For 2 breaches per hour, this amounts to 672. So for scenario 1, there are on average more than 2 breaches per hour only in the rectangle domain in the Botlek sector. All other shapes and sectors have an average of 2 or less breaches per hour.

However, the amount of unique vessel breaches per hour is of course never the same value every hour. Figure 7.5 shows the amount of breaches per hour for sector Maassluis, during scenario 1 for each of the shapes. The shapes are plotted on top of each other. This is possible because a breach of the diamond shape is also always a breach of the rectangle shape. So a green bar indicates that there is a blue and an orange bar hidden underneath it.

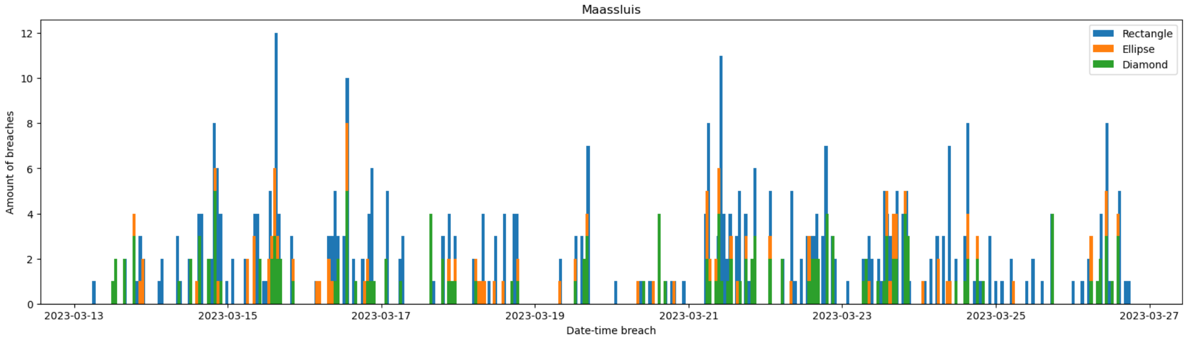

Figure 7.5: Exact amount of breaches per hour in sector Maassluis for scenario 1

It shows that there are some hours where there are no breaches at all while during others there are more than 10. This also highlights the difference between the three shapes. The diamond shape has a maximum of 6 breaches per hour, while this maximum for the rectangle lies at 12 breaches per hour. Furthermore, the most common amount of breaches is 1 or 2 breaches. It has to be noted that it is possible, if not quite likely, that two vessels both enter each other's domain, therefore causing two unique vessel breaches with one encounter. Appendix C shows the testing of the shapes for all three scenarios as well as timelines for all other locations and scenarios.

Table 7.3 shows the unique vessel breaches per scenario, domain shape and location. Both the total amount of unique vessel breaches is counted and the percentage is given.

Table 7.3: Comparing the three scenarios of application, based on unique vessel breaches

		Maassluis		**Botlek**		**Breeddiep**	
		Amount	**Percentage**	**Amount**	**Percentage**	**Amount**	**Percentage**
Scenario 1	**Diamond**	152	3.49	301	2.21	229	6.90
	Ellipse	234	5.37	490	3.59	350	10.55
	Rectangle	438	10.06	879	6.45	531	16.01
Scenario 2	**Diamond**	179	4.11	363	2.66	206	6.21
	Ellipse	271	6.22	605	4.44	332	10.01
	Rectangle	499	11.46	1028	7.54	493	14.86
Scenario 3	**Diamond**	158	3.63	321	2.35	167	5.03
	Ellipse	230	5.28	477	3.50	275	8.29
	Rectangle	440	10.11	824	6.04	420	12.66

When comparing the three scenarios, it is immediately very obvious that scenario 2 never has the lowest amount of data points or the least amount of unique vessel breaches. That is not to say that it is an unworkable scenario. The diamond shape shows less than 1 breach per hour for all sectors, the ellipse shape has almost 2 breaches for Botlek and almost 1 for the other two. For the rectangle however there are more than 3 breaches in sector Botlek and around 1.5 per hour in Maassluis and Breeddiep.

The lowest amount of points and unique vessels can be found mostly in scenario 3 and for some cases in scenario 1. That is to say; the amount of points is always lowest for scenario 3, while the unique vessel breaches are lowest in scenario 1 for the diamond shape in Maassluis and Botlek and the rectangle shape in Maassluis.

Appendix C shows all visual representations of the testing, similar to Figure 7.4. There it is obvious that the reason the numbers are so low in scenario 3 is because the shapes might actually be a little on the small side for some sectors. Scenario 2 is visually the closest approximation of the empty white space, which is why it also has the highest amount of breaches.

7.3. Conclusion

In conclusion, the domain can be related to a certain ship-specific parameter. The actual size subsequently depends on the encounter type, location in the port and scenario of application. A smaller approximation leads to less breaches, but is also not totally representative of the actual ship domain, while a larger approximation leads to more breaches which are not necessarily all relevant. Depending on the practical use, a scenario or even a new combination of parameters can be chosen. The recommendation for general use goes to scenario 3. It allows for good comparison of the effects of different locations and the parameters seem to have a logical influence on the critical distance.

It is evident however that the differentiation between location, encounter type and the direction around a vessel is vital to determine a valid ship domain. The differences between sectors and encounter types in these sectors is very large and therefore this cannot be excluded from any analysis.

As for the shape of the domain, there is again not one right answer. The least amount of breaches occur for the smallest shape. The recommended shape for the ship domain is the ellipse. This is visually the shape that most matches the domain and a good middle ground between the undersized diamond and the oversized rectangle. However, the other shapes could be used for gradients of warning. The warning then gets progressively more intense when going from the rectangle to the ellipse, and the encounter could be recorded as a near-miss if the diamond shape is breached.

8

Application of the ship domain

To answer research question 4, the possible applications of the determined ship domain are explored. In terms of safety management, the VTSO aid and near-miss analysis are discussed, while in terms of route planning the implementation of the determined ship domain on Trackpilots and Moving Havens is analysed.

8.1. Safety management

The ship domain can be applied to improve safety management. This section will discuss two hypothetical applications. The first is live assistance in the management of traffic in the form of VTSO aid. The other is more related to reflection and future improvement in the form of near-miss analysis

8.1.1. VTSO aid

VTSO manage the situation on the waterway by assisting the captains in their decision-making. The VTSO do this by assisting in communication as well as giving information. The VTSO keep track of the situation on the waterway partly via AIS data on vessel positions, as well as extra information provided by AIS, radar and the VHF channels. For example, the VTSO can see the expected path the vessel would sail as well as additional information on the vessels themselves. These extra functions could be expanded on by including the ship domain. Figure 8.1 shows what that could look like. The image is taken from MarineTraffic, a provider of ship tracking and maritime intelligence (MarineTraffic, n.d.), and shows 4 vessels in sector Maassluis. The ship domains are added manually and not based on the determined domain in the previous chapters. Both the diamond and ellipse shape shown as they are used in the VTSO aid and near-miss applications. The color is related to the vessel color. These ellipses show the space a captain would prefer to keep empty and give a good representation of the safety experience.

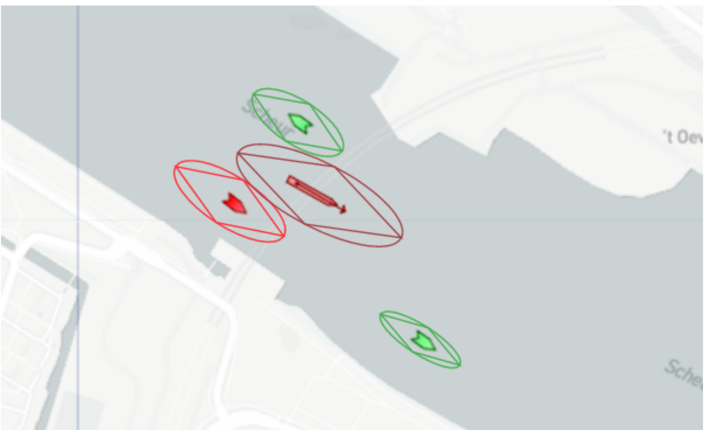

Figure 8.1: Example of visual VTSO aid with an indication of the ship domains drawn around the vessels.

For this kind of visual representation, the ship domain has to stay the same size, regardless of the encounter type or the TS. This would be difficult as the difference between overtakes and head-on encounters is very large. An alternative to this would be a notification of a breach when it occurs. The visual aid aspect would be gone, but the ship domain would be determined and implemented.

8.1.2. Near-miss analysis

Near-misses are defined by the IMO as ”A sequence of events and/or conditions that could have resulted in loss. This loss was prevented only by a fortuitous break in the chain of events and/or conditions.” This means that a breach of the ship domain is not necessarily a near-miss. A slight breach of the ship domain will not result in loss as there is plenty of space left. Only the safety experience is effected by it.

A near-miss is closely related to the combination of the distance between two vessels, the rate of change of this distance as well as their orientation towards each other. At a certain combination of the three values, it is defined as a near-miss. For example, when it becomes clear that if nothing is changed about the relative speeds and orientations within the next 30 seconds, the vessels will collide. The exact values that determine the near-miss vary between locations.

The determined ship domain could be applied by analysing the known near-miss cases to see how and if they occur when there is a domain breach. If they largely do, a domain breach is a good indication for these near-misses and ships could possibly be warned at an earlier moment.

8.2. Moving Havens

The Moving Haven as defined by Porathe is the first of two route planning applications of the ship domain explored in this chapter. Porathe defines a rectangle with a width of 50m on each side, and the length of the rectangle is equal to the distance a vessel can travel in 60 seconds. By normalising the distance in x-direction to the distance travelled by OS in 60 seconds, the Moving Haven can be plotted on top of the encounters. This is done in Figure 8.2. An important note: this chapter assumes that vessels stay perfectly in the middle of their Moving Havens.

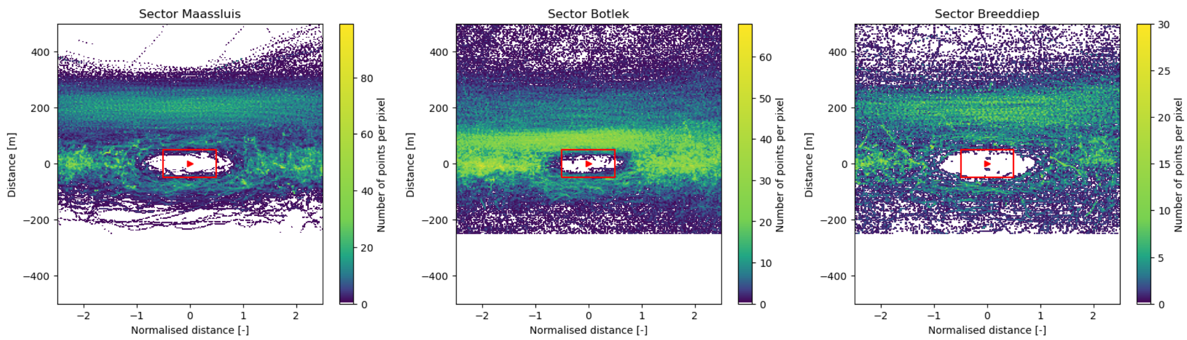

Figure 8.2: Ship domain as defined by Hansen et al. (2013) with the ship domain as defined by Porathe (2016) drawn over it.

It is important to remember that the Moving Haven concept works different from a ship domain. This goes back to Figure 2.1 in Chapter 2. This research has assumed a definition for a ship domain where the domains can overlap, but a breach occurs when individual vessels enter another domain. Moving Havens work under the principle that they cannot overlap. A vessel claims a part of the waterway and therefore it cannot be claimed by another vessel. This does however mean that the Moving Havens can be attached to each other. The minimum width on each side of the Moving Haven (assuming they are side by side attached) is therefore equal to half of the width of the ship domain. This principle is shown in Figure 8.3. The Moving Haven is represented by the red lines and the ship domain by the black dashed lines. Both vessels cannot enter the other vessel's ship domain but the Moving Havens are attached. The minimum size of the Moving Haven is determined by the size of the ship domain. A visual representation of the actual area around the Moving Haven where there should be no vessels is given in Figure 8.4 by the red dashed line.

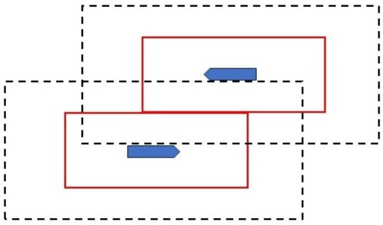

Figure 8.3: Combination ship domain and Moving Haven. The minimum size of the Moving Haven is determined by the size of the ship domain

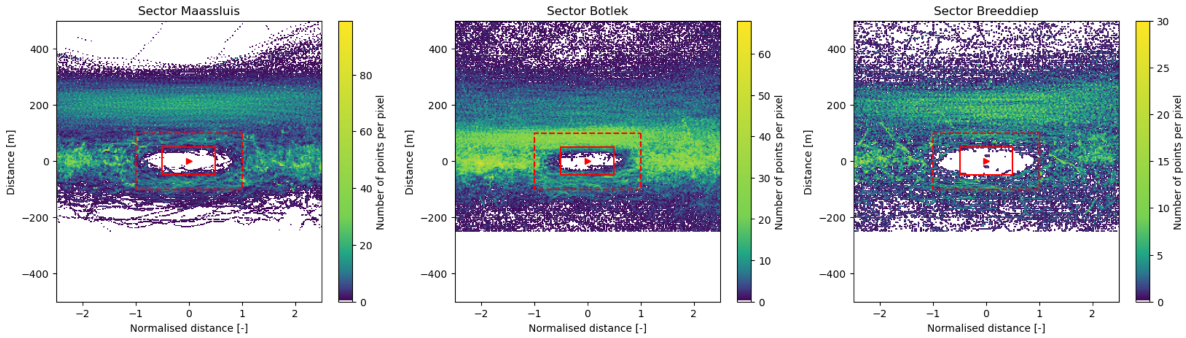

Figure 8.4: Ship domain as defined by Hansen et al. (2013) with the ship domain as defined by Porathe (2016) drawn over it in red. The red dashed line represents the actual area where there should not be any vessels, based on the Moving Havens definition.

Already it is clear from the visual representation that the amount of breaches will be much higher. This also becomes clear from Table 8.1. These breaches can be managed by adjusting vessel routes or making vessels go slower. However, this might impact the service time and accessibility of the port. Therefore, optimisation of the Moving Haven is recommended, especially in sector Botlek where there is an average of 9 breaches per hour. Based on the size of the ship domain, a minimum size for the Moving Haven can be determined.

Table 8.1: The amount of breaches for the Moving Haven concept, as defined by Porathe

	Maassluis	**Botlek**	**Breeddiep**
Points inside	25785	51620	7352
Percentage	7.85%	11.02%	5.69%
Unique vessels inside	445	3055	338
Percentage	10.22%	22.4%	10.19%
Average breaches per hour	1.32	9.09	1.01

8.2.1. Optimisation

There are two variables that determine the size of the Moving Haven. The first is the chosen width, which is at the moment the XTD which equals 50m, and the second is the time accuracy desired for the Haven. Porathe sets the time accuracy to 60s. The impact of these variables on the amount of unique vessels that breach the Haven is analysed.

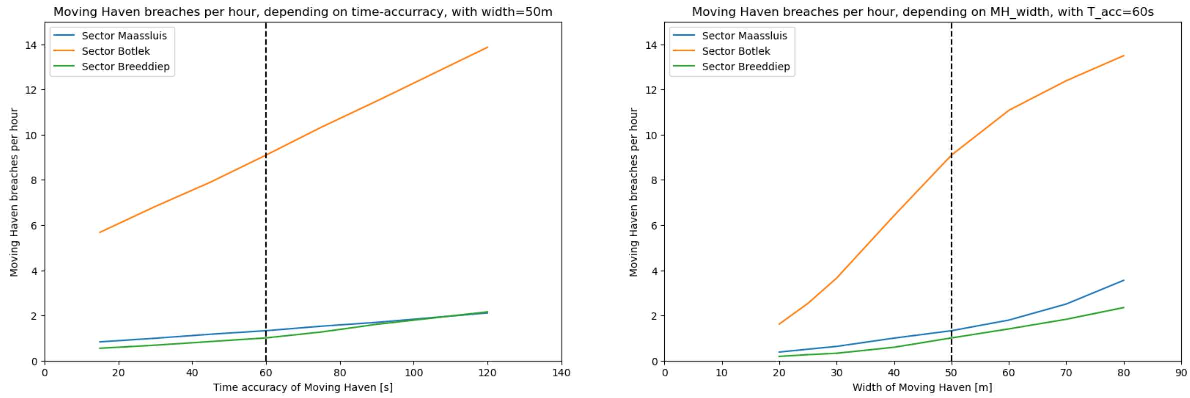

Figure 8.5: Influence of time accuracy and width on the Moving Haven breaches

Figure 8.5 shows the influence of each variable on the amount of breaches, per sector. By keeping one variable constant at the value determined by Porathe, the influence of the other is visible. The dashed black line shows Porathe's value of the changing variable.

It is once again very clear that the Botlek sector is exceptionally busy. Where the amount of breaches in the other two sectors is below 1 per hour in every situation, the Botlek never goes below that 1 per hour value. However, it is also clear that the influence of the changing variable is highest in the Botlek. Specifically, the influence of a changing width is very high. By reducing the width of the Moving Haven by 50%, the amount of unique breaches in two weeks goes from 3055 to 852, which is a reduction of 72%. In comparison, reducing the time accuracy by 50% leads to a decrease in breaches of only 25%. The variable with the highest impact is the width of the Moving Haven.

However, at what point will the size of the Moving Haven be too small to be considered safe? By decreasing the size of the Moving Haven the vessels will get closer to each other. The next paragraph will use the ship domain to determine the minimum width of the Moving Haven.

8.2.2. Moving Haven in combination with ship domain

By looking at the size of the ship domain, the width of the Moving Haven may be adjusted accordingly. The minimum distance between the two vessels is either determined by the size of the ship domain, or by the width of the two Moving Havens.

$$D_{min} = \text{Ship domain}_{OS}$$
$$D_{min} = \text{Moving Haven width}_{OS} + \text{Moving Haven width}_{TS}$$

Two times the minimum size of the Moving Haven therefore cannot be smaller than the OS ship domain as that would mean the vessels would get too close to each other. An analysis can be done to determine the safety aspect of lowering the Moving Haven width, based on the ship domain.

The chosen ship domain distance will be for overtake encounters. This is under the assumption that the head-on encounters would always be much further apart where the Moving Havens would not even touch each other. As the Moving Haven is a logistic planning concept, it should remain relatively constant for the duration of the journey. It should not change for every encounter a vessel has. Therefore it should only depend on the OS parameters, so OS_{length}, OS_{width} or OS_{SOG}. As the overtaking vessel's width determines the critical distance during overtakes in the recommended ship domain, the OS width in starboard direction during overtake encounters is chosen as the parameter to determine the critical distance. This also follows the theory by Kristić et al. (2020) where the XTL is partly determined by the OS_{width}.

The results are given in Figure 8.6. The figure shows the percentage of encounters where the OS ship domain is larger than the width of the Moving Haven. The percentages are given per location and the red dotted line is placed at the 5% line. It indicates the Moving Haven width that is larger than the ship domain width for 95% of all encounters. One-hundred percent of encounters require the Moving Haven to have a width of at least 15m in sector Maassluis and Botlek, and a slight increase in width immediately leads to lower percentages. This is different for sector Breeddiep. The Moving Havens clearly need to be largest in this sector and a width of 50 m leads to distances between vessels smaller than the ship domain width in 18% of all encounters. The 5% line indicates a width of 70m Therefore a Moving Haven width of 70m is recommended in sector Breeddiep, which is much larger than the 50m determined by Porathe has determined. In contrast, the Botlek sector shows that the size of the Moving Haven can be reduced significantly. The same is valid for sector Maassluis, although the reduction is smaller. In 95% of all encounters a Moving Haven width of 42m and 33m, in sector Maassluis and Botlek respectively, leads to distances between vessels larger than the determined ship domain. As mentioned before, the optimisation is exceptionally useful in the Botlek sector. A reduction of the width from 50m to 30m leads to a decrease in breaches of more than 50%, as visible in Figure 8.5.

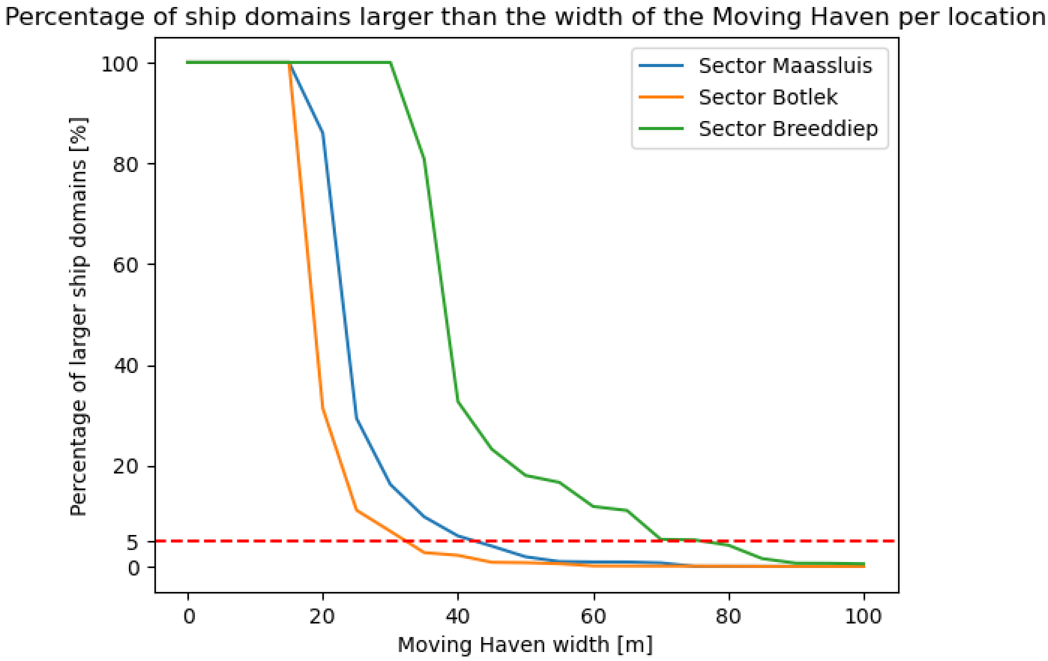

Figure 8.6: Percentage of ship domains larger than the width of the Moving Haven per location. Red line indicates a Moving Haven width larger than ship domain in 95% of all encounters.

8.2.3. Future of Moving Havens

The concept of Moving Havens is in its essence a planning problem. Both the analysis and exploration done in this chapter are based on the important principle that all vessels sail exactly in the center of the Haven. This is not necessarily unthinkable, but it will never be that way in reality. The amount of breaches are also a big aspect: the planner of the Moving Havens might be able to plan the vessel courses in such a way that there are never any breaches, without it impacting the service time and accessibility of the port.

A sensible planning strategy would be to start with a Moving Haven with a width of 50m and try to make that work. Making it work is here defined as all vessels being able to sail through the port and there being no loss in service for the PoR. From there optimization is possible in sectors Maassluis and Botlek by reducing the width of the vessel to 40 and 30m respectively. Any further reducing would definitely result in too many potentially unsafe situations.

What was not included in this chapter is the difference in encounters. The analysis of the results showed that there is quite a large difference between the overtake and head-on encounters. While this does not need to affect the size of the Moving Haven, some additional space between the Havens is definitely necessary in the head-on encounters.

8.3. Trackpilots

The next application of the ship domain can be found in Trackpilots. This is a system currently in development in the Netherlands. Falling into degree one in terms of the degrees of automation, a Trackpilot is a system that allows a vessel to sail a predetermined route. The captain determines the track and the vessel starts sailing. In the meantime the captain does have to keep paying attention, but can for example also work on some administration. A captain on a vessel equipped with the Trackpilot system described it as ”sailing with a captain in training: in principle everything works fine, but you do have to keep paying attention and sometimes assist them.” The degree of automation can be increased to two if the Trackpilot could warn the captain of a possible dangerous situation. By using route estimation and collision prediction the danger in a situation can be estimated.

When vessels share their track with each other, it allows them to see when and where a (possibly dangerous) encounter will occur. Consequently, they can adjust their route or slow down to avoid collisions. This principle is called Intent Sharing. By sharing the intention of being at a certain location at a certain time, collisions can be avoided. Rijkswaterstaat (RWS) also sees a lot of potential in Intent Sharing. The Maritime Research Institute Netherlands (MARIN) has carried out research to assess the benefits of intent sharing (Guiking, 2022). Three companies from The Netherlands, Germany and Belgium respectively collaborated in this research: Shipping Technology, Argonics and Tresco. Each of these has created its own Trackpilot system. The main result was that the situational awareness of the skipper was enhanced and RWS will continue with the implementation of Intent Sharing.

Internationally there have also been efforts to increase efficiency and safety in the maritime industry. The European Union funded several projects from which organisation Sea Traffic Management (STM) emerged. The projects, carried out on the Baltic Sea, were all centered around the concept of route exchange (STM, 2022). In combination with collision software, vessels can then make decisions earlier and this results in more efficient shipping. Route exchange is in essence quite similar to Intent Sharing, but with a large difference between research locations. The Baltic Sea is quite large, especially when compared to the inland waters in the Netherlands.

8.3.1. Trackpilots in combination with ship domain

The next step in the automation using Trackpilot is that the system gives an alarm when getting too close to another vessel. In a further stage it may even adjust the course on its own. The ship domain can assist in this, both by indicating the minimum distance that should be kept between planned routes, as well as determining when the vessel should adjust its course.

The distance the routes should be apart from each other can immediately be determined via the width of the ship domains. Figure 8.7 shows what that would look like. It shows a head-on encounter between two vessels. The ship domains are shown in by the black ellipses, while the planned routes are shown by the black dashed lines. The planned routes stay as far away from each other as the width of the largest ship domain.

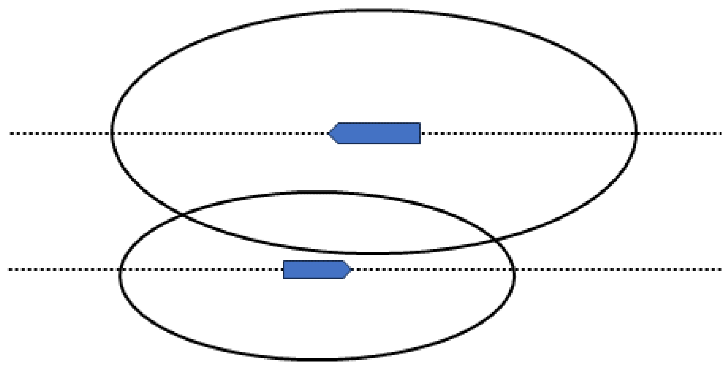

Figure 8.7: Application of ship domain on Trackpilots

Another application can be found for the adjustment of the routes. When it becomes clear that vessels are closing in on each other an adjustment of the route must be made. Figure 8.8 shows an overtaking manoeuvre. Using both ship domains, a path can be planned around the ship domain of the overtaken vessel, ensuring enough distances between the vessels at all times.

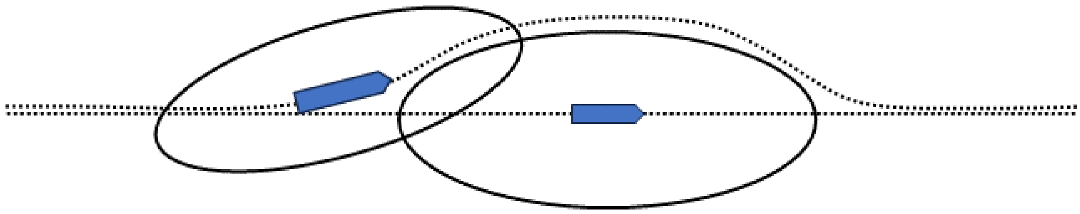

Figure 8.8: Application of ship domain on Trackpilots

8.4. Conclusion

This chapter explored how the ship domain can be used in the improvement of safety management and route planning. In regards to safety management, there are a couple of possibilities that can be explored. The assistance of VTSO can help via alarms if vessels enter each other's domain, or via visual aid on the VTSO screens. The ship domain could be used in the near-miss analysis, but further research must be done on the correlation between domain breach and near-miss.

The ship domain could also be used for route planning. A Trackpilot would be able to adjust their route automatically in order for the considered vessel to sail around the ship domain of the other vessel. The planned routes could also be determined upfront, based on how much distance is needed between two vessels. As for the Moving Haven concept, the implementation would definitely require more research. The minimum size of the Moving Haven can be found via the ship domain, but any form of implementation would need more research into the practicality of the concept.

9 Discussion

This chapter reflects on the carried out research. First, the determined domain is compared to those discussed in the literature analysis. Then, the choices made to compose the encounter data set are discussed. The choices made to determine the parameter influence are discussed next. Subsequently, the applications are discussed. And finally, some general reflection on the subject of automation is given.

9.1. Comparison to other ship domain theories

As the ship domain is determined, a compelling part of reflection is to compare it to the ship domains originally compared in Chapter 2. Only scenario 3, with the same parameter in all situations regardless of location, is plotted. Not all ship domains are plotted, only those that are relevant in this comparison. Therefore, in Figure 9.1, the ship domain theories by Fujii and Tanaka (1971), Hansen et al. (2013), N. Wang (2010), Pietrzykowski (2008) as well as the the Moving Haven by Porathe are compared to the determined ship domain in sectors Maassluis, Botlek and Breeddiep.

The ship domains are applied for the same conditions as presented in Chapter 2:

- This is a standard head-on encounter.
- Length OS = 95.5 [m]
- Length TS = 156.68 [m]
- Beam OS = 18.2 [m]
- Beam TS = 24 [m]
- Speed OS = 7 [kn]
- Speed TS = 10 [kn]
- Time accuracy = 60 [seconds]

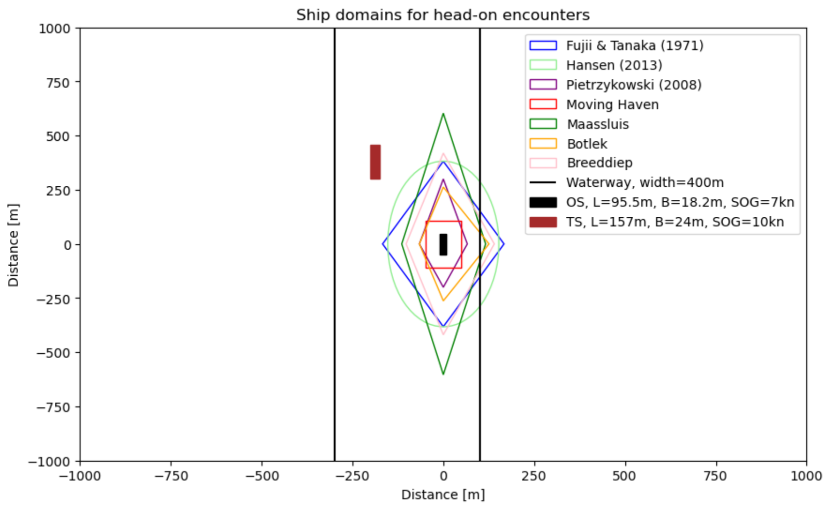

Figure 9.1: Overview of various ship domain theories compared to the waterway, including the domains in PoR

It shows ship domains in the PoR that are generally similar in length and smaller in width than the ship domains from literature. One exception is for the theory by Pietrzykowski (2008), which is the fuzzy ship domain. For this it must be noted that the ship domain by Pietrzykowski is determined in fairway with a width of 200m in total. The other exception is for sector Maassluis. It has a much larger distance fore and aft. This might actually have to do with the simplicity of the waterway. There are no vessels sailing on the "other" side of the waterway and that is why there is that much space. It does indicate when vessels should move out of the way in case of a head-on encounter. It also shows the distances on starboard being larger than those on port-side. The effect of the COLREGS is is much more visible in the PoR than in the other ship domains.

9.2. Encounter data set

The encounter data set has been composed based on certain choices and definitions. This section reflects on the decisions made for the filtering, interpolation, distinction of vessels, as well as the methodology of compiling the encounter data set.

Filtering is done to exclude any vessels that are not relevant in the shipping process. During the analysis many vessels had a vessel type 0. Vessel type 0 is most likely due to the captain not entering a vessel type into the system. Harati-Mokhtari et al. (2007) states that the vessel type is the most often an incorrect or inconsistent value. As these vessels could be anything, they are excluded from analysis. However, this does mean that relevant vessels have been excluded. The choice for exclusion is made under the principle that analysis based on incorrect data is worse than analysis based on data where some values are missing.

Next, the interpolation is considered. First and foremost, the data used in this research has already been edited so that all data points occur at T=0s, 3s, 6s etc. This interpolation is done by an external party and the exact methods are unknown. To deal with missing data, any further intervals up to 15 seconds have been linearly interpolated. Consequently, in every sector about 8% of all data is interpolated. Any larger intervals have been assumed to lead to incorrect interpolation, due to the incorrect interpolation of a route with bends. However, even for interpolation for intervals under 15 seconds the data points can be incorrect: if the initial data point is incorrect, the interpolated values are also going to be incorrect. Again, the inconsistency of the AIS plays a role. A data study done by Harati-Mokhtari et al. (2007) shows that about 8% of all AIS transmission contains at least one error value. As stated in the previous paragraph, the most common error is in the vessel type. The location is only incorrect in around 1% of all messages. In the PoR, radar and AIS are combined to determine the location, which leads to an even lower error rate (Habtemariam et al., 2015).

As for distinction between vessels, between sea-going vessel and inland vessels the assumption is made that sea-going vessels are longer than 135m. This is done as there is no other indication of the possible distinction between the two types. However, there are inland vessels larger than 135m as well as sea-going vessels that are smaller than this threshold. As there is no other possible indication, this seems to be the only option, even though it is not the most accurate.

And finally, a limitation of the method chosen is that only OS and TS are compared. However, in reality, there might be three or more vessels on the waterway that all interact simultaneously. For example, vessel A is overtaking vessel B but vessel C is approaching from the head-on direction. The overtake executed by vessel A must be influenced by the approach of vessel C. These multiple-vessel encounters can influence the distance between two vessels, but this is not included in the analysis unfortunately due to the method chosen.

9.3. Parameter influence

The paragraph discusses the chosen parameters considered in the analysis, as well as the trend lines fit for the relation between the normalised parameters and the critical distances.

The choice is made to exclude the crossings in the analysis. They are only a small part of the total of encounters but inclusion would mean all encounter types are accounted for. However, the empirical analysis does not lend itself well to the analysis of crossings. An important part of crossing is how they actually occur. Behind or in front of the vessel, which vessel does what, etc. The difference between front and back crossings is impossible to determine with the current analysis method. To include crossings, the analysis method must be changed. Additionally, in the overtakes there is no real distinction made between the overtaking and the overtaken vessel. Due to the lay-out of the PoR, the assumption can be made that a vessel on starboard is overtaking. However, for the vessels on fore and aft, there is no distinction made. By further analysing the difference in SOG, a more accurate ship domain could have been provided.

The historical AIS data analysis only allows parameters included in AIS data, or parameters easily deduced from AIS data like the encounter type. Parameters like environmental conditions are difficult to include as the AIS does not have numerical values for them. Of course, weather models do have the numbers but their effect is difficult to express. For instance, KNMI (2023) shows that the analysed time-period was more windy than average. However, the exact effects of the higher wind speeds cannot be determined in this analysis.

Further inaccuracies can be found in the relation for the extreme values. The parameter-critical distance relation depends on the minima of the minimum distances. The parameter is divided into bins and then per bin the minimum value is determined. However, if there are less data points in the bin (or maybe even zero) the minimum is not totally accurate. This often occurs for the higher (or extreme) values for parameters. Therefore, the relations determined are very accurate for the lower half of the parameter distribution, but less so in the upper half.

The equation chosen for the trend-line that was fitted through the critical distances was chosen to be simple. There is one quadratic term and the parameter only has influence via variable a. The assumption is that there is only one relevant ship-specific parameter determining the critical distance. Chapter 2 shows that multiple theories use more than one parameter. Therefore a more accurate ship domain could be given by including more ship-specific parameters. However, the simplicity does allow for straightforward analysis and Chapter 2 stated that multiple parameters could be related. The possible combination of ship-specific parameters should therefore be further researched.

Further research could also be done into the effects of the locations. The choice for locations inside the PoR is done to have three sectors that differ as much as possible. The consequence is that while the differences are very clear and the indication is clear, the actual influence on the sailing behaviour could be due to multiple factors. The factors already mentioned in this analysis might be the reason, but it is also possible that there is a factor not included in any theory.

Lastly, behaviour within a sector is now assumed to be the same, but it could also differ per specific location. Especially in sector Botlek, there are multiple different waterway widths as well as different environmental aspects within specific locations. These differences could be further analysed to further determine the effects of the differences in location.

9.4. Application

During the application of Moving Havens, the position of every vessel is assumed to be exactly in the middle of the Moving Haven but this is not realistic. Vessels will not be able to sail exactly in the middle of the Moving Haven at all times. The analysis determines a width for the Moving Haven that is very much on the limit, to the point where even a slight deviation from the middle would lead to a domain breach. The concept is a planning issue and only the minimal size is determined. However, it is prudent to take this into account when the actual planning and implementation is done. All this is also due to the fact that for this analysis the Moving Haven is determined by vessel behaviour while in the actual implementation the vessel behaviour will be determined by the Moving Haven.

Additionally, the distance is now assumed to be constant as it is defined as constant by Thomas Porathe. An option could also be to make the Moving Haven ship-specific by setting the width to be a certain percentage of the ship domain width. However, as domains differ in size, it is then possible for a smaller ship to breach the ship domain of a large ship without the Moving Havens overlapping. Therefore, it is important to keep the distances between vessels large enough.

9.5. Ship domains in the future

When discussing future of shipping and ship domains it seems impossible to not mention the continued development of Artificial Intelligence (AI). At the time of writing this thesis, the entire literature study could have been written by ChatGPT (don't worry, it's not). In combination with their Trackpilot, Shipping Technology has created and tested autonomous sailing technology. This technology is based on AI machine learning algorithms and learns from the vessel's patterns as well as other vessels around it. All this automation has to have a certain impact on everyone involved in shipping. Van den Bremen et al. (2022) states that one should not have too much or too little trust in AI.

This leads in to the future of the ship domain. The continued introduction of automation on the waterway leads to an ever increasing percentage of autonomous vessels on the waterway. The ship domain is determined by the behaviour of human captains. This behaviour is already influenced by communication with other vessels as well as the VTSO. As captains communicate via VHF and ensure that all vessels are aware of the situation, distances between vessels are possibly lower than if there was no communication. A fully automated vessel cannot communicate in a similar way. This might cause human captains to prefer to keep more distance, causing the ship domain to increase in size. It all has to do with trust in automation. More trust will decrease the ship domain size, while less trust will increase the size.

If the waterway was full of autonomous vessels, the situation is different. The awareness of other vessels is always there because of the smart systems, which also communicate with each other, just not via VHF. These systems also enable the vessel to react quicker to changes on the waterway. Therefore, the ship domains could be smaller. There would be no captain to determine the safety experience. However, it is unlikely for the distances between vessels to decrease to a distance of almost zero. The unpredictability of the waterway would always require a relatively large safety zone around a vessel. The ship domain might decrease in size, but will always be necessary to determine the minimum required distance between vessels,

10
Conclusions and recommendations

This chapter presents the conclusions and findings of each of the sub-questions after which the main research question is answered. Afterwards, recommendations are presented based on the discussion and conclusions.

10.1. Conclusions

The main objective of this research was to create a method that determines the ship domain, based on the relevant ship- and circumstance-specific parameters found in historical AIS data, in order for it to be applied to improve safety management and route planning. This objective is explored via four sub-research questions, each with their own subject. These were theoretical orientation, a historical AIS data analysis, the actual formation of the ship domain and the implementation. The main findings per subject are presented in this paragraph, along with the conclusion to the main research question.

Question 1 - Theoretical orientation: What are the most commonly used parameters to describe the ship domain?

Existing research on ship domains shows that there are multiple ways to define and determine the ship domain. This often also determines the parameters that have an influence on the domain. Parameters mentioned in various methods explored are the following:

- OS Length
- OS SOG
- OS Width
- OS Manoeuvrability
- TS Length
- TS SOG
- Encounter type
- Weather conditions
- Visibility
- Tidal currents
- Route depth
- Route width
- Route obstacles
- Traffic density
- COLREGs
- Captain's experience
- Vessel type
- Gross tonnage

A ranking of the parameters is made, based on the frequency of usage in ship domain theories. By far the most often used parameter is the OS length, at some distance followed by OS SOG and the COLREGs. The next ranked parameter is the weather conditions (in which visibility and tidal currents are also included). This is then followed by TS length, traffic conditions and OS manoeuvrability. All others are significantly less used in the ship domain theories. It must be stated that most of the domains are determined in open waters, which in practice means they are not applicable in the port of Rotterdam because their size is too large. The domains that are determined in restricted waters are often much smaller. This leads to the conclusion that even though traffic density and route conditions are not often included, they are very relevant.

A lot of the parameters mentioned above are available via AIS data, but not all of them. This includes the manoeuvrability, the weather conditions including visibility and tidal currents, the gross tonnage and the captain's experience. All others are available: obviously the OS length and SOG, but the encounter type can be determined via the difference in COG, and the COLREGs can be included by considering difference between port-side and starboard. Furthermore, different route and traffic density conditions can be explored via the different sections chosen in the analysis.

Question 2 - Historical AIS data analysis: Based on historical AIS data, how are critical distances between vessels, that are key inputs to ship domain definition, related to situation- and ship-specific parameters?
The analysis of the encounter data set obtained from the historical AIS data analysis leads to the conclusion that the different locations as well as the encounter types have a lot of influence on the ship domain. Sector Botlek would have the smallest ship domain, followed by sector Maassluis, with the largest domain occurring in sector Breeddiep. The head-on encounters have a much larger distance between them when compared to the overtake encounters. This was further confirmed via the determination of the parameter influence.

The influence of the situation-specific parameters is determined via sorting based on location, encounter type and direction around a vessel. The influence of these can not be expressed in numerical values. However, the results show clearly that the observations made from the encounter data set are correct. The differences in critical distances between the three locations are very clear. The differences between head-on and overtake encounters are also clearly visible. This justifies the sorting of the data set and individual analysis per situation.

The ship-specific parameters can be very similar in their influence, or very different. The choice for a ship-specific parameter is made based on the scenarios of application. These scenarios lead to different choices and therefore a different ship domain. However, on average it seems that in sailing direction the velocity-related parameters are influential, while the perpendicular direction is influenced by the width-related parameters. The same-for-all scenario must be mentioned specifically, as it chooses the same parameter for every location. This could allow for a better numerical comparison between the locations.

Question 3 - Formation ship domain: What shape and size can best be used to describe the ship domain as observed in historical AIS data?
The domain can be related to a certain ship-specific parameter. The actual size subsequently depends on the encounter type, location in the port and scenario of application. A smaller approximation leads to less breaches, but is also not totally representative of the actual ship domain, while a larger approximation leads to more breaches which are not necessarily all relevant. The same-for-all scenario would allow for good comparison of the effects of different locations and the parameters have a logical influence on the critical distance.

Furthermore, it is evident that the differentiation between location, encounter type and the direction around a vessel is vital to determine a valid ship domain. The differences between sectors and encounter types in these sectors is very large and therefore this cannot be excluded from any analysis.

As for the shape of the domain, there is again not one right answer. The least amount of breaches occur for the smallest shape. The recommended shape for the ship domain is the ellipse. This is visually the shape that most matches the ship domain as determined via the encounter data set. However, the other shapes could be used for gradients of warning. The warning then gets progressively more intense when going from the rectangle to the ellipse, and the encounter could be recorded as a near-miss if the diamond shape is breached.

Question 4 - Application: How can the AIS-based ship domain be used to improve safety management and route planning in port areas?
In regards to safety management, there are a couple of possibilities that can be explored. The assistance of VTSO can help via alarms if vessels enter each other's domain, or via visual aid on the VTSO screens. The ship domain could be used in the near-miss analysis, but further research must be done on the correlation between domain breach and near-miss.

In regards to the route planning, the ship domain could also be used to improve both Trackpilots and the Moving Haven concept. A Trackpilot would be able to adjust their route automatically in order for the considered vessel to sail around the ship domain of the other vessel. The planned routes could also determine their distances based on the ship domain. As for the Moving Haven concept, the implementation would definitely require more research. The minimum size of the Moving Haven can be found via the ship domain, but any form of implementation would need more research into the practicality of the concept.

Main research question: How can ship domains be defined and applied around vessels in port areas to improve safety management and route planning?
A method is created that is capable of determining the ship domain based on historical AIS data. The method considers both situation-specific parameters like encounter type and the relative positioning of the vessels as well as ship-specific parameters like the length, width and SOG. Furthermore, the domain varies in size per location inside the port area. By determining the relations of the parameters to the critical distance, the size of the domain is found, with the shape being recommended to be an ellipse.

The application of the domain could be used to assist VTSO and near-miss analyses. The latter would need more research into the correlation between a near-miss and a ship domain breach. The route planning concepts also benefit. Trackpilots would be able to adjust their routes based on the distances between vessels as determined by the ship domain. The minimum size of the Moving Haven concept can also be determined via the ship domain, although more research is needed for the actual implementation.

10.2. Recommendations

This paragraph gives recommendations for future research based on the conclusions as well as the discussion. These recommendations can be sorted into two categories: based on the ship domain definition or based on the ship domain application.

In regards to the ship domain definition, there are multiple recommendations. First, the research done is purely based on AIS data. Any parameter mentioned in the literature that was not included in AIS data could not be included in this research. This is especially relevant for the environmental conditions like visibility or tidal currents. Therefore, performing this analysis on data taken during a stormy period or poor visibility could determine the impact of various weather conditions on the ship domain. Furthermore, the influence of multiple-vessel encounters remains unknown. This is related to the exact traffic density at the moment of the encounters, which is another parameter not included in this analysis.

The exact differences in sectors should also be mapped out further. The method to determine the size and shape of the ship domain can be done for other sectors in the PoR as well as other ports. By performing the same analysis on similar sectors in other ports, the results can be compared and the effects of traffic intensity, route width and vessel types can be represented in a more exact manner. The chosen ship-specific parameter should be the same per encounter type and direction. The variables will then vary and the effects of the above mentioned location-bound parameters can be determined.

As for the ship domain application, there are multiple applications that require more research before they can be implemented. The first is the near-miss analysis. The correlation between the domain breaches and a near-miss needs to be analysed to determine if a domain breach is indicative of a near-miss.

The second application requiring more research is the Moving Haven concept. A study into the possibility of implementing the Moving Haven concept is necessary. This research has determined the minimum distance between vessels and therefore the minimum size of the Moving Haven. A feasibility study is the next step. The impact of implementation on service time must be determined. Subsequently, the size can be adjusted to find the ideal Moving Haven.

References

Ahmed, Y. A., Hannan, M. A., Oraby, M. Y., & Maimun, A. (2021). COLREGs compliant fuzzy-based collision avoidance system for multiple ship encounters. *Journal of Marine Science and Engineering*, *9*(8), 790.

Arimura, N., YAMADA, K., SUGASAWA, S., & OKANO, Y. (1994). Development of collisions preventing support system : Model of evaluation indices for navigation. *The Journal of Japan Institute of Navigation*, *91*, 195–201. https://doi.org/10.9749/jin.91.195

BIMCO & International Chamber of Shipping. (2021, June). *Seafarer workforce report: The global supply and demand for seafarers in 2021* (Yearly report).

Coldwell, T. (1983). Marine traffic behaviour in restricted waters. *The Journal of Navigation*, *36*(3), 430–444.

Davis, P., Dove, M., & Stockel, C. (1980). A computer simulation of marine traffic using domains and arenas. *The Journal of Navigation*, *33*(2), 215–222.

Davis, P., Dove, M., & Stockel, C. (1982). A computer simulation of multi-ship encounters. *The Journal of Navigation*, *35*(2), 347–352.

Department of the Treasury, U., Department of State. (2022, May 14). *Guidance to address illicit shipping and sanctions evasion practices* (Sanctions Advisory). United States of America. https://home.treasury.gov/policy-issues/financial-sanctions/recent-actions/20200514

Dinh, G. H., & Im, N.-K. (2016). The combination of analytical and statistical method to define polygonal ship domain and reflect human experiences in estimating dangerous area. *International Journal of e-Navigation and Maritime Economy*, *4*, 97–108.

Eliopoulou, E., & Papanikolaou, A. (2007). Casualty analysis of large tankers. *Journal of Marine Science and Technology*, *12*(4), 240–250.

Fujii, Y., & Tanaka, K. (1971). Traffic capacity. *The Journal of Navigation*, *24*(4), 543–552.

Goodwin, E. M. (1975). A statistical study of ship domains. *The Journal of Navigation*, *28*(3), 328–344.

Guiking, C. (2022, December 15). *Digital Intention Sharing: Simulation study on the benefits of intention sharing* (Research report No. 33281-1-MO-rev.2). MARIN.

Habtemariam, B., Tharmarasa, R., McDonald, M., & Kirubarajan, T. (2015). Measurement level ais/radar fusion. *Signal Processing*, *106*, 348–357. https://doi.org/https://doi.org/10.1016/j.sigpro.2014.07.029

Hansen, M. G., Jensen, T. K., Lehn-Schiøler, T., Melchild, K., Rasmussen, F. M., & Ennemark, F. (2013). Empirical ship domain based on AIS data. *The Journal of Navigation*, *66*(6), 931–940.

Harati-Mokhtari, A., Wall, A., Brooks, P., & Wang, J. (2007). Automatic identification system (ais): Data reliability and human error implications. *The Journal of Navigation*, *60*(3), 373–389. https://doi.org/10.1017/S0373463307004298

Harre, I. (2000). AIS adding new quality to VTS systems. *The Journal of Navigation*, *53*(3), 527–539.

He, Y., Li, Z., Mou, J., Hu, W., Li, L., & Wang, B. (2021). Collision-avoidance path planning for multi-ship encounters considering ship manoeuvrability and COLREGs. *Transportation safety and environment*, *3*(2), 103–113.

IALA. (2016, June 1). An overview of AIS: IALA Guidelines. *International Association of Marine Aids to Navigation and Lighthouse Authorities*.

IMO. (1999, November 25). Guidelines for Voyage Planning.

IMO. (2003, January 6). Guidelines For The Installation Of A Shipborne Automatic Identification System (AIS).

IMO. (2008, October 10). Guidance on near-miss reporting.

IMO. (2018). COLREG - preventing collisions at sea.

IMO. (2021, December 15). Guidelines For Vessel Traffic Services.

IMO. (2022). Guidelines for Maritime Autonomous Surface Ships.

Infrastructuur en Milieu. (2017). Binnenvaartpolitiereglement.

ITPCO. (2015). Folder 'Port Call Optimization': A reliable port starts with reliable information. https://portcalloptimization.org/images/Flyer%5C%20ITPCO%5C%20221220%5C%20(1).pdf

Kijima, K., & Furukawa, Y. (2003). Automatic collision avoidance system using the concept of blocking area [6th IFAC Conference on Manoeuvring and Control of Marine Craft (MCMC 2003), Girona, Spain, 17-19 September, 1997]. *IFAC Proceedings Volumes*, *36*(21), 223–228. https://doi.org/https://doi.org/10.1016/S1474-6670(17)37811-4

KNMI. (2023). Weergegevens Rotterdam maart 2023: Weerstatistieken KNMI 2023. https://weerstatistieken.nl/rotterdam/2023/maart

Kristić, M., Žuškin, S., Brčić, D., & Valčić, S. (2020). Zone of confidence impact on cross track limit determination in ecdis passage planning. *Journal of Marine Science and Engineering*, *8*(8). https://doi.org/10.3390/jmse8080566

Last, P., Hering-Bertram, M., & Linsen, L. (2015). How automatic identification system (AIS) antenna setup affects AIS signal quality. *Ocean Engineering*, *100*, 83–89.

Lin, C., Dong, F., Le, J., & Wang, G. (2008). AIS system and the applications at the harbor traffic management. *2008 4th International Conference on Wireless Communications, Networking and Mobile Computing*, 1–3.

Liu, J., Zhou, F., Li, Z., Wang, M., & Liu, R. W. (2016). Dynamic ship domain models for capacity analysis of restricted water channels. *The Journal of Navigation*, *69*(3), 481–503.

Mao, S., Tu, E., Zhang, G., Rachmawati, L., Rajabally, E., & Huang, G.-B. (2018). An automatic identification system (AIS) database for maritime trajectory prediction and data mining. *Proceedings of ELM-2016*, 241–257.

MarineTraffic. (n.d.). MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic. https://www.marinetraffic.com/en/ais/home/centerx:4.277/centery:51.903/zoom:15

Meyer, J., Stahlbock, R., & Voss, S. (2012). Slow Steaming in Container Shipping. *International Conference on System Sciences*, 1306–1314. https://doi.org/10.1109/HICSS.2012.529

Oanh Ha, K. (2022). Russian tankers going dark raises flags on sanctions evasion. *Bloomberg*. https://www.bloomberg.com/news/articles/2022-03-27/russian-tankers-going-dark-raises-flags-on-sanctions-evasion?utm_source=website&utm_medium=share&utm_campaign=copy

Pietrzykowski, Z. (2008). Ship's fuzzy domain–a criterion for navigational safety in narrow fairways. *The Journal of Navigation*, *61*(3), 499–514.

Pietrzykowski, Z., & Uriasz, J. (2009). The ship domain–a criterion of navigational safety assessment in an open sea area. *The Journal of Navigation*, *62*(1), 93–108.

Porathe, T. (2016). A navigating navigator onboard or a monitoring operator ashore? towards safe, effective, and sustainable maritime transportation: Findings from five recent eu projects. *Transportation research procedia*, *14*, 233–242.

Porathe, T. (2020a). Deconflicting maritime autonomous surface ship traffic using moving havens. *e-proceedings of the 30th European Safety and Reliability Conference and 15th Probabilistic Safety Assessment and Management Conference (ESREL2020 PSAM15)*.

Porathe, T. (2020b). Moving havens: An application of the e-navigation service route exchange. *Proceedings of the International Conference on Human Factors, 19-20 February 2020, The Royal Institution of Naval Architects, London*.

Porathe, T., Borup, O., Jeong, J. S., Park, J. H., Andersen Camre, D., & Brödje, A. (2014). Ship traffic management route exchange: Acceptance in korea and sweden, a cross cultural study. *Proceedings of the International Symposium Information on Ships, ISIS 2014*, 64–79.

Port of Rotterdam. (2020, May 28). *Portxchange leidt tot kortere wachttijd bij vertrek*. https://www.portofrotterdam.com/nl/nieuws-en-persberichten/portxchange-leidt-tot-kortere-wachttijd-bij-vertrek

Port of Rotterdam. (2023a). *Harbour master*. https://www.portofrotterdam.com/en/about-port-authority/our-organisation/harbour-master

Port of Rotterdam. (2023b). *VTS services and VHF communication procedure*. https://www.portofrotterdam.com/en/contact-harbourmaster/vts-services-and-vhf-communication-procedure

Port of Rotterdam. (2023c, January 27). *Presentation nautical annual figures 2022*. https://www.portofrotterdam.com/en/news-and-press-releases/presentation-nautical-annual-figures-2022

Potgraven, P., & de Lange, J. (2022, September 1). *Syllabus smart shipping: Introductie in de wereld van verregaand geautomatiseerde scheepvaart* (Syllabus). Smash! Nederlands Forum Smart Shipping.

Rawson, A., Rogers, E., Foster, D., & Phillips, D. (2014). Practical application of domain analysis: Port of london case study. *The Journal of Navigation*, *67*(2), 193–209.

Shu, Y., Daamen, W., Ligteringen, H., & Hoogendoorn, S. (2013). Vessel speed, course, and path analysis in the Botlek area of the Port of Rotterdam, Netherlands. *Transportation research record*, *2330*(1), 63–72.

Shu, Y., Daamen, W., Ligteringen, H., & Hoogendoorn, S. P. (2017). Influence of external conditions and vessel encounters on vessel behavior in ports and waterways using automatic identification system data. *Ocean Engineering*, *131*, 1–14.

Silveira, P., Teixeira, A., & Soares, C. G. (2022). A method to extract the quaternion ship domain parameters from AIS data. *Ocean Engineering*, *257*, 111568.

STM. (2022). *Projects: Previous projects*. Sea Traffic Management. https://www.seatrafficmanagement.info/projects/

Szlapczynski, R., & Szlapczynska, J. (2017). Review of ship safety domains: Models and applications. *Ocean Engineering*, *145*, 277–289.

Tu, E., Zhang, G., Rachmawati, L., Rajabally, E., & Huang, G.-B. (2017). Exploiting AIS data for intelligent maritime navigation: A comprehensive survey from data to methodology. *IEEE Transactions on Intelligent Transportation Systems*, *19*(5), 1559–1582.

van den Bremen, D., Verwers, A., Van Hout, C., Wöhrle, L., Labrijn, R., & Louwman, W. (2022, January 31). *Future VTS and the Port of Rotterdam: The human-factor impacts of digitalization and automation on its employees*. Erasmus University Rotterdam.

Van Iperen, W. (2015). Classifying ship encounters to monitor traffic safety on the North Sea from AIS data. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, *9*(1), 51–58.

Van Koningsveld, M., Verheij, H., Taneja, P., & de Vriend, H. (2021). *Ports and waterways: Navigating the changing world*. TU Delft Open. https://doi.org/https://doi.org/10.5074/T.2021.004

VT Explorer. (2023). *AIS ship types*. https://api.vtexplorer.com/docs/ref-navstat.html

Wang, N. (2010). An intelligent spatial collision risk based on the quaternion ship domain. *The Journal of Navigation*, *63*(4), 733–749.

Wang, N. (2013). A novel analytical framework for dynamic quaternion ship domains. *The Journal of Navigation*, *66*(2), 265–281.

Wang, Y., & Chin, H.-C. (2016). An empirically-calibrated ship domain as a safety criterion for navigation in confined waters. *The Journal of Navigation*, *69*(2), 257–276.

Yoo, W., & Kim, T.-w. (2022). Statistical trajectory-distance metric for nautical route clustering analysis using cross-track distance. *Journal of Computational Design and Engineering*, *9*(2), 731–754. https://doi.org/10.1093/jcde/qwac024

Zhang, J., Zhang, D., Yan, X., Haugen, S., & Soares, C. G. (2015). A distributed anti-collision decision support formulation in multi-ship encounter situations under COLREGs. *Ocean Engineering*, *105*, 336–348.

Zhao, J.-S., Wu, Z.-L., Wang, F.-C., & Goodwin, E. (1993). Comments on ship domains. *The Journal of Navigation*.

Zhu, X., Xu, H., & Lin, J. (2001). Domain and its model based on neural networks. *The Journal of Navigation*, *54*(1), 97–103.

List of Figures

List of Tables

A

Ship domains

This appendix shows a larger overview of all ship domain theories discussed in Chapter 2.

Szlapczynski and Szlapczynska (2017) gives a detailed overview of existing theories and distinguishes them for their basic properties (the aforementioned safety criterion, type of study) as well as the parameters that are used. The theory of Moving Havens is also added to give a complete overview and make comparison easy.

Not all parameters named in the explored theories are included. Some are combined, others are excluded. Weather conditions summarizes the actual weather conditions, tidal current and visibility. Traffic conditions summarizes the route conditions as well as the traffic density. Gross tonnage and vessel type are not included in the overview.

The overview is presented in Table A.1.

Table A.1: Overview of ship domain theories, as presented by Szlapczynski and Szlapczynska (2017).

Domain by	Safety criterion	Method	OS Length	OS Speed	OS Manoeuvrability	TS Length	TS Speed	Encounter type	Weather conditions	Traffic conditions	COLREGS	Human Factor
Fujii and Tanaka, 1971	(b)	Empirical: statistical processing of radar data	Yes	No	No	Yes	No	No	Yes	No	No	No
Goodwin, 1975	N/A	Empirical: statistical processing of radar data	Yes	No	No	N/A	No	No	Yes	No	Yes	No
Davis et al., 1982	(a)	Computer simulation	Yes	No	No	No	No	No	No	No	Yes	No
Coldwell, 1983	(a)	Empirical: statistical processing of radar data	Yes	No	No	No	No	Yes	No	No	Yes	No
Zhu et al., 2001	(a)	Expert's knowledge / neural networks	Yes	No	Yes	Yes	No	No	Yes	No	Yes	No
Pietrzykowski, 2008	(a)	Expert's knowledge / fuzzy neural networks	Yes	Yes	Yes	N/A	N/A	No	Yes	Yes	N/A	No
Pietrzykowski and Uriasz, 2009	(a)	Expert's knowledge / fuzzy neural networks	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	No
N. Wang, 2010 & N. Wang, 2013	(a)	Safety analysis	Yes	Yes	Yes	N/A	N/A	No	Yes (2013)	Yes (2013)	No	Yes (2013)
Hansen et al., 2013	(c)	Empirical: statistical processing of AIS data	Yes	No	No	N/A	N/A	No	No	No	N/A	No
Rawson et al., 2014	(d)	Safety analysis local traffic	No (ship type used instead)	Yes	No (ship type used instead)	N/A	N/A	No	No	No	N/A	No
Y. Wang and Chin, 2016	(d)	Empirical: statistical processing of data	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No
Liu et al., 2016	(a)	Analytical safety of local traffic	Yes	Yes	No	No	No	No	No	Yes	N/A	No
Dinh and Im, 2016	(b)	Expert's knowledge / analytical	No	Yes (for action area only)	No (target's manoeuvrability)	Yes	Yes (for action area only)	Yes	No	No	Yes	No
Porathe, 2020b	(d)	Expert's knowledge	Yes	Yes	No	No	No	No	No	No	No	Yes

B
Relevant parameters

This appendix shows the results of the normalised parameters per situation. For every situation there are two different graphs and a corresponding table. The first section aims to explain the meaning and relevance of each of those three. It also further elaborates the chosen normalisation and trend line equations.

B.1. Explanation of figures

This paragraph aims to explain each of the figures shown in this appendix. For every situation (combination of encounter type and direction around a vessel) and location, there are two figures and a table.

Figure 1: Minimum distances plotted to parameters
The first figure shows the minimum distances per ship-ship encounter. These distances are plotted to the chosen parameters (OS_{length}, OS_{width}, OS_{SOG}, $L_{combined}$, $B_{combined}$, $SOG_{relative}$). Vessels tend to keep more distance than strictly necessary, as that is always safer. Therefore the area of interest lies in the minima of the minima, indicated by the yellow lines. Every parameter is divided up into bins and the minimum per bins is determined. These bins differ in size, as the parameters also have different ranges:

- Length parameters: bin-size = 5m
- Width parameters: bin-size = 1m
- SOG parameters: bin-size = 0.5m/s

The minima are plotted and connected by the yellow dashed-dots line . The relation between the ship domain and the parameter can now be found by fitting a line over the dashed yellow line.

Figure 2: Minimum distances plotted to normalised parameters
The second figure contains three different plots and aims to determine the difference in relevance between the six parameters. In some cases (for example: sector Breeddiep, head-on encounter, fore), there are multiple parameters that seem to have a strong influence on the size of the ship domain. The parameters are normalised and subsequently plotted to the minimum distances. As the parameters must be compared to each other and they are normalised, all of them are plotted together in the first plot. The normalisation was tested with two different approaches, Equation (B.1) and Equation (B.2). The first equation ranges the parameters from 0 to 1, while the second equation ranges the parameters in a distribution around zero. However, as the parameters each had their own distribution, any sort of comparing between them became very difficult as visible in Figure B.1

$$x_{normalised} = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{B.1}$$

$$x_{normalised} = \frac{x - x_{average}}{x_{STD}} \tag{B.2}$$

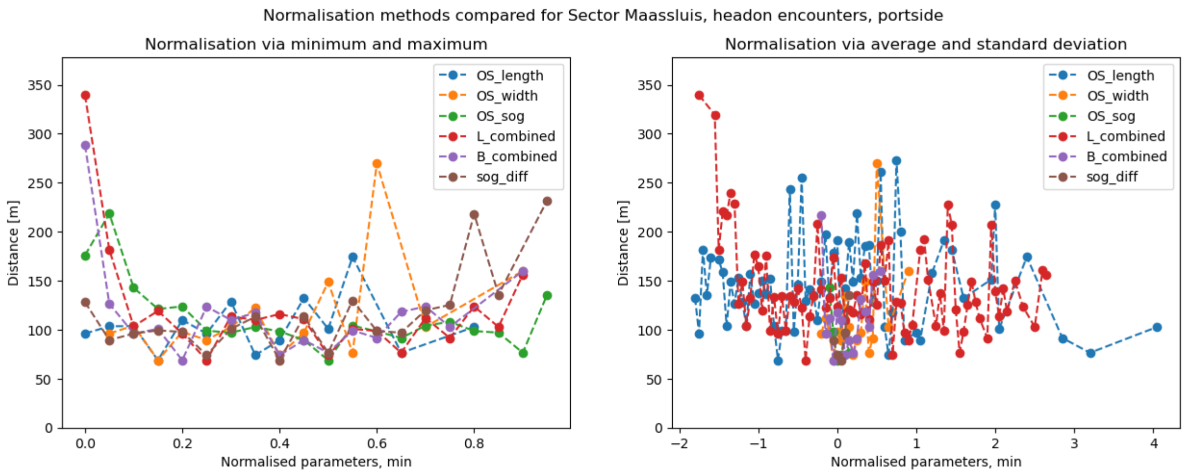

Figure B.1: Comparison for normalisation methods for sector Maassluis, head-on encounters, port-side

Again, the interest lies in the minima of the minima and the same method is applied by dividing them up into bins and determining the minimum distance. The bins for this step are equal for all parameters and have size 0.05. The second plot shows the familiar dashed-dots lines.

The third plot shows the line that is fitted through the dashed-dots line. Via the curve-fit function the equation is determined based on a simplified quadratic formula; Equation (B.5). Other approximations were tried, but did not give the same results, as visible in Figure B.2. It shows the dashed-dots lines and consequently the trend line fits for each of the equations presented below. The first trend line below is also shown in the first frame of Figure B.2.

$$D_{min} = a \cdot x + b \quad (B.3)$$

$$D_{min} = a \cdot x^2 + b \cdot x + c \quad (B.4)$$

$$D_{min} = a \cdot x^2 + b \quad (B.5)$$

The linear formula (Equation (B.3)) did not approach the right fit at all. And while the full quadratic formula (Equation (B.4)) did approach the result, for the analysis it was much more convenient for the parameter to be influenced by only one variable. The final choice is made for Equation (B.5).

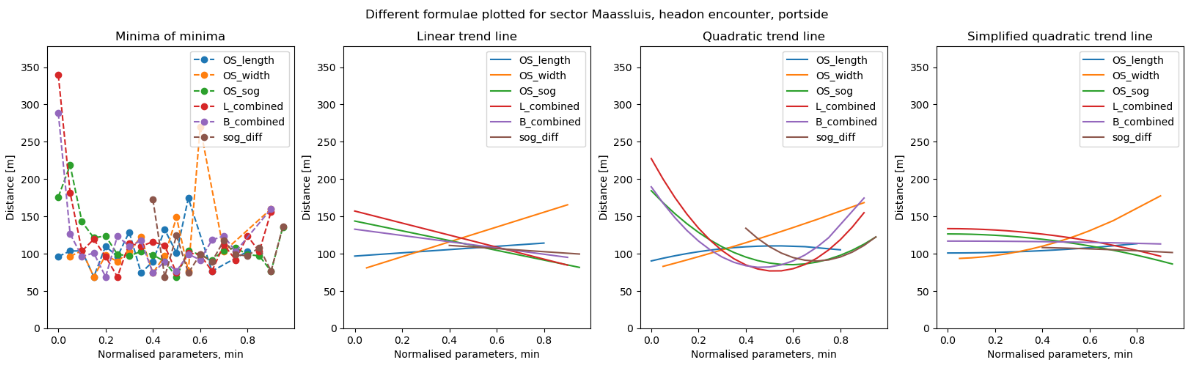

Figure B.2: Approximation formulae in comparison for sector Maassluis, head-on encounters, port-side

Table 1: Normalised trendline variables

And then finally, the table shows the values for the variables for the normalised parameters as well as the RMSE. The value for a_{norm} determines the influence of the parameter, b_{norm} shows the minimum distance at all times and the RMSE shows the quality of the fit. Ideally, the value for a is high, the value for b is average and the value for RMSE is low.

B.2. Head-on encounters, port-side

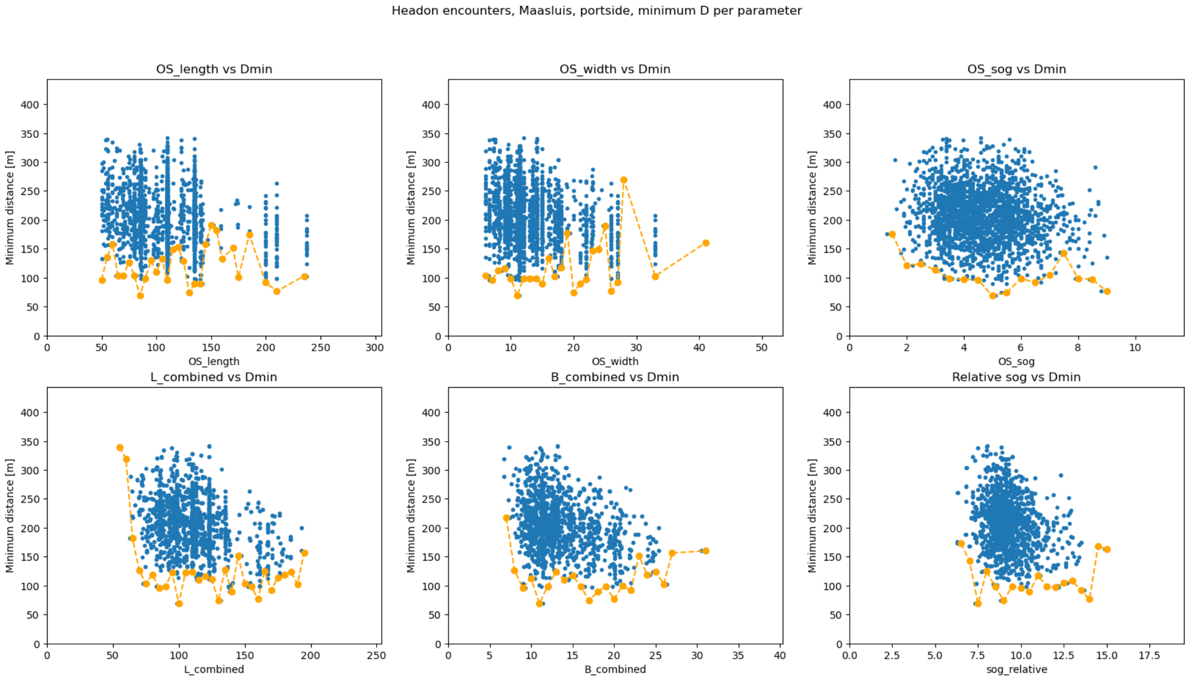

Figure B.3: Sector Maassluis, parameters plotted to minimum distance

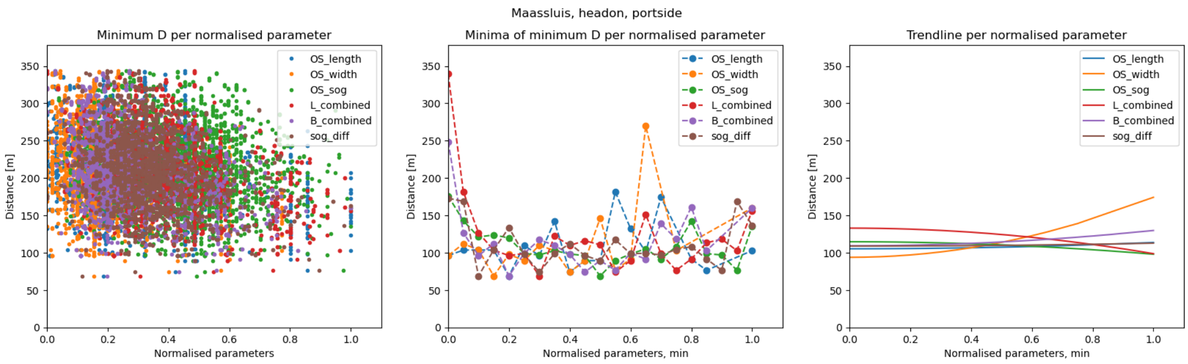

Figure B.4: Sector Maassluis, normalised parameters plotted to minimum distance

Table B.1: Sector Maassluis, variables normalised trend lines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	RMSE$_{norm}$
Maassluis Head-on Port-side	OS_length	8.406985665468627	105.28780168684179	30.28660066119275
	OS_width	80.3711586897567	93.80280000948015	41.99639015359919
	OS_sog	-16.728929971930572	114.70254884788586	23.565586577800584
	L_combined	-34.217328380415736	132.94294745463904	54.572362390419514
	B_combined	20.473875844522222	109.2855390292672	39.70656361406037
	sog_diff	3.914541991068795	108.86768921140214	29.260759392613227

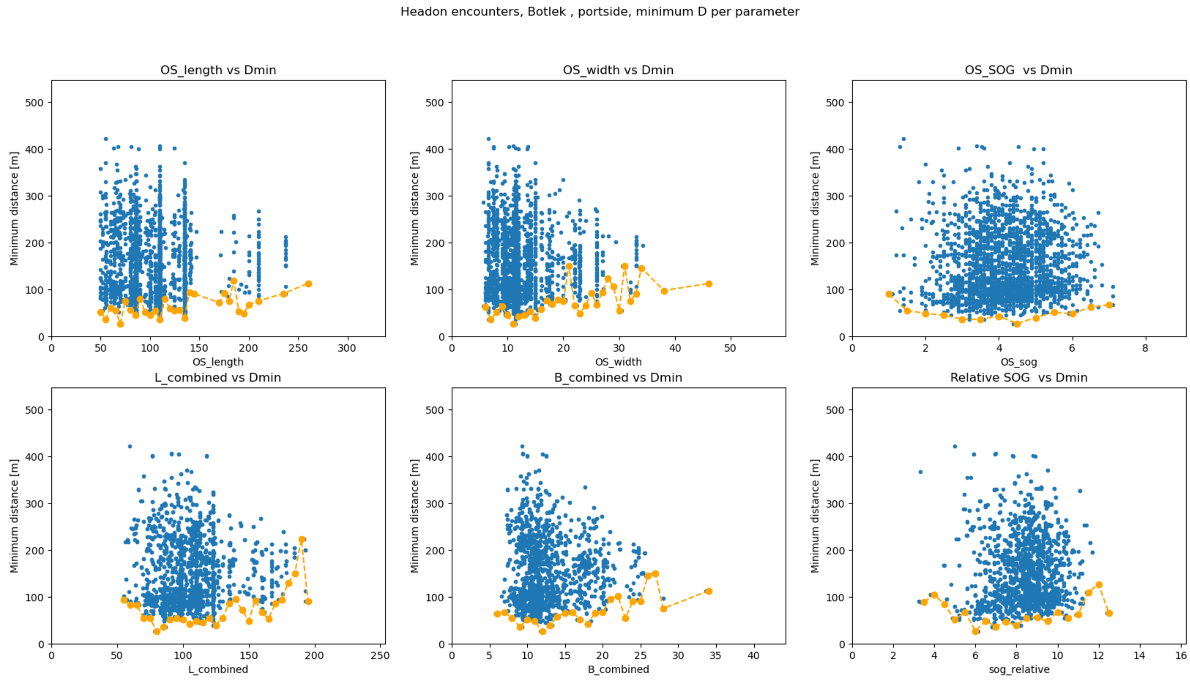

Figure B.5: Sector Botlek, parameters plotted to minimum distance

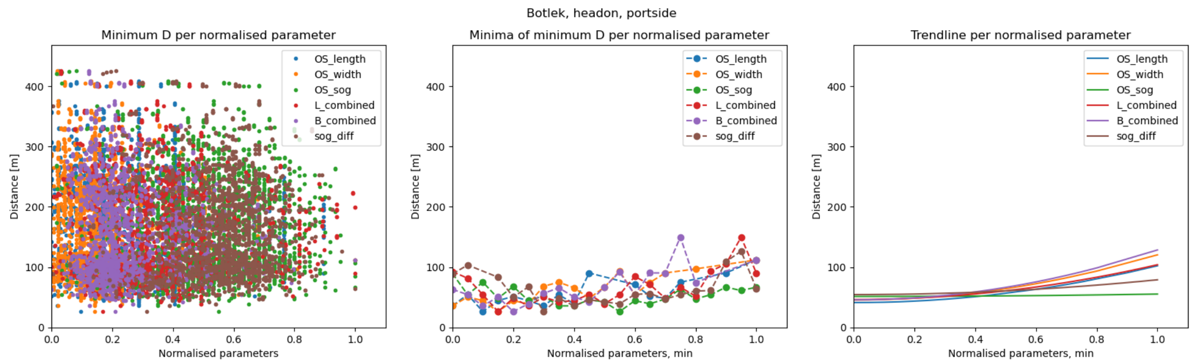

Figure B.6: Sector Botlek, normalised parameters plotted to minimum distance

Table B.2: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	$\mathbf{a}_{norm}$	$\mathbf{b}_{norm}$	$\mathbf{RMSE}_{norm}$
Botlek Head-on Port-side	OS_length	61.06174614904891	41.13929079414266	13.796822896649454
	OS_width	74.88150478956231	45.43432891002295	12.620152166187358
	OS_sog	3.9814246356773175	51.31747103753585	14.554647112045684
	L_combined	57.731193767625236	46.190696536817555	21.817756170065095
	B_combined	82.81020769285804	45.59714102597987	19.622658630072923
	sog_diff	24.58625381928387	54.38351487389884	24.398945803718522

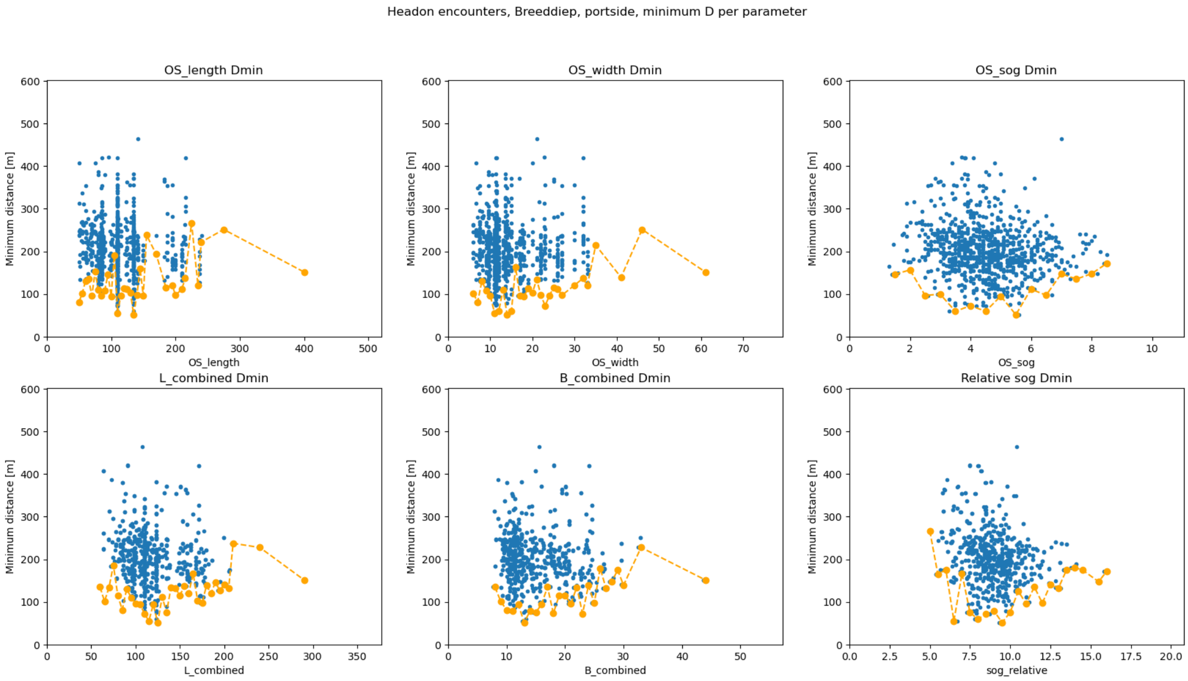

Figure B.7: Sector Breeddiep, parameters plotted to minimum distance

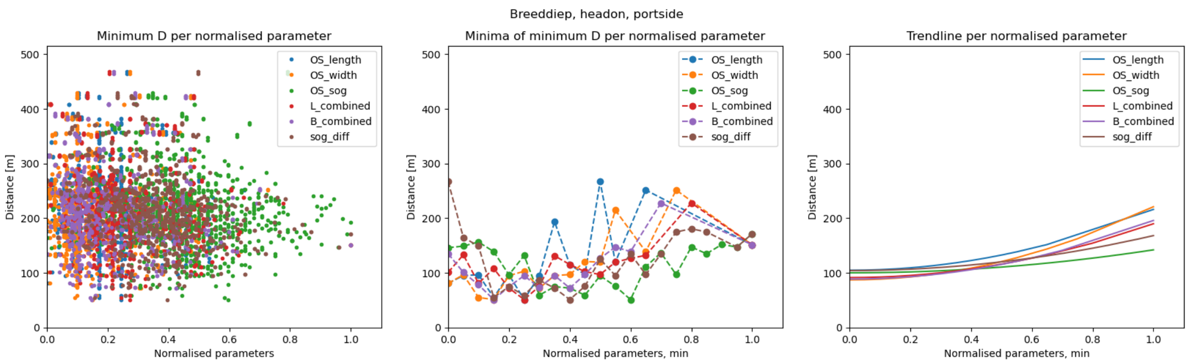

Figure B.8: Sector Breeddiep, normalised parameters plotted to minimum distance

Table B.3: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	RMSE$_{norm}$
Breeddiep Head-on Port-side	OS_length	111.27229292900917	104.70395704979589	57.85811005878061
	OS_width	133.7513000748862	87.12619705569305	40.1352152354887
	OS_sog	42.03143923224765	100.01626384409526	34.46906466800465
	L_combined	98.48540767161764	91.30245836066904	29.140316700521733
	B_combined	107.11543884492973	88.63157064292407	33.422253989971935
	sog_diff	63.98167359369688	104.12830762776994	50.65354121531738

B.3. Head-on encounters, starboard

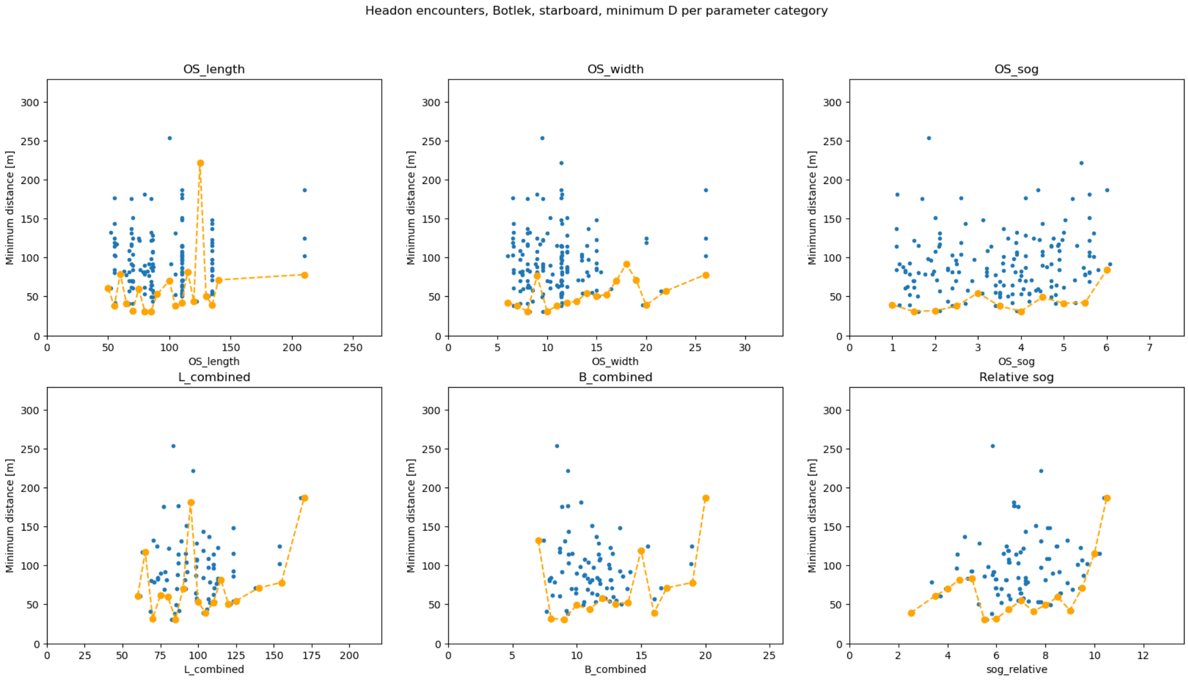

Figure B.9: Sector Botlek, parameters plotted to minimum distance

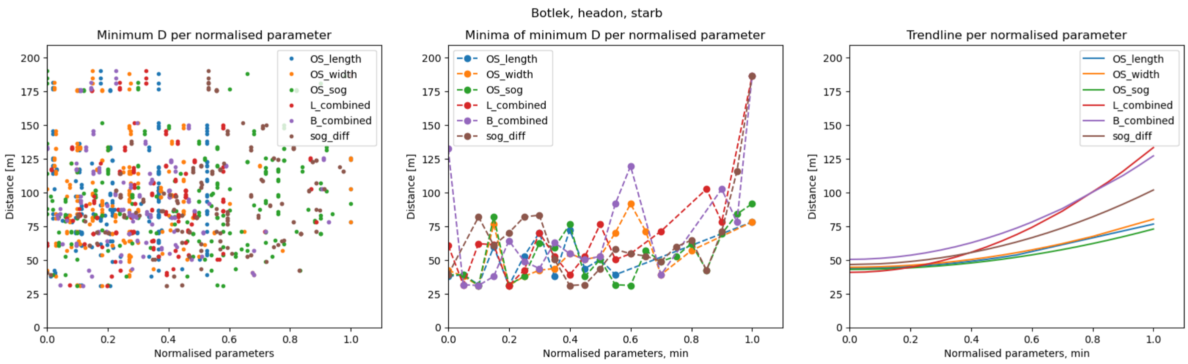

Figure B.10: Sector Botlek, normalised parameters plotted to minimum distance

Table B.4: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Botlek	OS_length	32.806444513483704	43.776794530931355	12.837984817668437
Head-on	OS_width	35.602788858438565	44.62119823765137	14.85760645107928
Starboard	OS_sog	29.95161056683149	42.97274846891142	15.931641395641028
	L_combined	92.50351528321062	40.820680295016274	21.10641096557232
	B_combined	76.76993214435693	50.417832303263644	32.93275250454045
	sog_diff	55.27037820373035	46.59869128175665	29.205247415925406

Figure B.11: Sector Breeddiep, parameters plotted to minimum distance

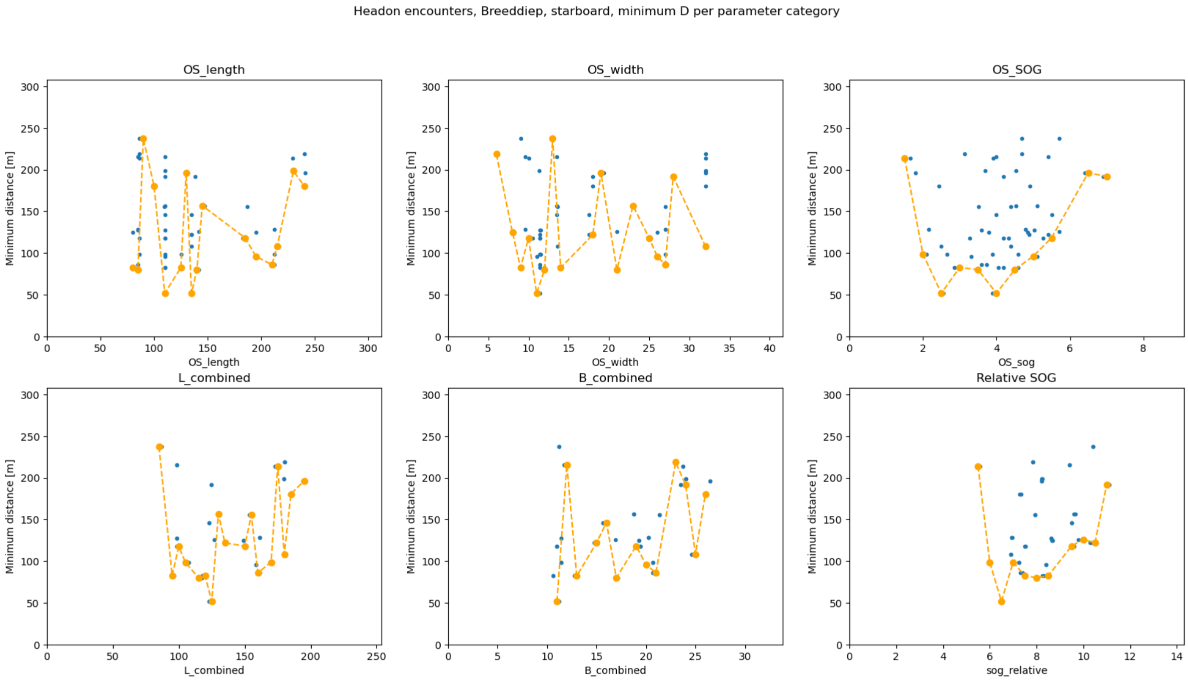

Figure B.12: Sector Breeddiep, normalised parameters plotted to minimum distance

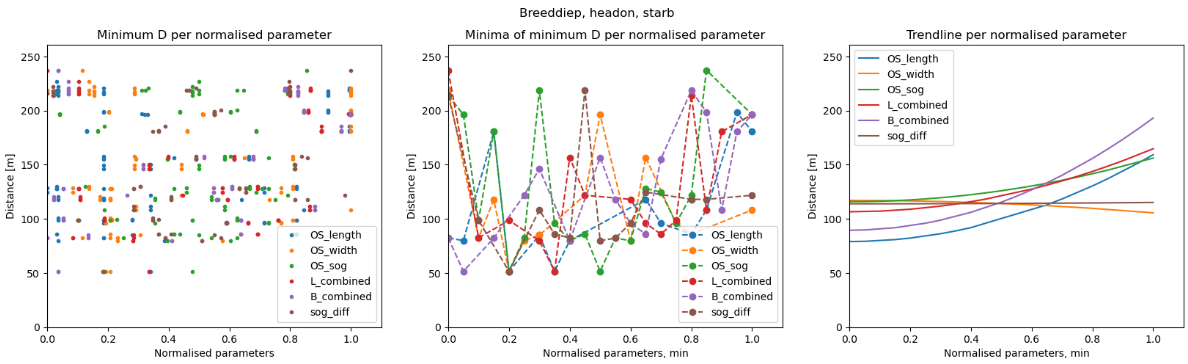

Table B.5: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	RMSE_{norm}
Breeddiep Head-on Starboard	OS_length	80.22219708897352	79.03236047568575	37.630474362230494
	OS_width	-11.477203332746086	117.04332990068889	46.97208385999793
	OS_sog	40.27476463757501	115.86550534847416	57.335387545789885
	L_combined	58.19220425109284	106.524339874789	50.343788385447425
	B_combined	103.62688755538665	89.46233929050949	35.100228732775754
	sog_diff	1.2296039503696177	113.90395144239532	45.99649215875231

B.4. Head-on encounters, fore

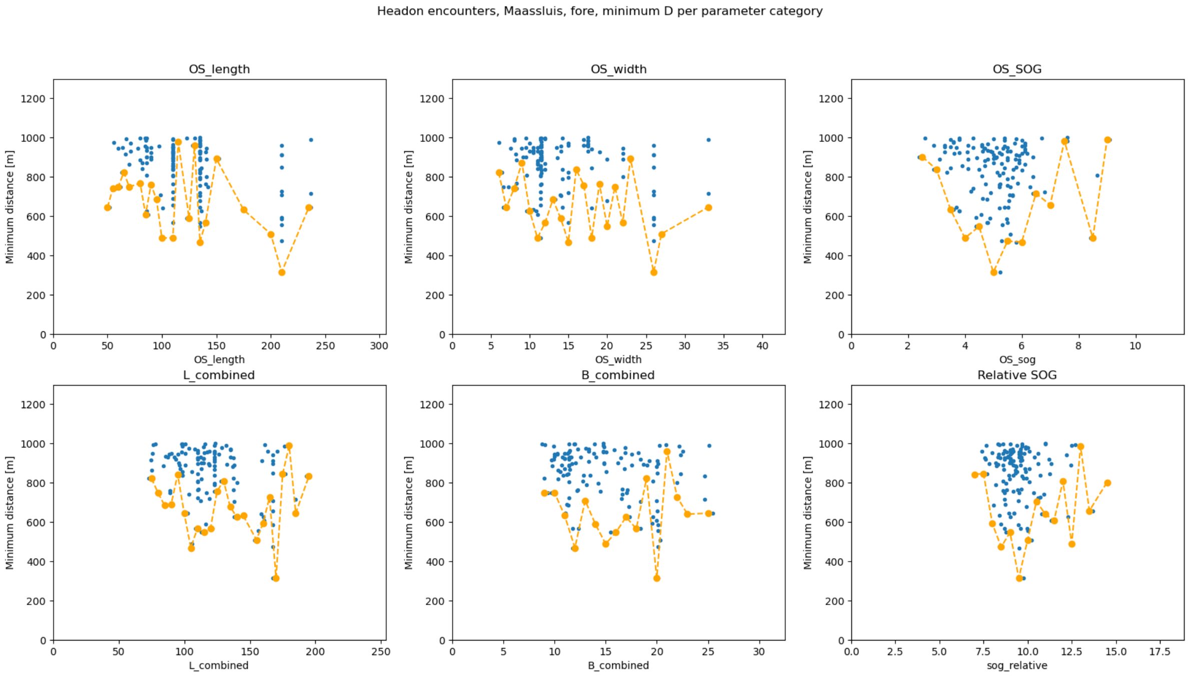

Figure B.13: Sector Maassluis, parameters plotted to minimum distance

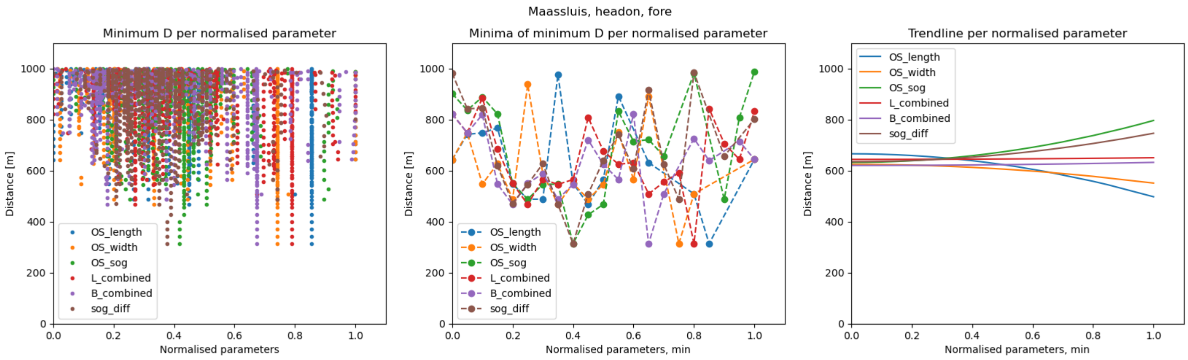

Figure B.14: Sector Maassluis, normalised parameters plotted to minimum distance

Table B.6: Sector Maassluis, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Maassluis Head-on Fore	OS_length	-168.40249407402402	665.7939385206691	157.1783981781031
	OS_width	-73.33537817450292	624.3246031073979	150.22121588473496
	OS_sog	164.2899364738207	632.0430201521954	189.96942262996
	L_combined	6.6264174867835095	643.8118578892683	139.66774500798488
	B_combined	12.027843196357196	620.118253901825	132.78654179634145
	sog_diff	111.35979237845561	634.870342500627	179.6156916910436

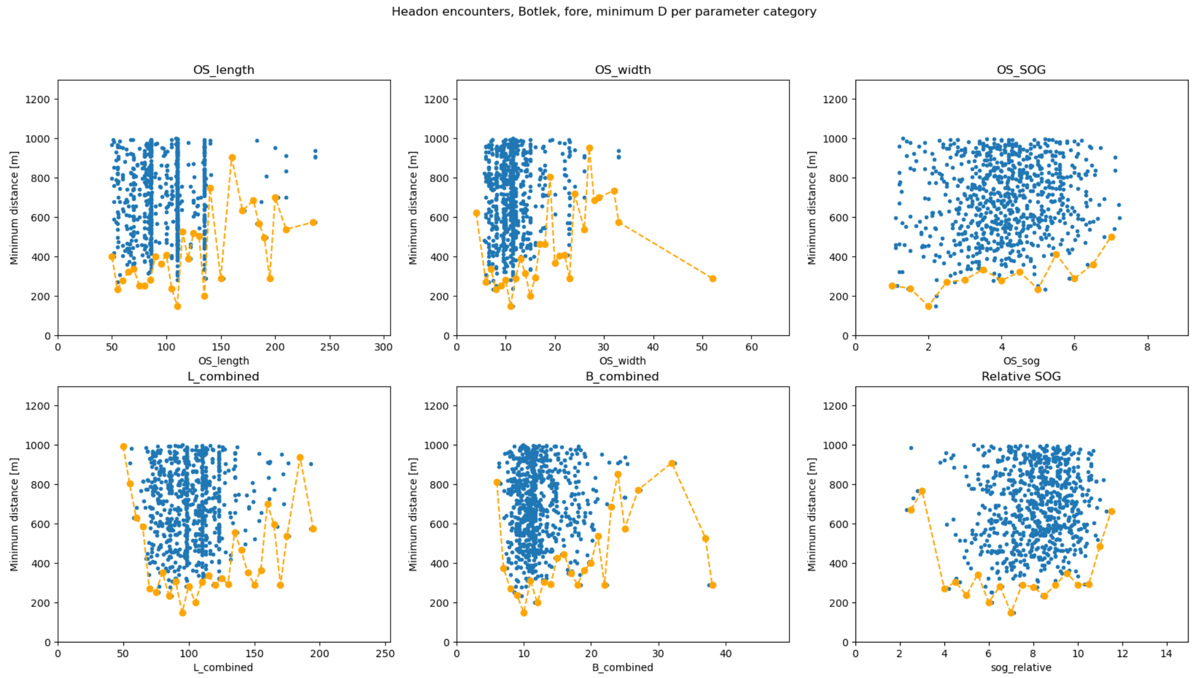

Figure B.15: Sector Botlek, parameters plotted to minimum distance

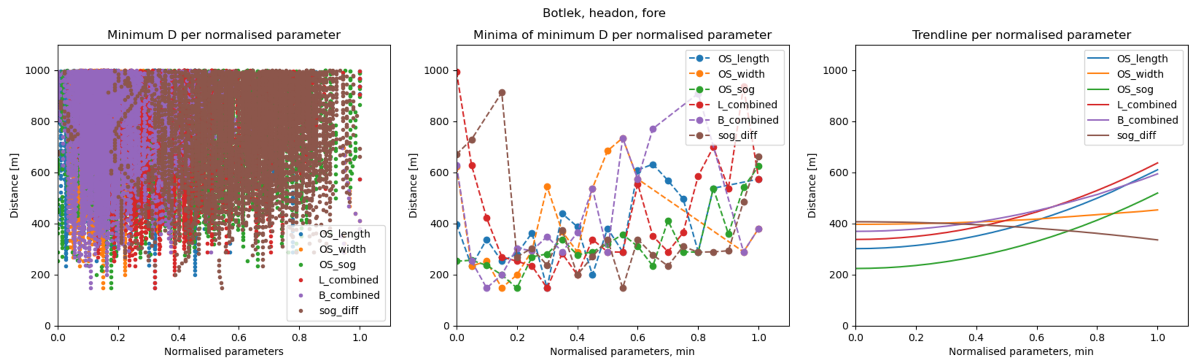

Figure B.16: Sector Botlek, normalised parameters plotted to minimum distance

Table B.7: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	$\mathbf{a}_{norm}$	$\mathbf{b}_{norm}$	$\mathbf{RMSE}_{norm}$
Botlek Head-on Fore	OS_length	308.63124161616815	301.2857013260266	112.82381580646977
	OS_width	56.362160728626485	396.57149991657536	182.23913621803126
	OS_sog	295.3528717559035	223.50401544375765	67.95743631716336
	L_combined	299.5210347421728	337.18302049527165	207.38897599253977
	B_combined	225.09335211712764	368.93165885310964	203.61335817455435
	sog_diff	-71.04691637876978	406.4835454229256	196.5648484090371

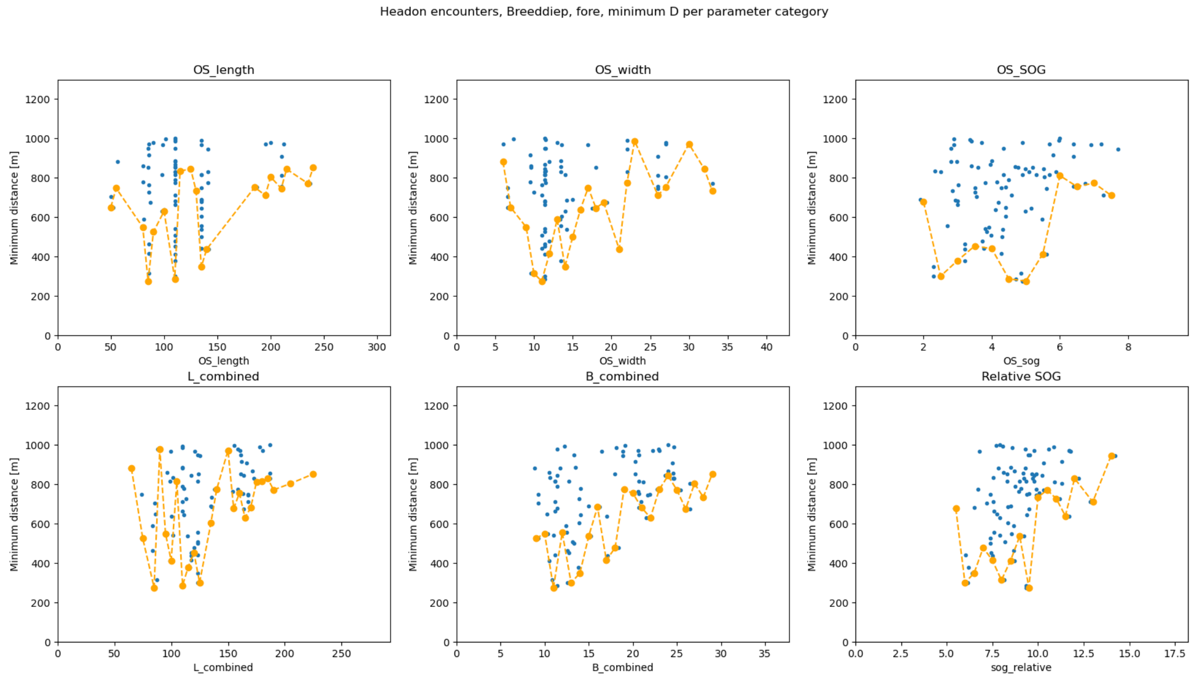

Figure B.17: Sector Breeddiep, parameters plotted to minimum distance

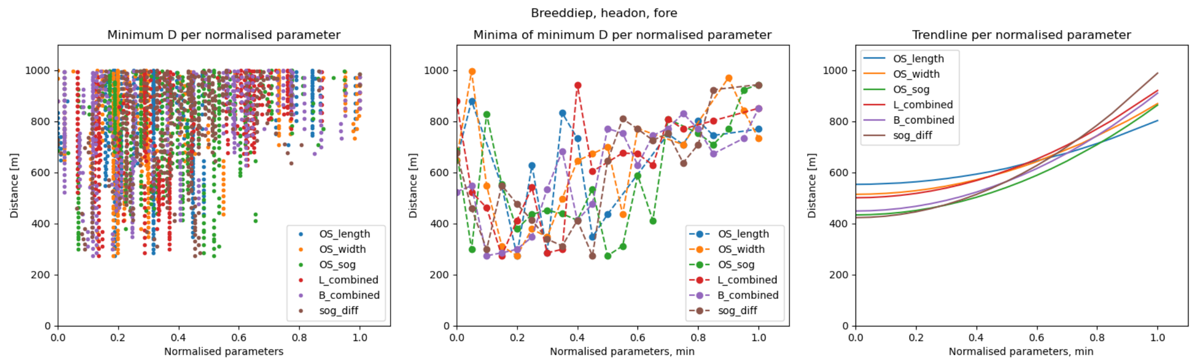

Figure B.18: Sector Breeddiep, normalised parameters plotted to minimum distance

Table B.8: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	a$_{norm}$	b$_{norm}$	RMSE$_{norm}$
Breeddiep Head-on Fore	OS_length	249.75533431848362	552.8435124283151	179.26516752695707
	OS_width	355.0506800313909	513.9529865694467	179.60067940120814
	OS_sog	429.9422826464077	433.2933853560125	156.09650766177458
	L_combined	419.7609840594001	500.5572266626597	172.33238918362423
	B_combined	461.29408256584566	448.5043429656799	124.87217436100042
	sog_diff	565.5612230555306	422.6854448385836	132.88664259523608

B.5. Overtake encounters, port-side

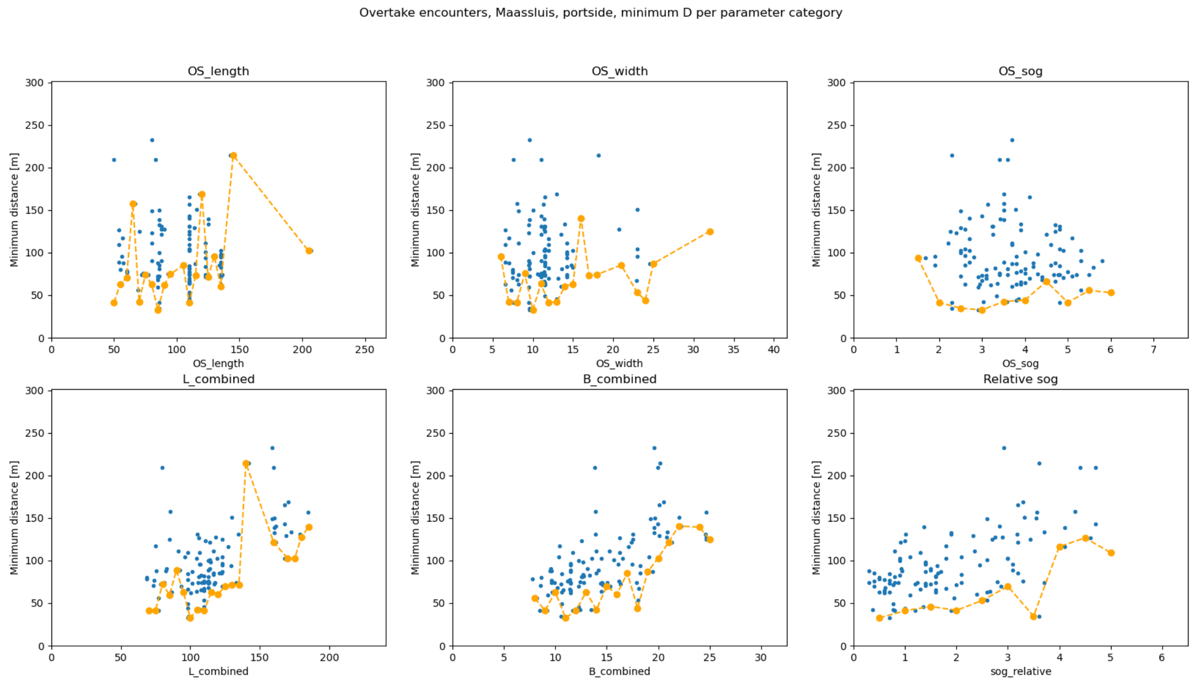

Figure B.19: Sector Maassluis, parameters plotted to minimum distance

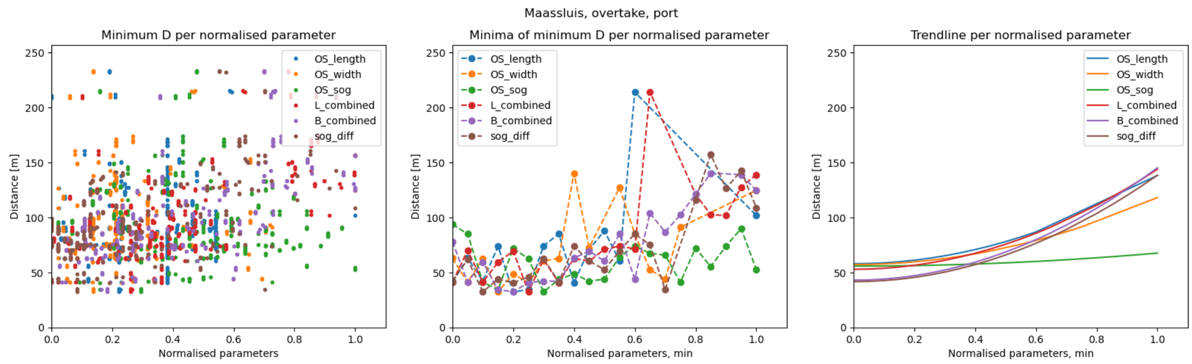

Figure B.20: Sector Maassluis, normalised parameters plotted to minimum distance

Table B.9: Sector Maassluis, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	RMSE$_{norm}$
Maassluis	OS_length	80.25172764645437	57.92456106518149	39.484319466078944
Overtake	OS_width	60.89455371839585	57.15967480438917	27.895992100205248
Port-side	OS_sog	11.825877084025121	55.74925886517229	17.376038501998597
	L_combined	91.01784926847324	52.85374850106208	31.240067831656418
	B_combined	102.22172824600199	42.96944256370182	16.11322411406239
	sog_diff	96.84453260506172	41.6046862428776	19.699117580519346

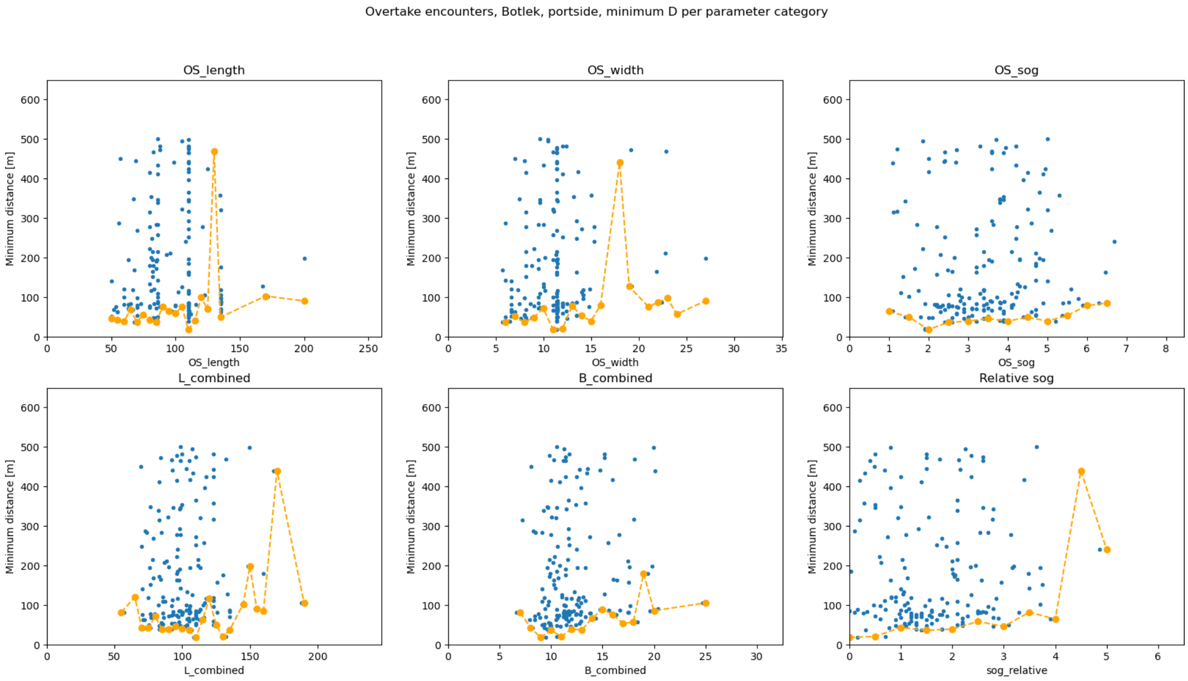

Figure B.21: Sector Botlek, parameters plotted to minimum distance

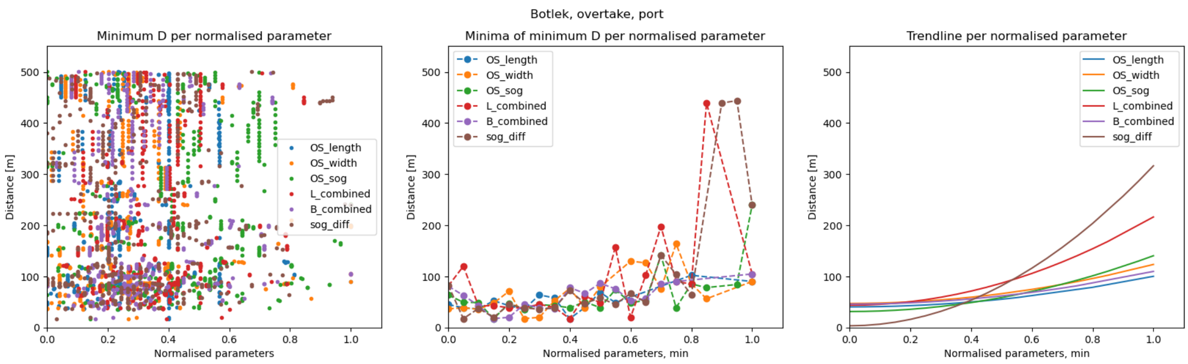

Figure B.22: Sector Botlek, normalised parameters plotted to minimum distance

Table B.10: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Botlek Overtake Port-side	OS_length	59.85733659787174	40.34484372667184	14.225015113049857
	OS_width	76.30504174308989	47.082521555625846	31.862483900408826
	OS_sog	109.20539746213828	31.25150662878436	33.94477049977707
	L_combined	172.70703224170956	43.5825558162411	80.27126337140821
	B_combined	64.01911603255988	45.7618047262115	18.313995831244235
	sog_diff	313.0535185250168	3.32714793607029	74.95603470420889

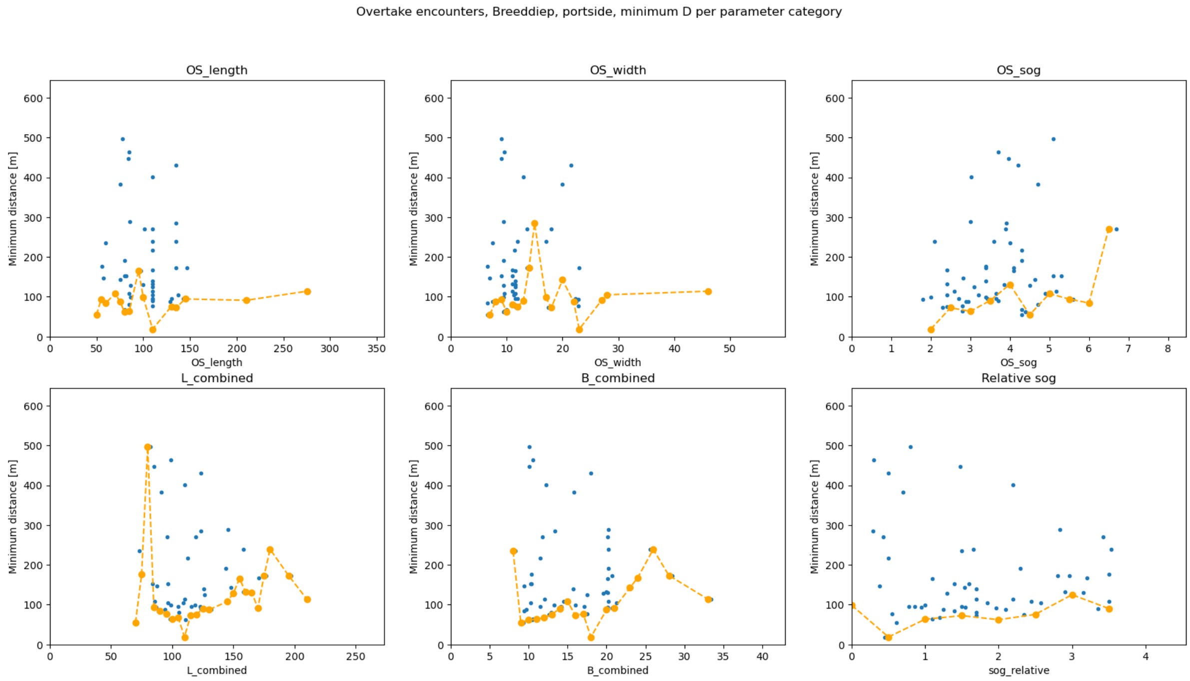

Figure B.23: Sector Breeddiep, parameters plotted to minimum distance

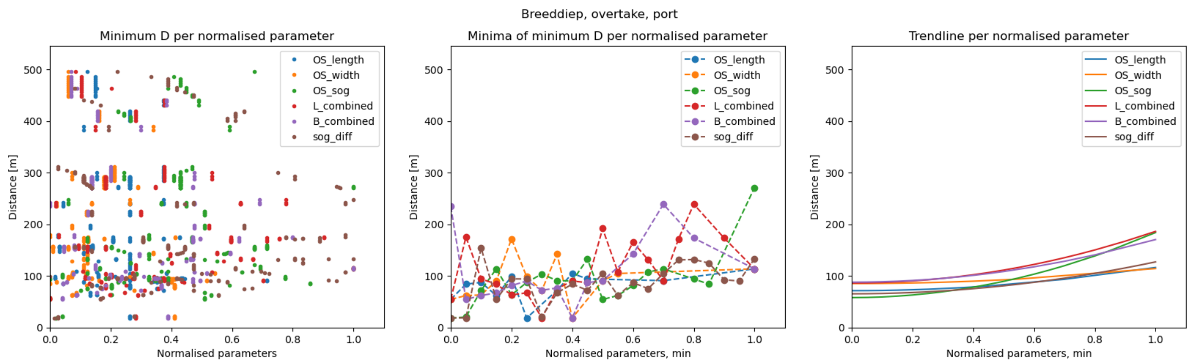

Figure B.24: Sector Breeddiep, normalised parameters plotted to minimum distance

Table B.11: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Breeddiep Overtake Port-side	OS_length	44.90584916365129	71.35209213614272	22.248295633759682
	OS_width	29.072744263031982	85.1039962411683	38.45679085996594
	OS_sog	125.91240858967188	57.933443474448	38.868978757371316
	L_combined	99.88031026780344	86.20649518384081	46.85855827724739
	B_combined	82.4938680695039	87.80999141265598	57.45800394004987
	sog_diff	61.7382361483392	65.31405171378279	31.633440287208217

B.6. Overtake encounters, starboard

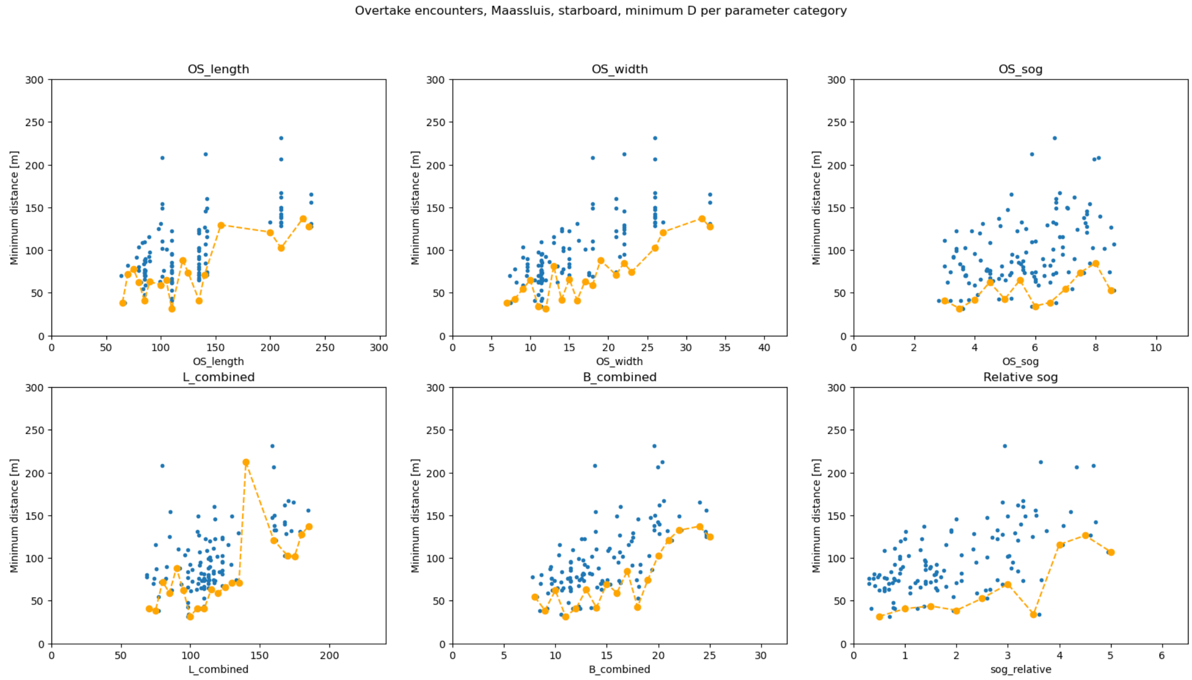

Figure B.25: Sector Maassluis, parameters plotted to minimum distance

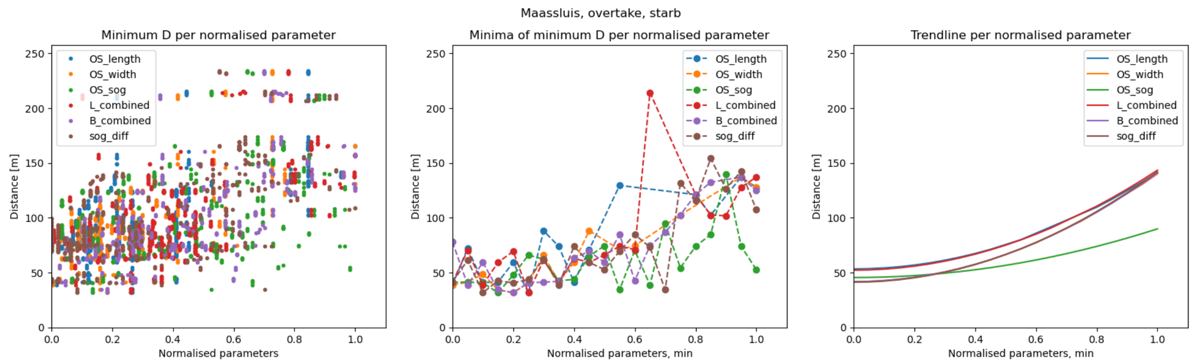

Figure B.26: Sector Maassluis, normalised parameters plotted to minimum distance

Table B.12: Sector Maassluis, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Maassluis Overtake Starboard	OS_length	87.8120227934781	53.35082710179682	20.289047405254124
	OS_width	98.3617512989841	41.68305364972926	10.692734889907605
	OS_sog	44.38521522599965	45.45835054104811	20.26199505944889
	L_combined	91.1412614671044	52.18742892923746	31.433935490824652
	B_combined	98.85619405804077	41.728629353281704	15.380405423310865
	sog_diff	100.58173863983829	41.21175465116535	20.5584892797264

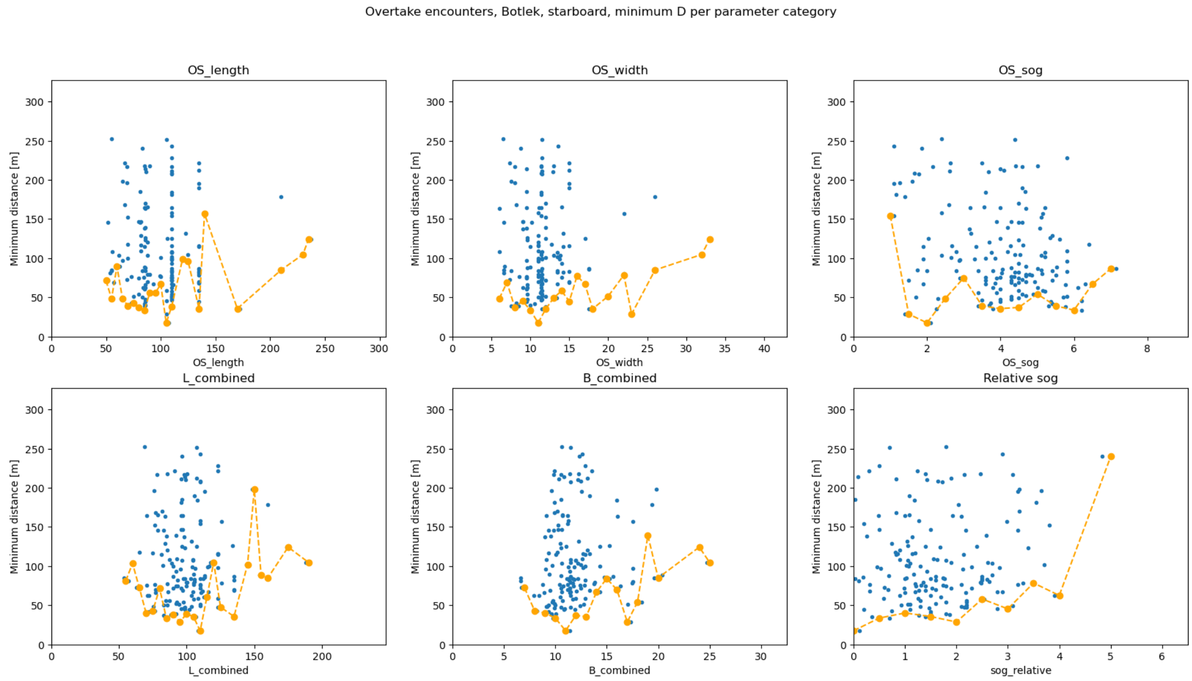

Figure B.27: Sector Botlek, parameters plotted to minimum distance

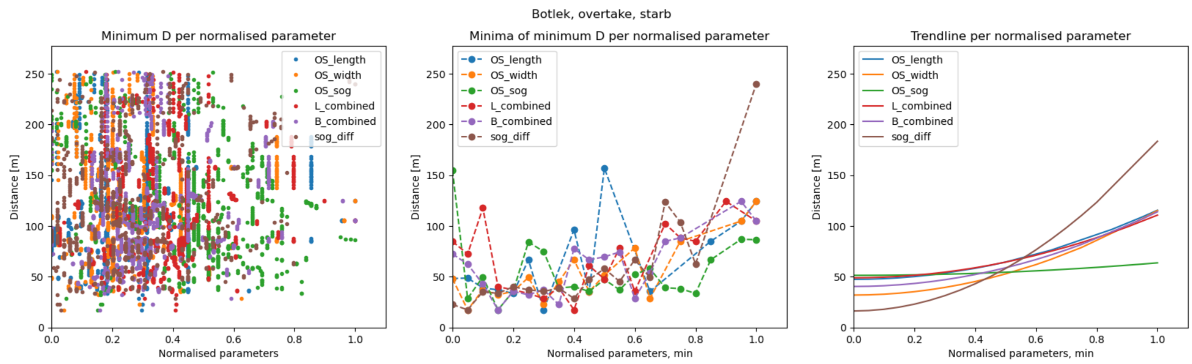

Figure B.28: Sector Botlek, normalised parameters plotted to minimum distance

Table B.13: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	RMSE$_{norm}$
Botlek Overtake Starboard	OS_length	68.08481191859603	47.41415987986218	32.25976610243515
	OS_width	83.24205585114736	31.94586663461378	14.728507214459794
	OS_sog	12.291766731322136	51.35717013843916	29.82314849725938
	L_combined	61.685149929017776	48.94814158044172	26.593286064040335
	B_combined	73.54714970688215	40.40609815272505	18.935372338308976
	sog_diff	167.10441133440335	16.27845708810735	24.403685621368382

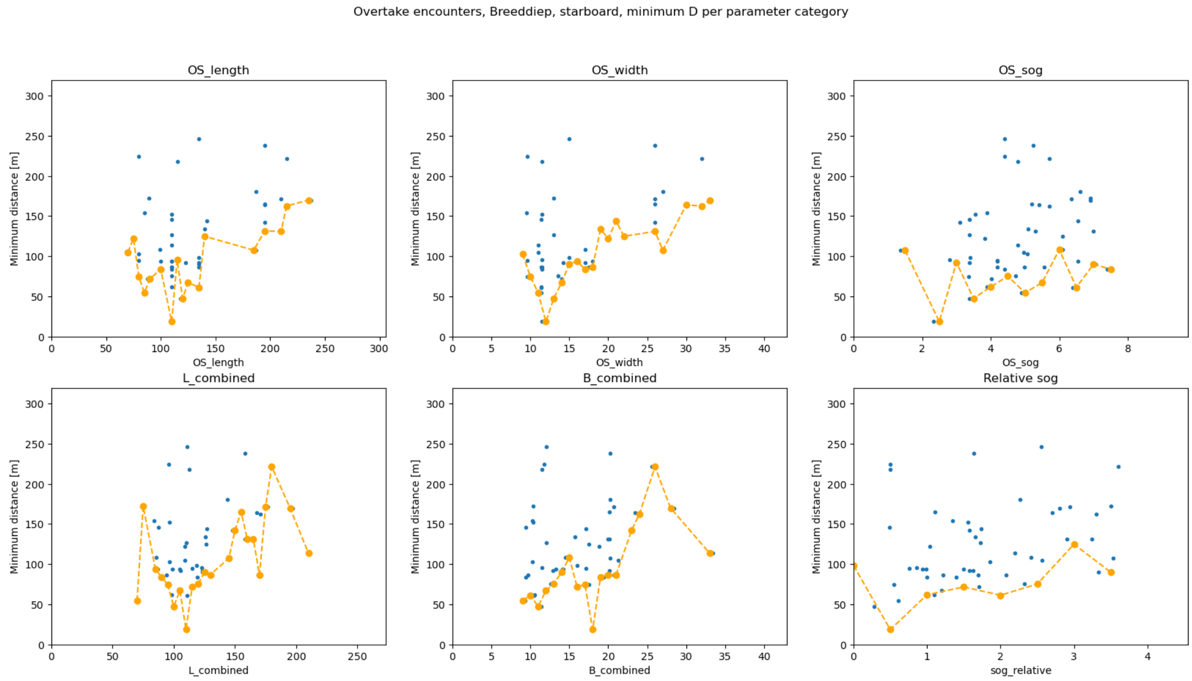

Figure B.29: Sector Breeddiep, parameters plotted to minimum distance

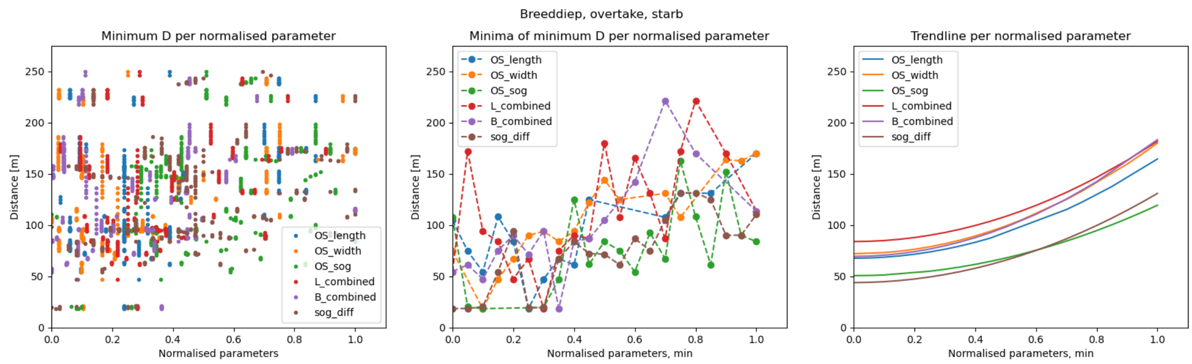

Figure B.30: Sector Breeddiep, normalised parameters plotted to minimum distance

Table B.14: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	$\mathbf{a}_{norm}$	$\mathbf{b}_{norm}$	$\mathbf{RMSE}_{norm}$
Breeddiep Overtake Starboard	OS_length	96.77882760793274	67.60848752961351	25.916862928930623
	OS_width	107.94569871578526	71.97202234663531	22.612280102142012
	OS_sog	68.66932004623052	50.583310355121796	35.683632720126006
	L_combined	97.84310043860235	83.83170649345892	44.68860385849309
	B_combined	113.81879200889325	69.41307361651756	37.85782168217852
	sog_diff	87.00490986690592	43.81529501846589	24.42011442760372

B.7. Overtake encounters, fore

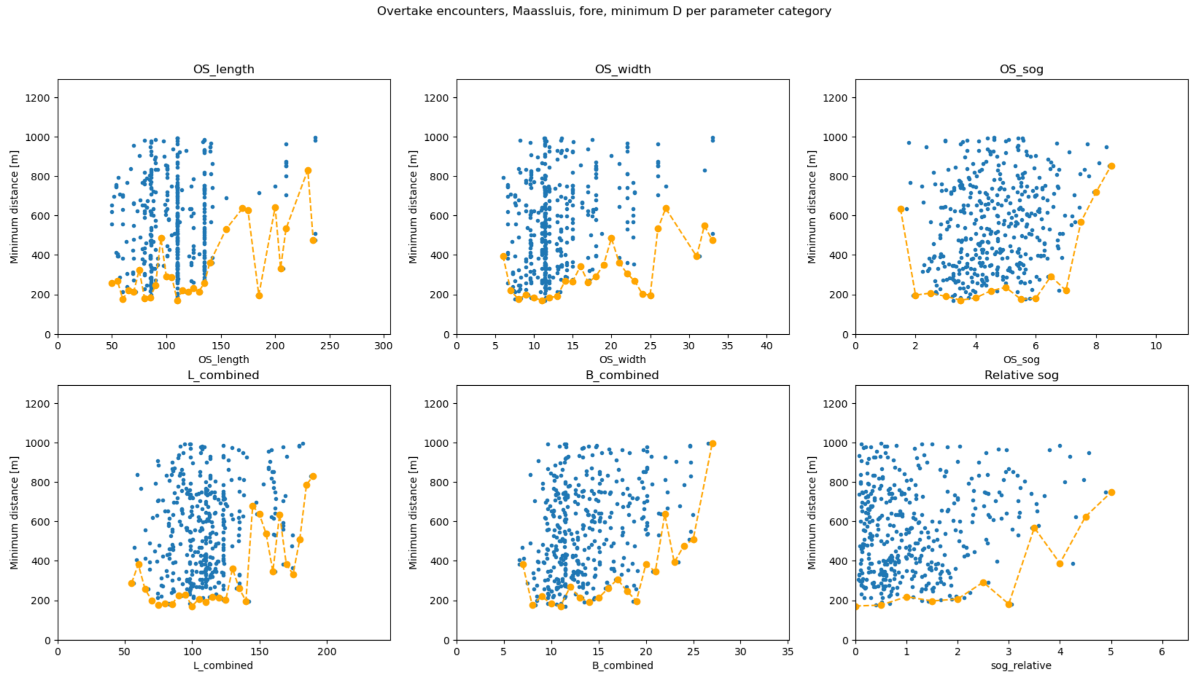

Figure B.31: Sector Maassluis, parameters plotted to minimum distance

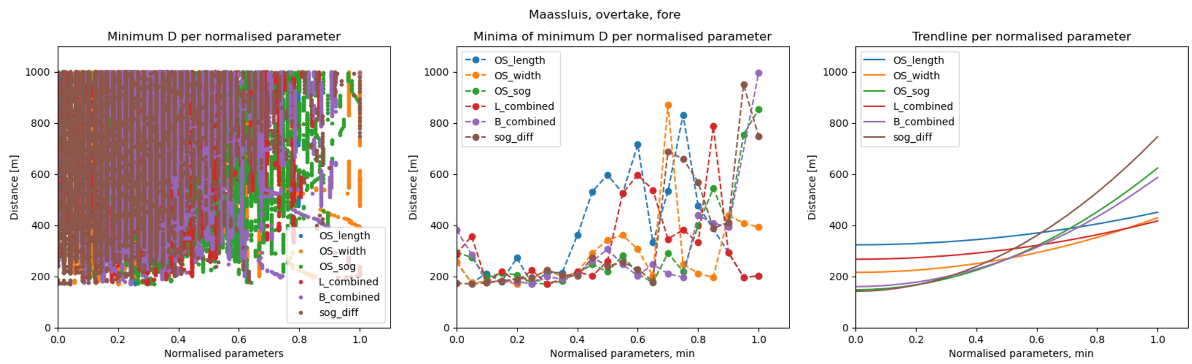

Figure B.32: Sector Maassluis, normalised parameters plotted to minimum distance

Table B.15: Sector Maassluis, variables normalised trendlines

Sector Encounter Region	Parameter	$\mathbf{a}_{norm}$	$\mathbf{b}_{norm}$	$\mathbf{RMSE}_{norm}$
Maassluis Overtake Fore	OS_length	127.39025715765607	323.4399702497914	189.2047929425933
	OS_width	213.5811551268978	215.73052416332297	138.19605170575565
	OS_sog	475.9279832877229	147.60551067240766	107.70040556360192
	L_combined	149.62371937223665	267.0508787011712	154.62369255075876
	B_combined	426.4548223142839	159.99053786336364	130.71962690982912
	sog_diff	604.0572330230088	141.82756320210535	124.88358628365742

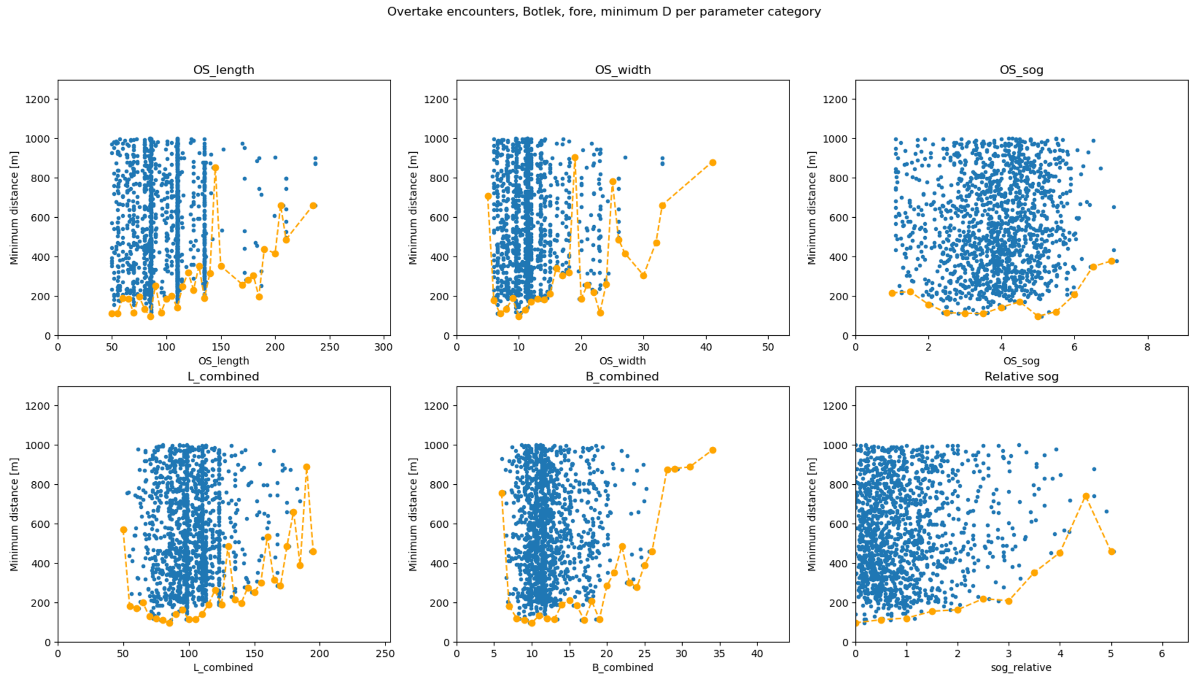

Figure B.33: Sector Botlek, parameters plotted to minimum distance

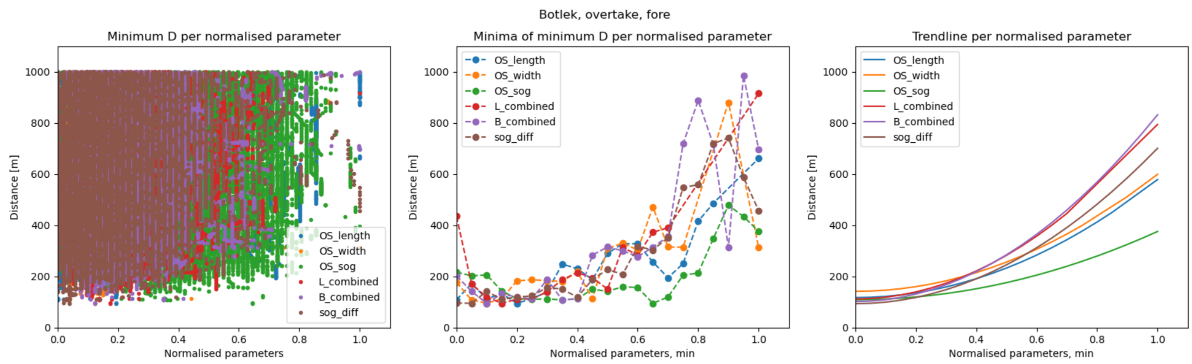

Figure B.34: Sector Botlek, normalised parameters plotted to minimum distance

Table B.16: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Botlek Overtake Fore	OS_length	461.40361519680187	117.16743771268239	62.17347953715926
	OS_width	457.42131676095494	141.53655075363525	123.25523499994151
	OS_sog	266.66207291298093	108.86176852376113	71.87215668451469
	L_combined	682.1714698181945	111.82912012246402	99.12437781746442
	B_combined	730.1320648906217	101.64045949549009	142.46198021665654
	sog_diff	607.5304846855424	93.23189067601986	86.45273315317345

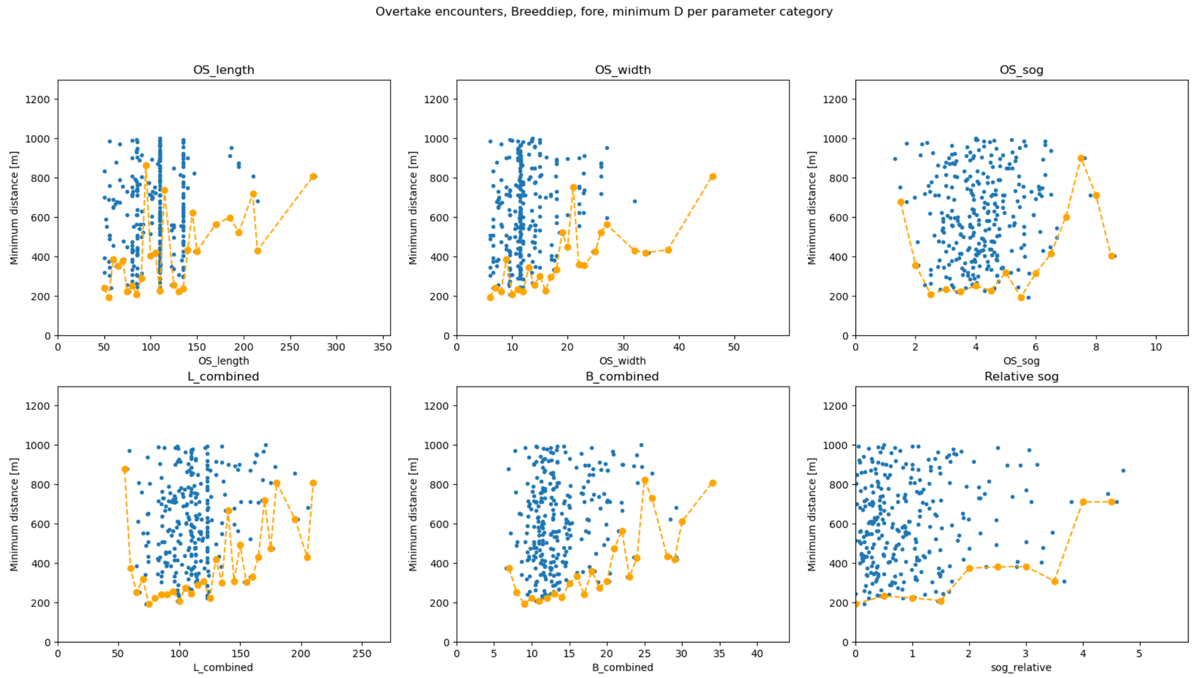

Figure B.35: Sector Breeddiep, parameters plotted to minimum distance

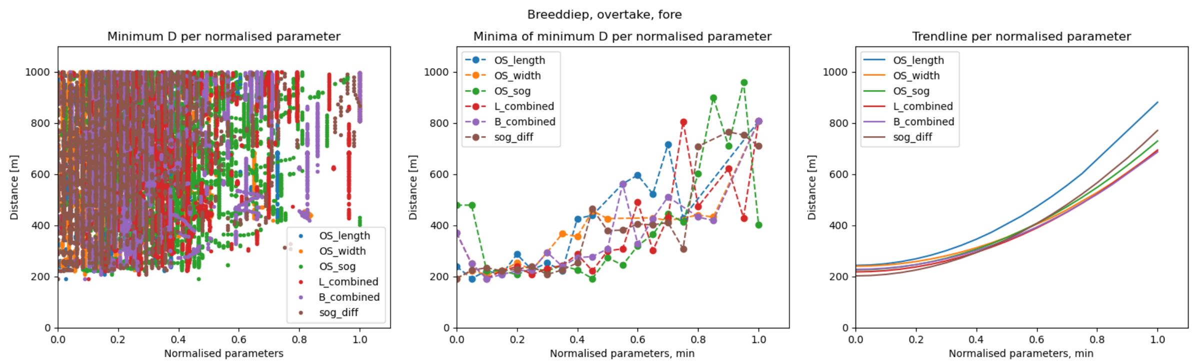

Figure B.36: Sector Breeddiep, normalised parameters plotted to minimum distance

Table B.17: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Breeddiep Overtake Fore	OS_length	637.5857257579777	243.04127836240573	88.43610390174752
	OS_width	450.16875416195626	239.82132829551833	68.8859576145043
	OS_sog	503.6364017553942	225.53277694458728	153.6957743619129
	L_combined	476.3124932954455	217.643990115811	107.74541885700089
	B_combined	458.5071706033416	227.48122193850674	81.61545681827394
	sog_diff	568.4928408459538	202.0073321467401	76.91289900661798

B.8. Overtake encounters, aft

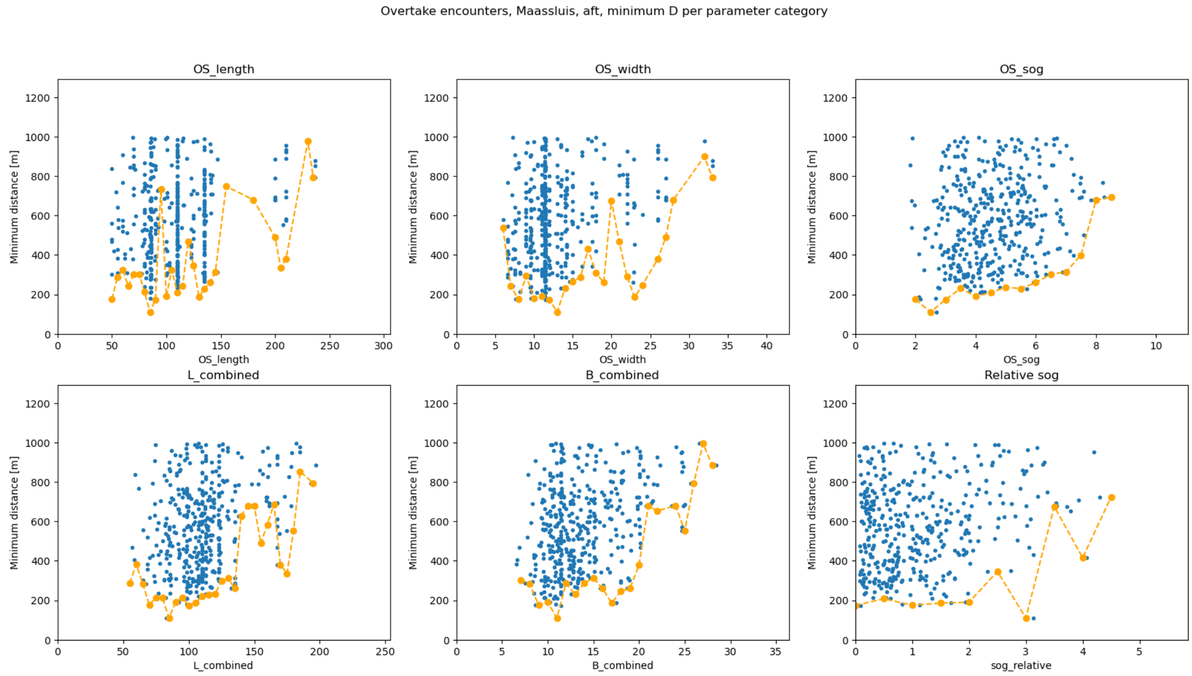

Figure B.37: Sector Maassluis, parameters plotted to minimum distance

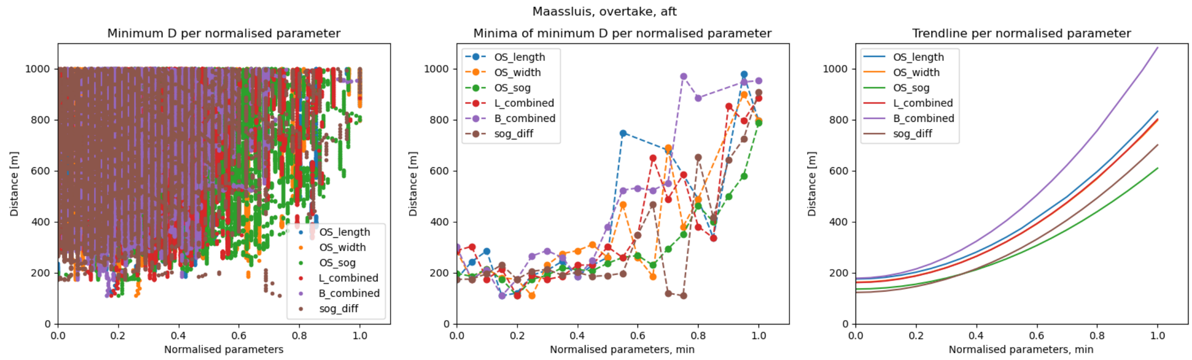

Figure B.38: Sector Maassluis, normalised parameters plotted to minimum distance

Table B.18: Sector Maassluis, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Maassluis Overtake Aft	OS_length	657.3768696150557	175.1079671402889	149.662193233456
	OS_width	634.2042244146824	162.47330361254717	108.19130280163228
	OS_sog	473.7674880322173	135.64706869537918	60.218387152830694
	L_combined	640.2605873216846	161.18662926230434	114.59541220381881
	B_combined	903.9181274161087	177.95942485391413	99.69201032509821
	sog_diff	578.1177050730537	122.46247539027735	127.72227345273068

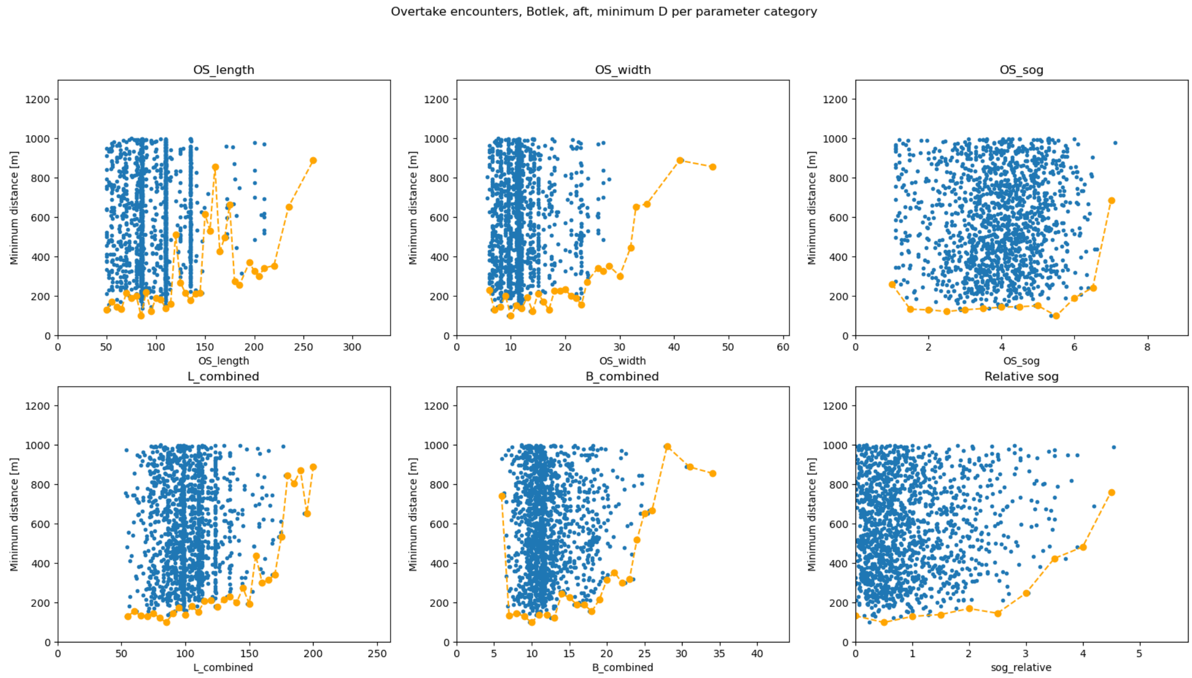

Figure B.39: Sector Botlek, parameters plotted to minimum distance

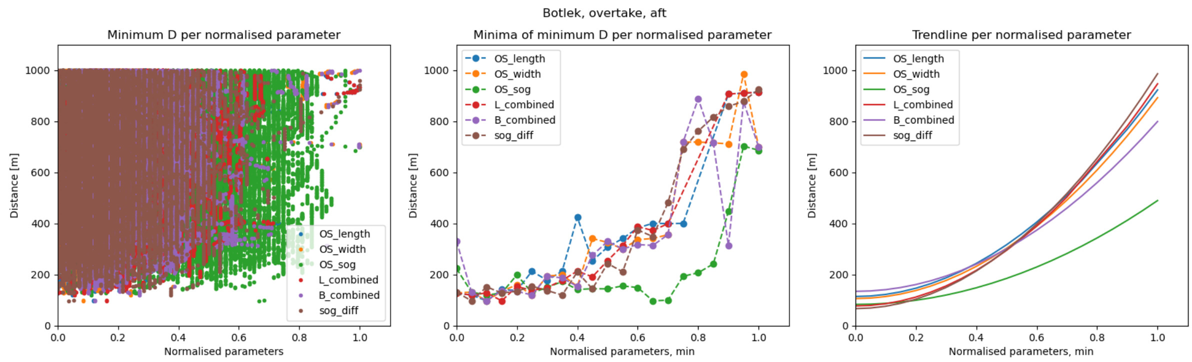

Figure B.40: Sector Botlek, normalised parameters plotted to minimum distance

Table B.19: Sector Botlek, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Botlek Overtake Aft	OS_length	808.6300545639641	113.96324356492269	74.25819389246891
	OS_width	786.4342042138488	105.81849665023312	86.6617409365906
	OS_sog	406.5127574403797	82.94291173092286	111.52754630855927
	L_combined	869.5894058911624	76.93294955679951	52.232718102251596
	B_combined	664.888609421879	134.09443461367295	138.10351631852367
	sog_diff	919.3434364417101	66.53107001256431	68.87684159075326

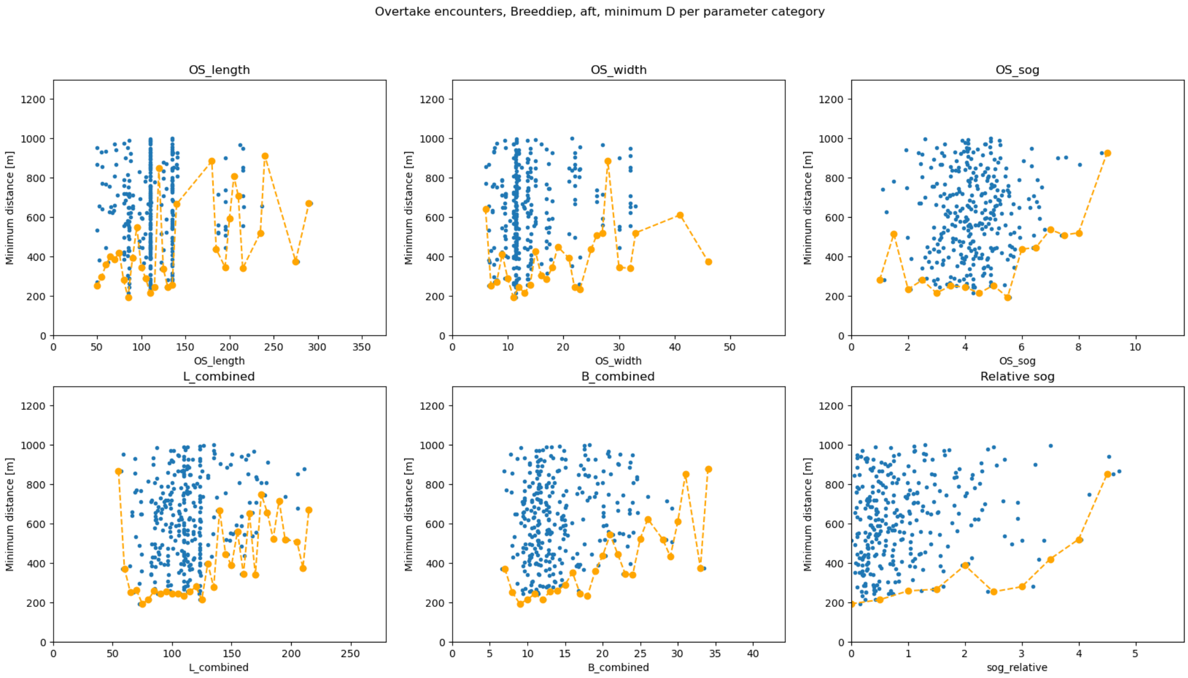

Figure B.41: Sector Breeddiep, parameters plotted to minimum distance

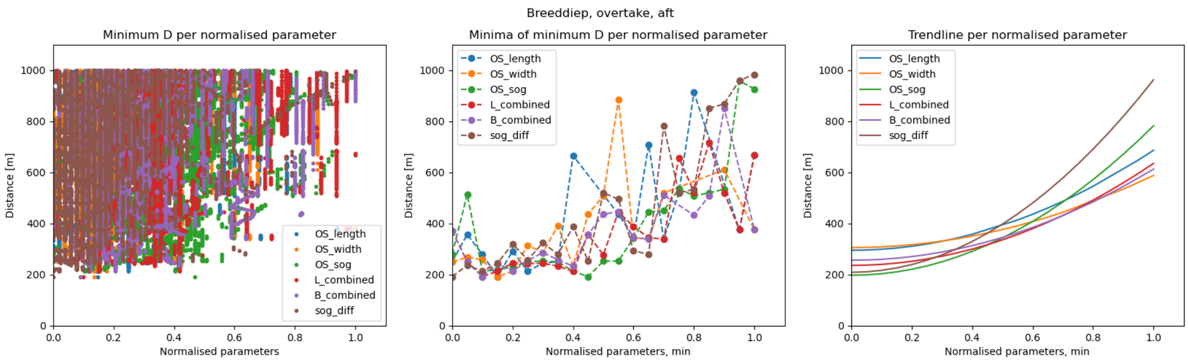

Figure B.42: Sector Breeddiep, normalised parameters plotted to minimum distance

Table B.20: Sector Breeddiep, variables normalised trendlines

Sector Encounter Region	Parameter	a_{norm}	b_{norm}	$RMSE_{norm}$
Breeddiep Overtake Aft	OS_length	391.41089790995466	294.85716307306814	161.36701209167953
	OS_width	282.1147478075836	305.45702125145965	150.51642545159837
	OS_sog	584.913887052343	197.10910314035868	112.31553774856815
	L_combined	399.2287189749013	235.6419360098666	94.30103495094602
	B_combined	356.5961097712318	255.8732183272175	105.54780554213771
	sog_diff	753.4363707303974	208.67256342655543	106.20381861496186

C
Ship domain size and breaches

This appendix presents the relations between all parameters and the ship domain size per situation. It then continues to show the chosen domain per scenario as well as the timelines of the domain breaches.

C.1. All relations

Table C.1: Parameters per situation and their corresponding variables for the trend line

Sector Encounter Direction	Parameter	a	b	RMSE
Maassluis Head-on Port-side	OS_length	0.0	120.383	32.605
	OS_width	0.045	99.432	40.01
	OS_SOG	-0.385	117.463	24.076
	L_combined	-0.002	161.034	56.187
	B_combined	0.024	105.47	32.403
	SOG_diff	0.017	106.755	28.333
Botlek Head-on Port-side	OS_length	0.001	52.528	32.733
	OS_width	0.044	51.427	25.711
	OS_SOG	0.068	47.962	15.529
	L_combined	0.002	34.131	30.904
	B_combined	0.081	41.489	21.395
	SOG_diff	0.14	54.57	25.016
Breeddiep Head-on Port-side	OS_length	0.001	113.91	48.21
	OS_width	0.033	91.635	34.674
	OS_SOG	0.745	87.451	34.032
	L_combined	0.001	96.277	34.96
	B_combined	0.062	85.831	31.175
	SOG_diff	0.167	108.529	52.43
Maassluis Head-on Starboard	OS_length	0.0	120.383	32.605
	OS_width	0.045	99.432	40.01
	OS_SOG	-0.385	117.463	24.076
	L_combined	-0.002	161.034	56.187
	B_combined	0.024	105.47	32.403
	SOG_diff	0.017	106.755	28.333
Botlek Head-on Starboard	OS_length	0.001	46.182	15.983
	OS_width	0.057	39.947	14.666
	OS_SOG	0.906	31.714	11.138
	L_combined	0.003	46.189	40.676
	B_combined	0.201	34.512	38.903

Table C.1 continued from previous page

Sector Encounter Direction	Parameter	a	b	RMSE
	SOG_diff	0.718	28.354	29.579
Breeddiep Head-on Starboard	OS_length	0.001	87.006	46.521
	OS_width	-0.013	119.688	43.763
	OS_SOG	1.205	87.026	50.908
	L_combined	0.002	93.263	48.783
	B_combined	0.111	90.02	49.754
	SOG_diff	-0.206	117.866	43.087
Maassluis Head-on Fore	OS_length	-0.004	718.255	141.471
	OS_width	-0.132	678.587	155.642
	OS_SOG	2.064	576.897	207.024
	L_combined	0.001	668.966	154.072
	B_combined	0.156	581.44	134.491
	SOG_diff	1.114	524.268	168.131
Botlek Head-on Fore	OS_length	0.008	280.214	141.509
	OS_width	0.034	425.702	192.795
	OS_SOG	7.42	166.647	104.105
	L_combined	0.005	367.162	211.125
	B_combined	0.202	372.686	225.339
	SOG_diff	-0.022	354.53	164.512
Breeddiep Head-on Fore	OS_length	0.005	519.43	160.256
	OS_width	0.337	515.69	171.088
	OS_SOG	8.996	302.709	158.497
	L_combined	0.008	494.187	188.845
	B_combined	0.539	396.355	114.434
	SOG_diff	3.499	230.439	137.317
Maassluis Overtake Port-side	OS_length	0.002	62.038	49.274
	OS_width	0.051	53.928	25.956
	OS_SOG	-0.06	51.227	17.326
	L_combined	0.003	31.387	32.122
	B_combined	0.189	21.683	15.721
	SOG_diff	3.658	31.551	17.843
Botlek Overtake Port-side	OS_length	0.003	46.139	86.863
	OS_width	0.114	52.723	86.256
	OS_SOG	0.876	34.335	13.582
	L_combined	0.005	13.208	76.168
	B_combined	0.158	29.603	31.602
	SOG_diff	11.467	-1.954	78.721
Breeddiep Overtake Port-side	OS_length	0.0	79.972	29.785
	OS_width	0.003	100.229	56.097
	OS_SOG	3.648	25.299	46.198
	L_combined	0.001	112.078	92.295
	B_combined	0.088	75.946	54.232
	SOG_diff	6.291	37.247	19.586
Maassluis Overtake Starboard	OS_length	0.002	44.328	19.292
	OS_width	0.101	31.091	9.801
	OS_SOG	0.38	36.778	12.454
	L_combined	0.003	30.736	32.143
	B_combined	0.184	21.38	15.464
	SOG_diff	3.707	30.057	17.893
Botlek Overtake Starboard	OS_length	0.001	47.35	29.66
	OS_width	0.075	29.606	15.769
	OS_SOG	0.275	50.319	34.062

Table C.1 continued from previous page

Sector Encounter Direction	**Parameter**	**a**	**b**	**RMSE**
	L_combined	0.002	39.957	36.249
	B_combined	0.152	25.784	24.885
	SOG_diff	6.939	10.886	29.601
Breeddiep Overtake Starboard	OS_length	0.002	57.309	27.705
	OS_width	0.109	58.264	23.245
	OS_SOG	1.31	25.859	16.42
	L_combined	0.003	57.32	39.571
	B_combined	0.124	49.8	35.872
	SOG_diff	7.347	27.918	19.077
Maassluis Overtake Fore	OS_length	0.002	283.266	163.881
	OS_width	0.203	209.446	131.024
	OS_SOG	5.157	136.894	120.593
	L_combined	0.006	221.783	170.713
	B_combined	0.72	81.448	121.016
	SOG_diff	19.593	151.122	102.855
Botlek Overtake Fore	OS_length	0.01	100.446	131.945
	OS_width	0.181	170.979	135.76
	OS_SOG	4.2	102.315	68.228
	L_combined	0.011	67.826	125.908
	B_combined	0.539	90.469	182.942
	SOG_diff	21.742	85.983	90.989
Breeddiep Overtake Fore	OS_length	0.007	268.116	110.418
	OS_width	0.201	251.771	69.004
	OS_SOG	5.838	195.261	147.642
	L_combined	0.009	235.004	166.616
	B_combined	0.465	181.147	88.989
	SOG_diff	26.594	174.59	71.494
Maassluis Overtake Aft	OS_length	0.01	167.508	140.603
	OS_width	0.555	151.942	124.646
	OS_SOG	6.108	110.339	60.484
	L_combined	0.016	96.35	125.392
	B_combined	0.886	80.659	92.56
	SOG_diff	19.221	111.437	121.375
Botlek Overtake Aft	OS_length	0.007	118.486	112.529
	OS_width	0.335	88.471	117.964
	OS_SOG	6.808	64.297	105.335
	L_combined	0.015	4.063	96.215
	B_combined	0.551	99.307	179.071
	SOG_diff	29.907	42.244	64.056
Breeddiep Overtake Aft	OS_length	0.005	321.455	192.799
	OS_width	0.121	311.283	142.289
	OS_SOG	7.63	170.091	128.408
	L_combined	0.008	254.579	159.207
	B_combined	0.437	198.061	109.139
	SOG_diff	26.49	155.244	94.029

C.2. Scenarios of application

This part of the appendix will go into each scenario and present the chosen parameters, the relations to the critical distances that follow from those parameters. Then the three possible shapes for the normalised domain are plotted, followed by a timeline of the domain breaches per sector for each of the possible shapes.

C.2.1. Scenario 1: The condition-free scenario

Table C.2: Relevant parameters for scenario 1

Situation		Maassluis	Botlek	Breeddiep
Head-on	**Port-side**	OS_width	B_combined	OS_width
	Starboard	OS_width	L_combined	B_combined
	Fore	OS_SOG	OS_length	SOG_relative
Overtake	**Port-side**	B_combined	OS_SOG	L_combined
	Starboard	SOG_relative	OS_width	OS_width
	Fore	SOG_relative	SOG_relative	OS_length
	Aft	B_combined	L_combined	SOG_relative

Table C.3: Relations to the critical distances for the chosen parameters in scenario 1

Encounter Direction	Parameter	Sector	a	b	RMSE
Head-on Port-side	OS_width	Maassluis	0.045	99.432	40.01
	B_combined	Botlek	0.081	41.489	21.395
	OS_width	Breeddiep	0.033	91.635	34.674
Head-on Starboard	OS_width	Maassluis	0.045	99.432	40.01
	L_combined	Botlek	0.003	46.189	40.676
	B_combined	Breeddiep	0.111	90.02	49.754
Head-on Fore	OS_SOG	Maassluis	2.064	576.897	207.024
	OS_length	Botlek	0.008	280.214	141.509
	SOG_diff	Breeddiep	3.499	230.439	137.317
Overtake Port-side	B_combined	Maassluis	0.189	21.683	15.721
	OS_SOG	Botlek	0.876	34.335	13.582
	L_combined	Breeddiep	0.001	112.078	92.295
Overtake Starboard	SOG_diff	Maassluis	3.707	30.057	17.893
	OS_width	Botlek	0.075	29.606	15.769
	OS_width	Breeddiep	0.109	58.264	23.245
Overtake Fore	SOG_diff	Maassluis	19.593	151.122	102.855
	SOG_diff	Botlek	21.742	85.983	90.989
	OS_length	Breeddiep	0.007	268.116	110.418
Overtake Aft	B_combined	Maassluis	0.886	80.659	92.56
	L_combined	Botlek	0.015	4.063	96.215
	SOG_diff	Breeddiep	26.49	155.244	94.029

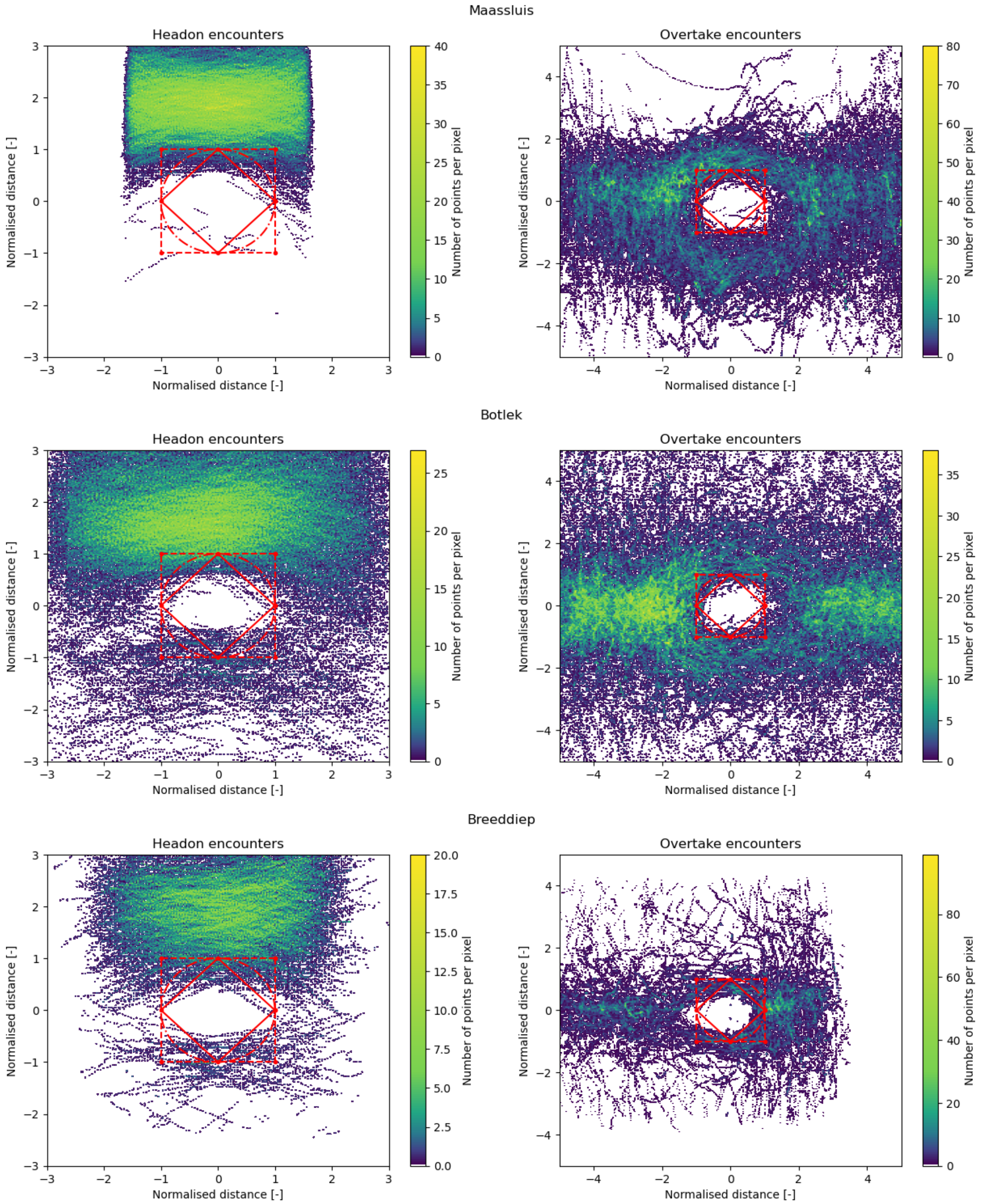

Figure C.1: Normalised ship domain for three possible shapes in all sectors for scenario 1

Table C.4: Testing of shapes in scenario 1

		Maassluis		Botlek		Breeddiep	
		Amount	**Percentage**	**Amount**	**Percentage**	**Amount**	**Percentage**
Diamond	**Data points**	1305	0.40	1718	0.37	2989	2.31
	Unique vessels	152	3.49	301	2.21	229	6.90
Ellipse	**Data points**	4041	1.23	4873	1.04	7427	5.75
	Unique vessels	234	5.37	490	3.59	350	10.55
Rectangle	**Data points**	8146	2.48	9381	2.00	11428	8.85
	Unique vessels	438	10.06	879	6.45	531	16.01

Figure C.2: Timeline of domain breaches for three possible shapes in all sectors for scenario 1

C.2.2. Scenario 2: The OS scenario

Table C.5: Relevant parameters for scenario 2

Situation		Maassluis	Botlek	Breeddiep
Head-on	**Port-side**	OS_width	OS_width	OS_width
	Starboard	OS_width	OS_width	OS_length
	Fore	OS_SOG	OS_length	OS_SOG
Overtake	**Port-side**	OS_width	OS_SOG	OS_SOG
	Starboard	OS_width	OS_width	OS_width
	Fore	OS_SOG	OS_length	OS_length
	Aft	OS_width	OS_length	OS_SOG

Table C.6: Relations to the critical distances for the chosen parameters in scenario 2

Encounter Direction	Parameter	Sector	a	b	RMSE
Head-on Port-side	OS_width	Maassluis	0.045	99.432	40.01
	OS_width	Botlek	0.044	51.427	25.711
	OS_width	Breeddiep	0.033	91.635	34.674
Head-on Starboard	OS_width	Maassluis	0.045	99.432	40.01
	OS_width	Botlek	0.057	39.947	14.666
	OS_length	Breeddiep	0.001	87.006	46.521
Head-on Fore	OS_SOG	Maassluis	2.064	576.897	207.024
	OS_length	Botlek	0.008	280.214	141.509
	OS_SOG	Breeddiep	8.996	302.709	158.497
Overtake Port-side	OS_width	Maassluis	0.051	53.928	25.956
	OS_SOG	Botlek	0.876	34.335	13.582
	OS_SOG	Breeddiep	3.648	25.299	46.198
Overtake Starboard	OS_width	Maassluis	0.101	31.091	9.801
	OS_width	Botlek	0.075	29.606	15.769
	OS_width	Breeddiep	0.109	58.264	23.245
Overtake Fore	OS_SOG	Maassluis	5.157	136.894	120.593
	OS_length	Botlek	0.01	100.446	131.945
	OS_length	Breeddiep	0.007	268.116	110.418
Overtake Aft	OS_width	Maassluis	0.555	151.942	124.646
	OS_length	Botlek	0.007	118.486	112.529
	OS_SOG	Breeddiep	7.63	170.091	128.408

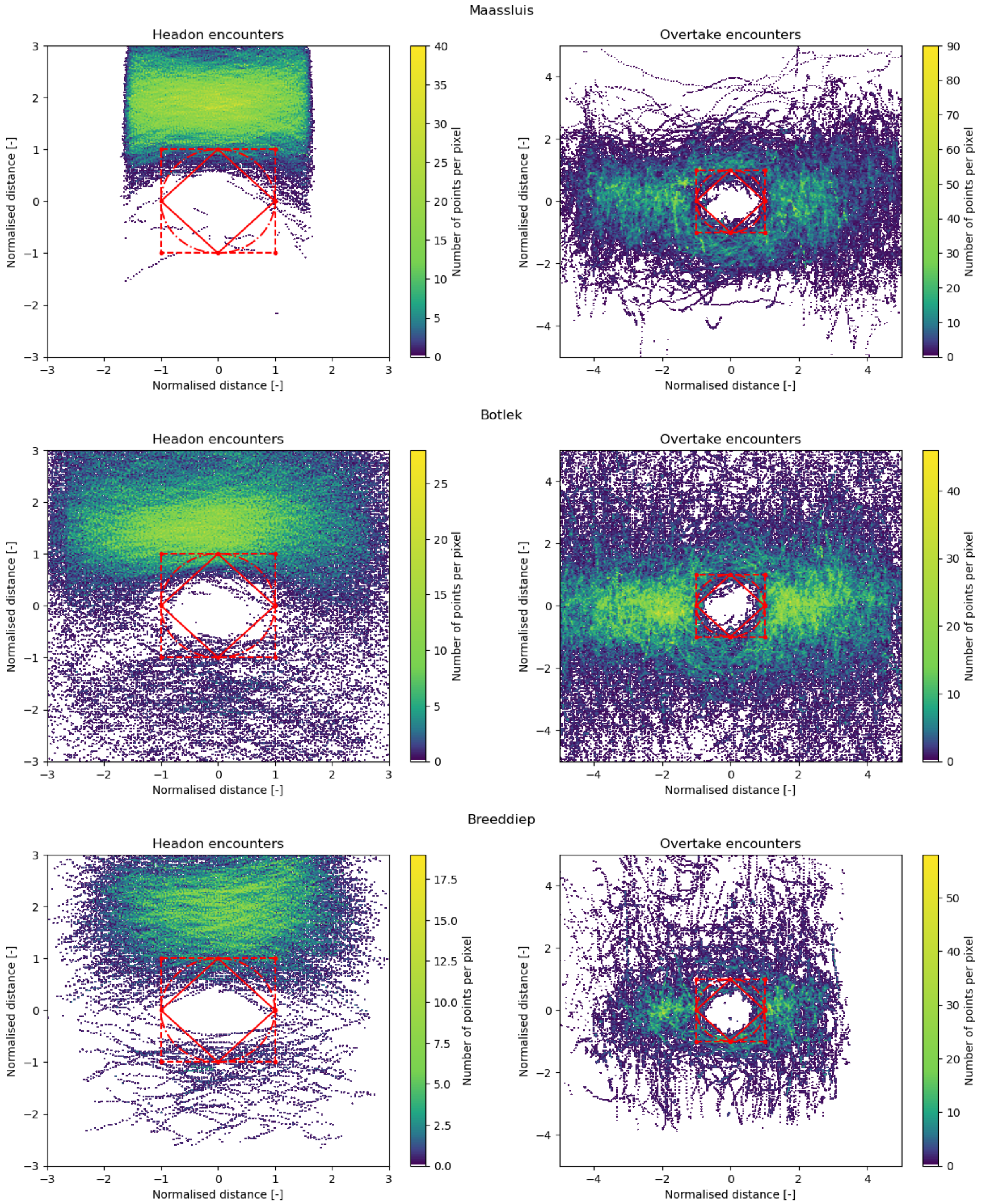

Figure C.3: Normalised ship domain for three possible shapes in all sectors for scenario 2

Table C.7: Testing of shapes in scenario 2

		Maassluis		Botlek		Breeddiep	
		Amount	**Percentage**	**Amount**	**Percentage**	**Amount**	**Percentage**
Diamond	**Data points**	2027	0.62	2248	0.48	2292	1.77
	Unique vessels	179	4.11	363	2.66	206	6.21
Ellipse	**Data points**	6244	1.90	6945	1.48	6863	5.31
	Unique vessels	271	6.22	605	4.44	332	10.01
Rectangle	**Data points**	12112	3.69	13369	2.85	10889	8.43
	Unique vessels	499	11.46	1028	7.54	493	14.86

Figure C.4: Timeline of domain breaches for three possible shapes in all sectors for scenario 2

C.2.3. Scenario 3: The same-for-all scenario

Table C.8: Relevant parameters for scenario 3

Situation		Maassluis, Botlek and Breeddiep
Head-on	**Port-side**	OS_width
	Starboard	B_combined
	Fore	OS_SOG
Overtake	**Port-side**	B_combined
	Starboard	OS_width
	Fore	SOG_relative
	Aft	SOG_relative

Table C.9: Relations to the critical distances for the chosen parameters in scenario 3

Encounter Direction	Parameter	Sector	a	b	RMSE
Head-on Port-side	OS_width	Maassluis	0.045	99.432	40.01
		Botlek	0.044	51.427	25.711
		Breeddiep	0.033	91.635	34.674
Head-on Starboard	B_combined	Maassluis	0.024	105.47	32.403
		Botlek	0.201	34.512	38.903
		Breeddiep	0.111	90.02	49.754
Head-on Fore	OS_SOG	Maassluis	2.064	576.897	207.024
		Botlek	7.42	166.647	104.105
		Breeddiep	8.996	302.709	158.497
Overtake Port-side	B_combined	Maassluis	0.189	21.683	15.721
		Botlek	0.158	29.603	31.602
		Breeddiep	0.088	75.946	54.232
Overtake Starboard	OS_width	Maassluis	0.101	31.091	9.801
		Botlek	0.075	29.606	15.769
		Breeddiep	0.109	58.264	23.245
Overtake Fore	SOG_diff	Maassluis	19.593	151.122	102.855
		Botlek	21.742	85.983	90.989
		Breeddiep	26.594	174.59	71.494
Overtake Aft	SOG_diff	Maassluis	19.221	111.437	121.375
		Botlek	29.907	42.244	64.056
		Breeddiep	26.49	155.244	94.029

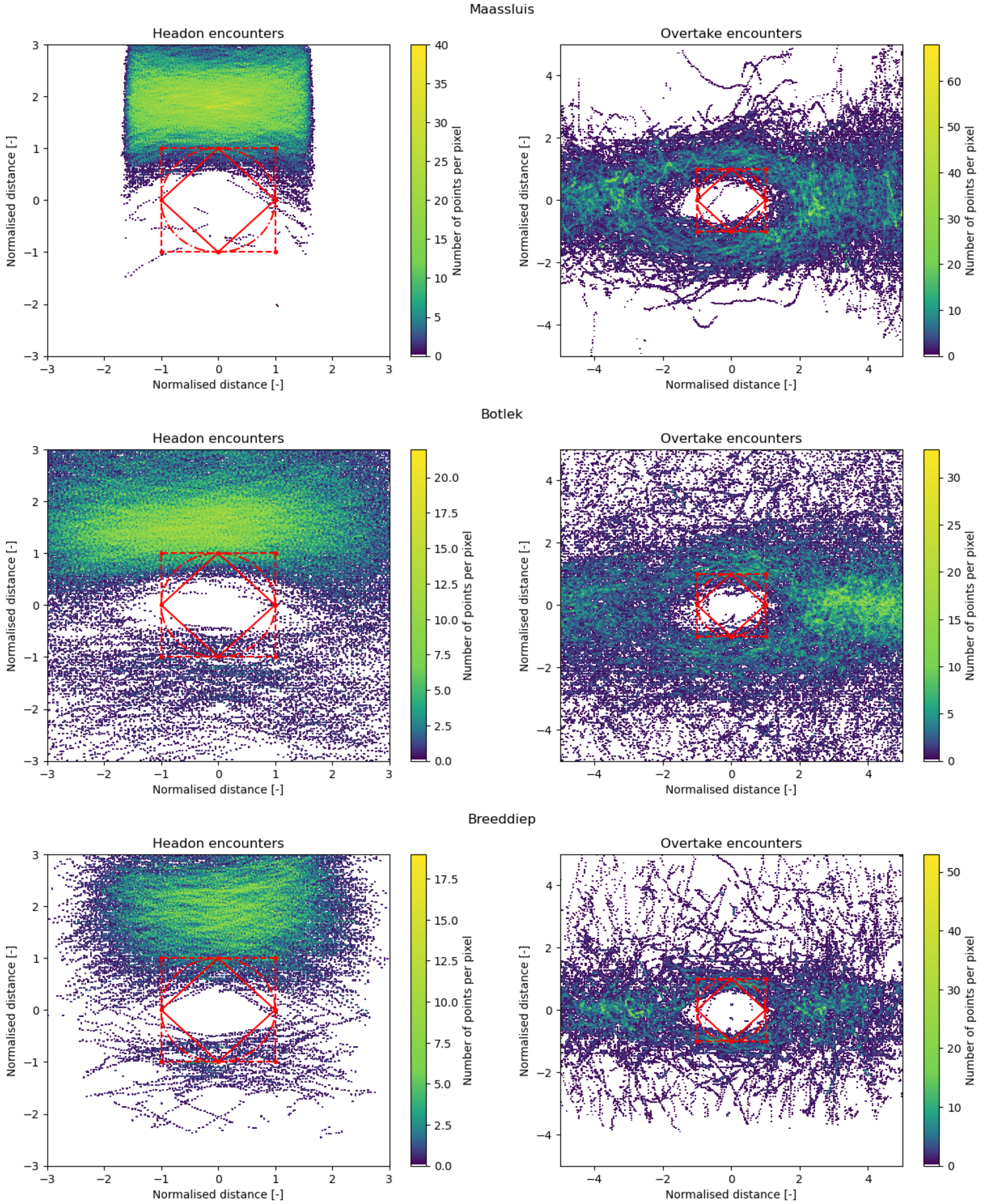

Figure C.5: Normalised ship domain for three possible shapes in all sectors for scenario 3

Table C.10: Testing of shapes in scenario 3

		Maassluis		Botlek		Breeddiep	
		Amount	**Percentage**	**Amount**	**Percentage**	**Amount**	**Percentage**
Diamond	**Data points**	1162	0.35	1378	0.29	1484	1.15
	Unique vessels	158	3.63	321	2.35	167	5.03
Ellipse	**Data points**	3559	1.08	4087	0.87	4433	3.43
	Unique vessels	230	5.28	477	3.50	275	8.29
Rectangle	**Data points**	7125	2.17	8124	1.73	7749	6.00
	Unique vessels	440	10.11	824	6.04	420	12.66

Figure C.6: Timeline of domain breaches for three possible shapes in all sectors for scenario 3