

**Title:**

Project Results Report

**Performed by:**

RISE Research Institutes of Sweden, Chalmers University of Technology, and SEAMADE

**Project:**

Simulator based risk identification for autonomous shipping

Project number: TrV 2019/29782

Doc. No: *RfAF\_project\_results*

Version: 3.0

Datum: 2022-12-23

## Sammanfattning på svenska

Digitalisering och automatisering är trender som påverkar samhällen och industrier. Forskning och innovation av mer autonoma system är konsekvensen av denna utveckling, men att säkerställa säkerhet och tillförlitlighet för dessa system är den största utmaningen. Lite forsknings- och innovationsarbete har utförts och publicerats med avseende på lämpliga metoder för att testa och säkerställa säker drift av mer autonoma fartyg, vilket är avgörande för fartygsägarna innan man investerar i nya tekniker.

Syftet med projektet har därför varit att identifiera risker relaterade till mer autonom sjöfart baserat på bland annat fartygssimuleringar. Fartygstrafiken på tre typiska rutter (öppet hav, trång farled och farleden i Göteborg) har använts för att identifiera förändrade risknivåer för en mer autonom navigering. Resultaten från projektet är framförallt en validerad riskmodell som kan användas för att utvärdera navigationskontrollen på autonoma fartyg. Detta bidrar också till att öka kunskapen och tillhandahålla en riskbedömningsmetod för införandet av autonoma fartyg till den konventionella maritima trafikdomänen och deras påverkan på sjösäkerheten. Projektet bidrar som en del i en större färdplan för att rederier kan ta mer faktabaserade beslut om framtida investeringar.

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# 1 INTRODUCTION

## 1.1 Scope

This report summarizes the results from the project “Simulatorbaserad riskidentifiering för autonom fartygstrafik” funded by Trafikverket, the Swedish Transport Agency. The objective of the project has been to derive a risk evaluation method to support ship owners in the decision-making process of introducing autonomous systems on their ships. The project was conducted by RISE Research Institutes of Sweden (RISE) as coordinator, and the project partners Chalmers University of Technology (Chalmers) and SEAMADE.

Figure 1 presents an overview of the logic followed throughout the project. The methodology commences with a hazard identification analysis (HAZID) where domain experts have identify possible hazards associated to the introduction of autonomous vessels (work package (WP) 1). The results of the HAZID have then been used as basis for the selection of a number of simulation scenarios. These scenarios are aimed at facilitating the identification and understanding of the risks associated with the introduction of autonomous vessels (WP 2). In WP3 the simulation scenarios have been carried out, the simulation runs are recorded, and the operators interviewed. Afterwards, both datasets are used as the input to a risk method/model that provides the desired insights regarding risks (WP 4). Finally, for the identified risks, risk-reducing measures are proposed (WP 5) and recommendations for decision-making are outlined (WP 6).

This report documents the work and results of WP 2 to 6.

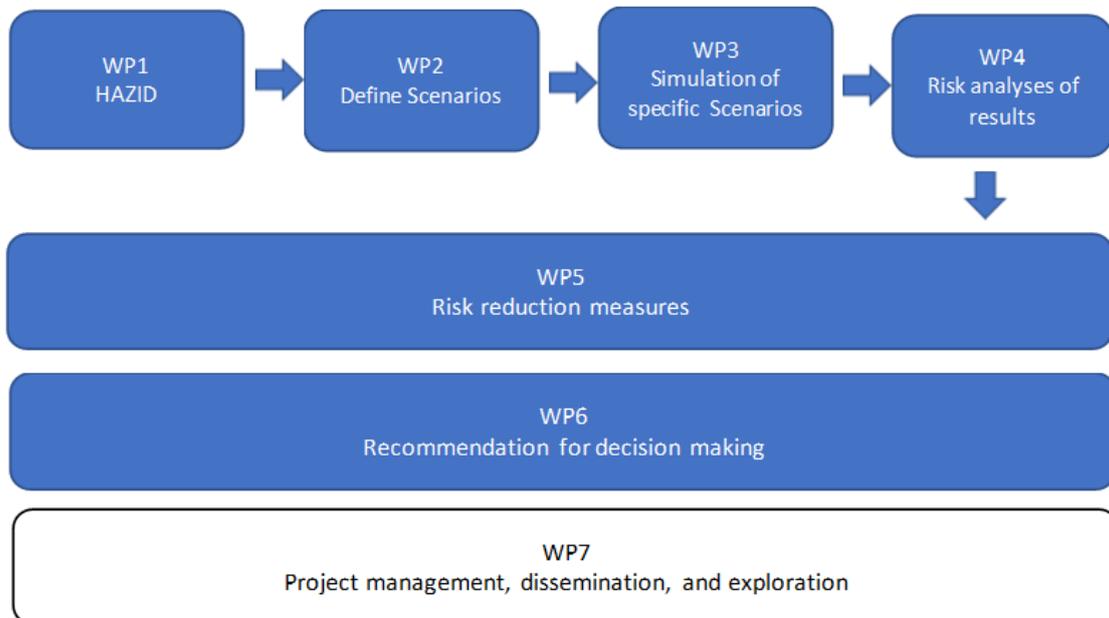


Figure 1 Overview of the study logic followed by the project.

The work and results of WP 1 are documented in the HAZID Report [HAZID, 2020]. Together, this report and the HAZID report constitutes the “final report” for the project, see Figure 2 below.

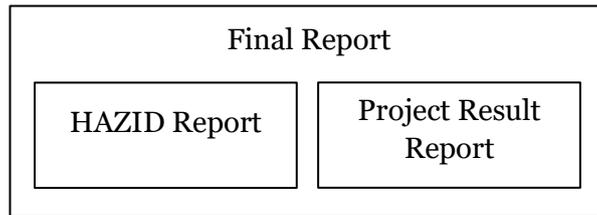


Figure 2 Structure of the final report that consists of the "HAZID report" and the "Project Results Report".

## 1.2 Objective

As stated above, the main objective of the project was to derive a risk evaluation method to support ship owners in the decision-making process of introducing autonomous systems on their ships and their “management of change”. Currently, ship owners are confronted with an increased level of automation and digitalization in their domain. These changes can hardly be addressed by the current “management of change” practices, and therefore new methods are necessary.

To derive the new methods, the following specific objectives were pursued:

- Develop a risk assessment method that encompasses the technical advances in digitalization and automation in shipping to derive equivalent safety levels.
- Perform desktop and full-mission simulations of typical traffic scenarios involving autonomous, semi-autonomous and manned ships in confined waters and port approaches.
- Increase the competence and competitiveness of Swedish organizations and companies when it comes to independently validating and verifying that smart and autonomous vessels are rule-compliant and safe.

## 1.3 Background

New technologies are introduced constantly having a significant influence on crews working environment and shipping safety, which can hardly be covered by the current “management of change” practices. In today’s and in a future operational environment, consisting of manned, semi-automatic and un-manned vessels, resilient navigation is paramount. This future environment includes SOLAS ships navigating in restricted waters in conjunctions with smaller vessel both manned and un-manned. When partly autonomous vessels will be introduced, they will initially be able to handle only a restricted set of scenarios. It is of interest in terms of functionality, comfort, and safety to maximise the number of scenarios that the autonomous navigation systems can handle, thus minimising the number of operator handover requests. Being able to handle even more complex fairway navigation scenarios is therefore of high interest. Fairway and port navigation provide a controlled environment and are therefore generally considered as being the first setting to be automated. However, ship-ship passages and congested fairways are two of the more complicated scenarios in this setting as well as safety critical. Modelling of complex systems that are implemented in highly automated smart systems requires independent testing of algorithms.

## 1.4 Methodology

Figure 3 presents an overview of the methodology followed throughout the project. This methodology is based on the Formal Safety Assessment (FSA) principles of the International Maritime Organisation (IMO). In this project's methodology, WP 1 corresponds to "Step 1: HAZID", WP 2-4 to "Step 2: risk assessment", and WP 5 to "Step 3: risk control options", and finally, WP 6 to "Step 5; decision making recommendations". "Step 4: cost benefit assessment" is not covered in this project. IMO's FSA methodology was modified to emphasize the risk assessment step where simulations of autonomous ships are used to identify new operational and technical risks coupled to different traffic scenarios and provide new insights.

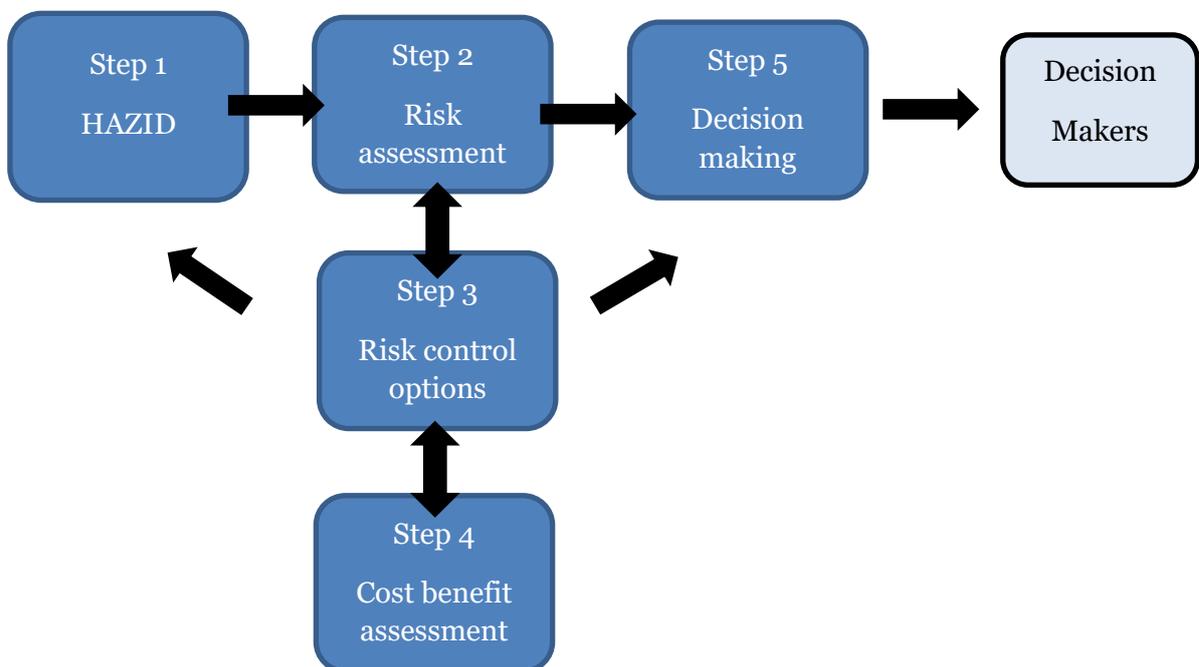


Figure 3 Formal Safety Assessment methodology based on [IMO 1, 2018].

Figure 4 presents a detailed view of the project's methodology for work packages 2 to 6. The output of WP 2 is the descriptions of the simulation scenarios. The simulation scenarios are grouped in sets corresponding to the environment where they take place and the autonomy of the vessels involved. Table 1, in section 2, presents a description of the 7 sets, each of which contain several simulation scenarios and objectives. A full descriptions of the scenarios and the objectives are presented in Section 2. As described in the table, simulation scenarios in the "Restricted fairway" environment only involved autonomous vessels. The simulation scenarios are carried out in one of three different simulators used: a desktop simulator, a full-mission bridge simulator, and a hybrid simulator where a desktop simulator and a full-mission bridge simulator are coupled. Autonomous vessels at A3 level of automoution, according to definitions in [IMO 2, 2021] were used. Recordings of the simulations (e.g. vessel movements, actions taken on the bridge, etc.) are obtained from all the three types of simulations. Then, in WP 4, the recordings were processed in a numerical risk analysis to obtain quantitative data on the risks: risk scores and Key Performance Indicators (KPIs). Additionally, qualitative data on the risks are obtained from the simulations where bridge teams were involved. The

quantitativ and qualitative data where then used as the input for the risk-reducing measures analysis, which in turn provides the input for the recommendations for decision making analysis.

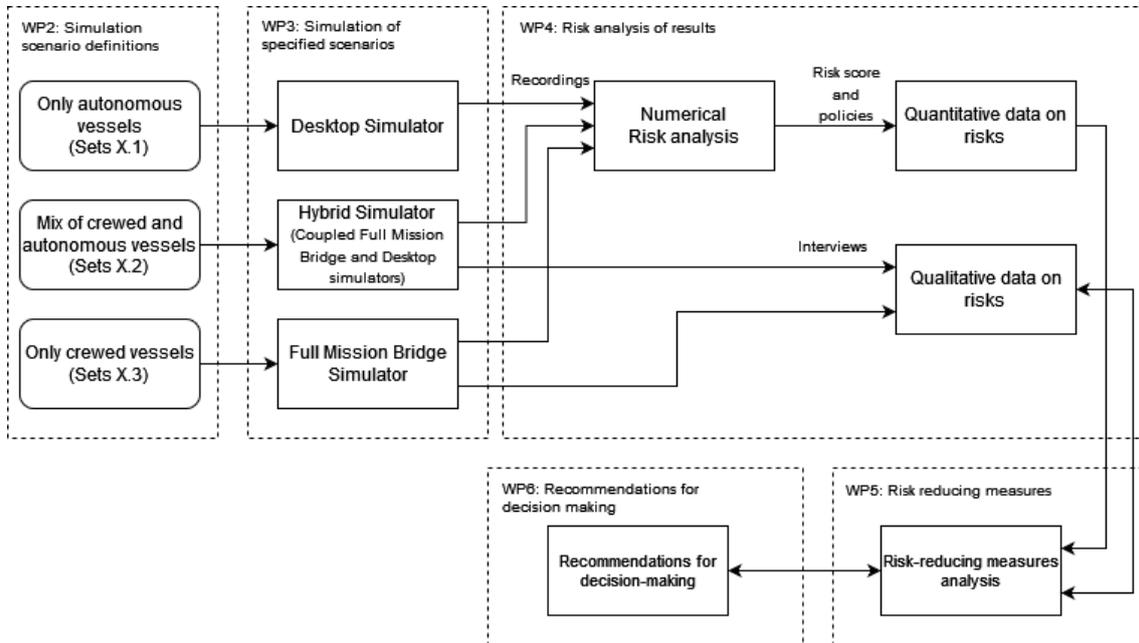


Figure 4 Detailed view of the project's methodology for work packages 2 to 6.

## 1.5 Conclusion from the HAZID

The performed HAZID is reported in [HAZID, 2020] and was based on the evaluation of two different shipping lanes. One was the Ljusterö crossing of the Swedish road ferries, provided by Trafikverket, the other one was the Stena Line Ferry sailing between Frederikshavn/ Denmark and Gothenburg/ Sweden. For both areas, background details on the traffic, weather, etc were given. HAZID connected to traditional ships were identified using different sources. Further, HAZID connected to future autonomous ships were identified by an questioner to subject matter experts. On the question:

*“What is in your opinion the major technical challenge with autonomous navigation?”*

the replies can be summarized in order by: [HAZID, 2020]

- 1) The reliability of integration and redundancy of critical sub-systems are an important issue.
- 2) The lack of possibility to manually override a system.
- 3) Emergency repairs while underway.
- 4) Traffuc situations that which are regulated by COLREG.
- 5) All the “small stuff” that normally gets fixed easily by experienced crew.
- 6) Having enough fail-safe options. Difficulty with defect rectification in event of failure of key components.
- 7) Preventative maintenance and observation of warning signs.
- 8) The mix between manned ships and autonomous.
- 9) All ships to have the same technical build up and have them talking with each other

- 10) Weather effects.
- 11) Route optimization en route.
- 12) The fact that every ship needs maintenance all the time. We know that stuff breaks all the time.
- 13) To find people that thinks this is a good idea.
- 14) Navigating safe in confined water.

Further, the outcome of the HAZID report was that “It is expected that similar accidents and incident types will occur on more automated and totally autonomous ships. This implies that risk reducing measures that are provided in today’s ships by humans need to be covered by automated functions. These risks occur during all stages of the ship’s operation and involves various technical systems.”

Based on this, the developed risk model presented in this report is focusing on navigation control functions, which are today performed by the bridge team and potentially in future performed by navigation control algorithms addressing points: 4), 8), 10), 11), and 14). The points 1), 2), 3) 5), 6), 7) 9), and 12), which are further discussed in chapter 4.

## 1.6 Structure of the report

This report is organised as follows:

**Chapter 1** introduces the project and the contents of the report followed by describing the methodology carried out.

**Chapter 2** describes the simulation test campaign and the simulation scenarios. It also describes the algorithms for representing the autonomous vessels.

**Chapter 3** presents a detailed description of the developed risk model and the results of the simulations.

**Chapter 4** describes how risk mitigation fits in to the project’s overall methodology and gives recommendations for future decisions.

**Chapter 5** lists the references used in the report.

## 1.7 Abbreviations

This section includes a list of abbreviations used in this report.

A	Levels of autonomy
AIS	Automatic Identification Signal
AL	Lateral wind area
B	Beam
CG	Correspondence Group
COLREG	Regulations for the Prevention of Collision at Sea
CPA	Closest Point of Approach

DIS	Distributed Interactive Simulations
Disp	Displacement
EMSA	European Maritime Safety Agency
EMSN	European Maritime Simulator Network
FTA	Fault Tree Analysis
FMBS	Full Mission Bridge Simulator
HAZID	Hazard Identification
HMI	Human-Machine Interfaces
IMO	International Maritime Organisation
Iprop	Number of propellers
KPI	Key Performance Index
Loa	Length over all
Lpp	Length between perp.
MSC	Maritime Safety Committee
NTPro	Navi Trainer Professional (simulator software by Wärtsilä)
OS	Own Ship
ODD	Operational design domain
R	Recommendation
RCC	Remote Control Center
RCO	Risk Control Options
RCM	Risk Control Measures
RoPax	Roll On/Roll Off/Passenger
ROT	Rate Of Turn
PDU	Protocol Data Units
SOLAS	Safety of Lives at Sea
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafares
Ta	Draught, aft
TCPA	Time to Closed Point of Approach
Tf	Draught, fore
VHF	Very High Frequency
Vdes	Design speed

VTS      Vessel Traffic Service  
WP      Work Package

## 2 SIMULATION SCENARIOS

### 2.1 Introduction

As has been discussed in § 1.5, a HAZID analysis has been conducted and reported in [HAZID, 2020] giving input to the risk model. It was concluded that the developed risk model should be focusing on navigation during varies traffic conditions. The risk model would be applicable on general-purpose navigation onboard autonomous and manned vessels representing different geographical areas and traffic. The geographical areas were selected based on the differences in available navigable waters and expected traffic behaviour and pattern in the area. The risk model analysis has been focused on the outcome of actions by the navigators or algorithms. Actions from a navigator affected the vessel's movement, impact on nearby traffic, and relative vessel position to geographical restrictions or danger. Hence, risk tolerance is much dependent on the navigator culture and other subjective factors. The risk model can be used to validated future navigation control algorithms with the purpose of evaluating the navigator's performance.

The selected sets of simulation scenarios were based on the two use cases discussed in [HAZID, 2020] - the Ljusterö crossing of the Swedish road ferries and the Stena Line Ferry sailing between Frederikshavn/ Denmark and Gothenburg/ Sweden. These two cases were divided into three sets of simulations; restricted, fairway and open sea, which are detailed in Table 1 and §2.3 below.

Table 1 Sets of simulation scenarios and their objective. A: generate results for the risk analysis (recordings and/or interviews); B: develop, tune, and test the autonomous steering algorithm; C: develop tune and test the numerical risk analysis functions.

	Only autonomous vessels	Mix of crewed and autonomous vessels	Only crewed vessels
Restricted fairway	A, B		
Fairway	A, C	A, C	A, C
Open water	A, C	A, C	A, C

## 2.2 Ships models

The following four different ship models have been developed and used in the project.

Table 2 Particulars of the ships available in the desktop simulator SHIPMAN.

Type	Road ferry	Feeder container	RoPax	Chemical tanker
Length over all Loa in m	99.7	169.0	175.4	182.55
Length between perp. Lpp in m	87.0	158.0	164.0	170.0
Beam B in m	18.2	27.2	31.5	27.34
Draught, aft Ta in m	2.2	9.49	6.65	10.85
Draught, fore Tf in m	2.2	8.51	6.65	10.85
Displacement Disp in m <sup>3</sup>	3 200	24 080	20 300	44 288
Lateral wind area AL ni m <sup>2</sup>	750	2 750	2 920	1 200
Design speed Vdes in knots	11.0	19.0	19.0	14.5
Number of propellers iprop	2	1	2	1

## 2.3 Simulation scenarios

Table 1 above, presents an overview of the simulation scenarios. The simulation scenarios can be divided into groups according to the environment where they take place and the autonomy of the vessels involved.

Three types of environments were used in the simulations:

1. Restricted fairway – A narrow channel bound on both sides by shore or shallow water depth. The available area for resolving traffic conflicts is small relative to the size of the involved vessels.
2. Fairway – A harbour approach channel designed for the safe navigation of vessels in one or two-way traffic. The channel is bound on both sides primarily by limits imposed through aids to navigation. Suitable areas for resolving traffic conflicts are available throughout the fairway.
3. Open sea – A nearly unrestricted area. Suitable areas for resolving traffic conflicts are widely available.

And the autonomy of the vessels involved was divided into three types:

1. Only autonomous vessels – All the vessels involved in the scenario are steered by an autonomous algorithm (i.e., an algorithm that decides the appropriate action to a situation without input of a human).
2. Only crewed vessels – All the vessels involved in the scenario are steered by an experienced navigator.
3. Mix of autonomous and manned vessels – The vessels are steered by either an experienced navigator (manned vessel) or an autonomous algorithm (autonomous vessel). The scenario includes at least one autonomous and one crewed vessel.

Table 1 also indicates the objectives of the simulation groups. The objectives of the simulations are:

- A. Generate results to be used as input for the risk analysis.
- B. Development, tuning, and testing of the algorithm for steering the autonomous vessels.
- C. Development, tuning, and testing of the numerical risk analysis functions.

Besides the environment and the autonomy of the vessels involved, the simulation scenarios differ with regards to two additional characteristics: communication and risk taking. The autonomous vessels cannot communicate their intentions; however, the manned vessels may or may not be able to communicate them through VHF radio. Similarly, the autonomous vessels do not have different risk-taking modes; however, the crews are asked to navigate and sail the vessels in a manner they would deem to be low, medium, or high risk. It is up to the crew's best judgement to apply the risk level. The medium risk level reflects an average risk level mimicked in everyday real-life navigation, whereas high and low-risk levels are adjusted relative to the medium risk.

The following subsections present detailed descriptions of the simulation scenarios.

### 2.3.1 Restricted fairway scenarios

Figure 5 presents an overview of the restricted fairway scenarios. The scenarios contain a passenger ferry navigating in the centre of the fairway and a road ferry trying to cross the main fairway. The road ferry must decide between stand and wait for the passenger ferry to pass or going ahead or astern of the passenger ferry.

The environment in which the scenarios take place corresponds to the road ferry crossing of Ljusterö. The crossing is almost a straight line over the main fairway connecting Stockholm and the Baltic Sea. The main fairway is commonly trafficked by large passenger ferries and is about 450 meters wide at the crossing.



Figure 5 Overview of the restricted fairway scenarios. The scenarios resemble the traffic around the Ljusterö ferry crossing. A road ferry (red) attempts to cross the main fairway as a passenger ferry (green) approach.

The restricted fairway scenarios are part of a set of Monte-Carlo simulations designed to develop, tune, and test the algorithm for steering the autonomous vessels, as well as provide input to the risk analyses. In layman's terms, Monte-Carlo simulations are a large set of simulations in which a set of parameters are varied randomly. The variation in the parameters enables the identification of their effect on the outcome of the simulations, and therefore, they can be used to develop, tune, and test the steering algorithm. Each of the simulation scenarios are then a variation of the own shown in Figure 5 (e.g., different headings, speeds, course over ground). As shown in Table 1, only autonomous vessels were used in the restricted fairway scenarios. The reason for this limitation is that Monte-Carlo simulations require a large number of simulations to be carried out (hundreds to thousands), so it is unpractical to carry them out in real-time with manned vessels.

### 2.3.2 Fairway scenarios

Figure 6 presents an overview of the fairway scenarios. The fairway scenarios take place in the archipelago outside Gothenburg. Three vessels are involved in the scenarios: two outbound; one taking the northern fairway and the other one taking the southern one; and one inbound vessel set to take the northern fairway. Based on their sailing speed, a close-quarters situation will occur roughly 20 minutes after the simulation start at the intersection of the northern and southern fairways. Then, each vessel needs to take collision avoidance actions. Overall, the scenarios are designed to provoke collision risk in a restricted water space in fairway navigation. Table 3 presents all the fairway scenarios. VHF radio communication between vessels is allowed except in one of the medium-risk scenarios. Vessel Traffic Service (VTS) or other reporting points are excluded.

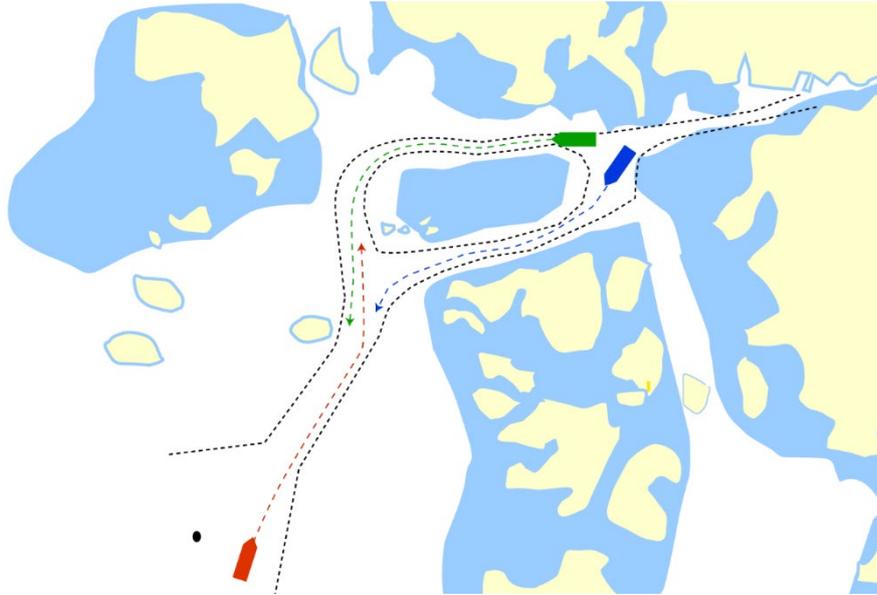


Figure 6 Overview of the fairway scenarios. The scenarios correspond to a challenging situation that can occur in Gothenburg's archipelago. Two outbound vessels, a chemical tanker (green) and a RoPax (blue) meet an inbound vessel, a feeder containership (red), at the intersection of the northern and southern fairways.

Table 3 Fairway scenarios

Autonomy of the involved vessels	Variations
Only manned vessels	All vessels low risk with no external communication
	All vessels low risk with external communication
	All vessels medium risk
	All vessels high risk
Only autonomous vessels	All vessels low risk
	All vessels medium risk
	All vessels high risk
Mix of autonomous and crewed vessels	manned vessels follow low risk and autonomous vessels follow medium risk
	Manned vessels follow medium risk and autonomous vessels follow medium risk
	Manned vessels follow high risk and autonomous vessels follow medium risk
	Two autonomous vessels follow low risk settings and manned vessels follow medium risk

Autonomy of the involved vessels	Variations
	Two autonomous vessels follow medium risk settings and manned vessels follow medium risk
	Two autonomous vessels follow high risk settings and manned vessels follow medium risk
	All manned vessels continuously operated by medium risk

### 2.3.3 Open water scenarios

Figure 7 presents an overview of the open water scenarios. The scenarios take place in the area east of Anholt. Three vessels follow their planned routes (shown in the figure below) and about 20 minutes from the simulation start, the vessels will find themselves in a close quarter situation. The situation is such that each for each of the vessels multiple COLREG rules apply, and all the vessels must avoid the shallow waters. Overall, the scenarios are designed to provoke collision risk in open water space. Table 4 presents all the open sea scenarios. VHF radio communication between vessels is allowed except in one of the medium-risk scenarios. VTS or other reporting points are excluded. The weather is favourable: good visibility, light wind and smooth seas.

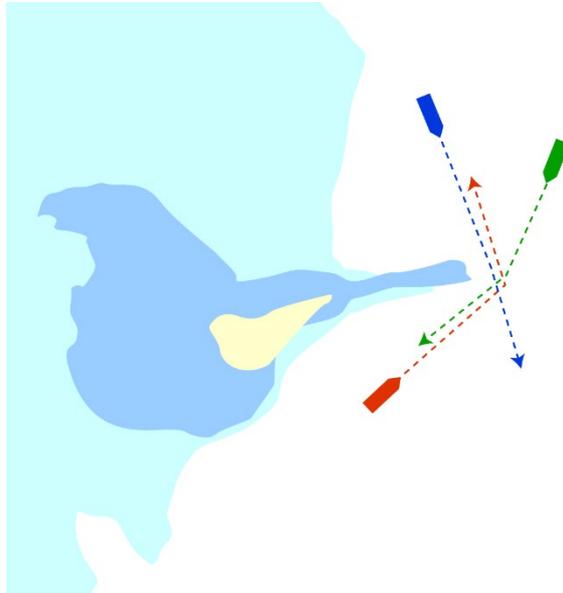


Figure 7 Overview of the open water scenarios. The scenarios correspond to a challenging situation that can occur in an area east of Anholt. Three vessels, a chemical tanker (green), a RoPax (red), and a feeder container (blue) follow their routes (dashed lines) and meet close to a shallow water area. Multiple COLREG rules apply to all the vessels.

Table 4 Open water scenarios

Autonomy of the involved vessels	Simulations and risk level
Only manned vessels	All vessels low risk with no external communication
	All vessels low risk with external communication
	All vessels medium risk
	All vessels high risk
Only autonomous vessels	All vessels low risk
	All vessels medium risk
	All vessels high risk
Mix of autonomous and manned vessels	Manned vessels follow low risk and autonomous vessels follow medium risk
	Manned vessels follow medium risk and autonomous vessels follow medium risk
	Manned vessels follow high risk and autonomous vessels follow medium risk
	Two autonomous vessels follow low risk settings and manned vessels follow medium risk
	Two autonomous vessels follow medium risk settings and manned vessels follow medium risk
	Two autonomous vessels follow high risk settings and manned vessels follow medium risk
	All manned vessels continuously operated by medium risk

## 2.4 Simulators

### 2.4.1 Desktop simulator

The desktop simulator application SHIPMAN allows up to three autonomous vessels to be simulated simultaneously, each of them controlled by a track-keeping algorithm and algorithms for representation of COLREG rules. The autonomous ships were also run in a scenario including one or two full mission-controlled ships, simulated in an external full-mission simulator communication with SHIPMAN over a Distributed Interactive Simulations (DIS) protocol. In this case the autonomous ships were also considering the latter ships with regards to COLREG rules.

## 2.4.2 Available fairways

Two alternative fairways are available:

1. Torshamnsleden, see Figure 8
2. Böttöleden, see Figure 8

Each of the fairways is represented by a reference line and port and starboard fairway limits. The former forms the basis for the control of a ship going through the fairway and the latter represents the limits which the ship may not exceed.

After fairway has been selected the direction, in or out, is chosen.

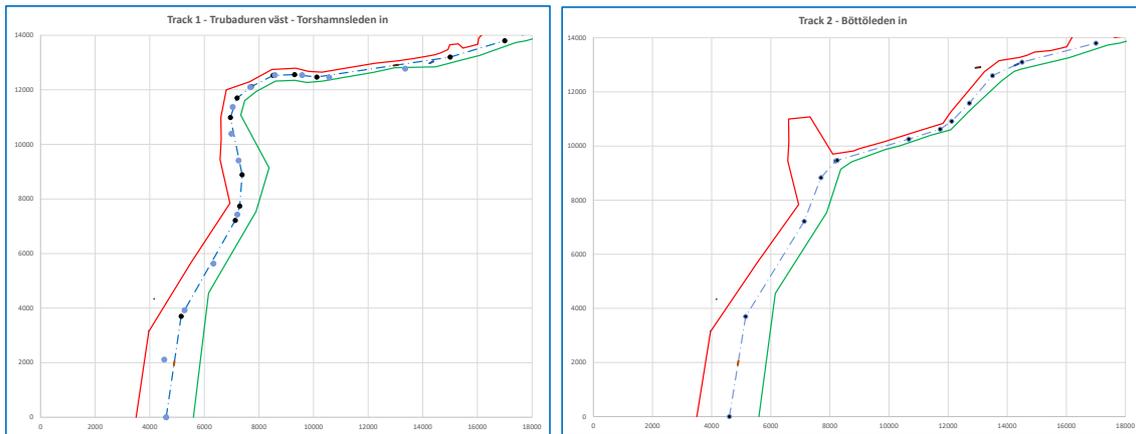


Figure 8 Available fairways. Gothenburg's northern fairway, Torshamnsleden (left), and southern fairway Böttöleden (right).

## 2.4.3 Example – Scenario with three ships meeting outside Böttö in Gothenburg archipelago

In order to demonstrate how the weighing rules described above are realised a simulation is shown below in the form of a sequence of plots.

The 175 m RoPax ship (blue in the pictures below) is outbound using the southern fairway (Böttö), the 182.5 m tanker (green) is outbound using the northern fairway (Torshamnsleden) and the 169 m container ship (red) is entering Torshamnsleden on the way to the container terminal. All three ships have an intention to keep a speed of 15 knots. In the first phase (see Figure 9), the container ship (red) has identified the RoPax vessel (blue) coming from starboard. It has also identified the tanker (green) approaching in a head on encounter. The RoPax (blue) has identified the tanker coming from starboard and the container coming from port. There is, depending on fairway limitations not enough space to make an evasive manoeuvre to starboard. Thus, it reduces speed in order to pass behind the tanker. The tanker prepares to go out to starboard in order to meet the inbound container ship.

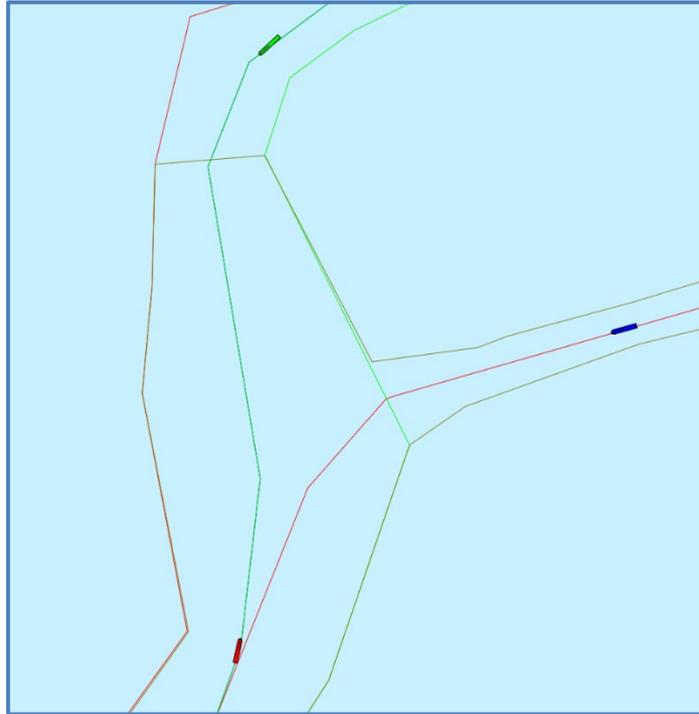


Figure 9 Three ships meeting outside Böttö - Phase 1.

The container vessel passes, in the next phase, ahead of the RoPax vessel, see Figure 10 and has gone out to starboard in order to meet the tanker. The RoPax vessel has reduced its speed, down to about 7-8 knots, see Figure 10 and is now preparing to steer out to starboard to come in behind the tanker.

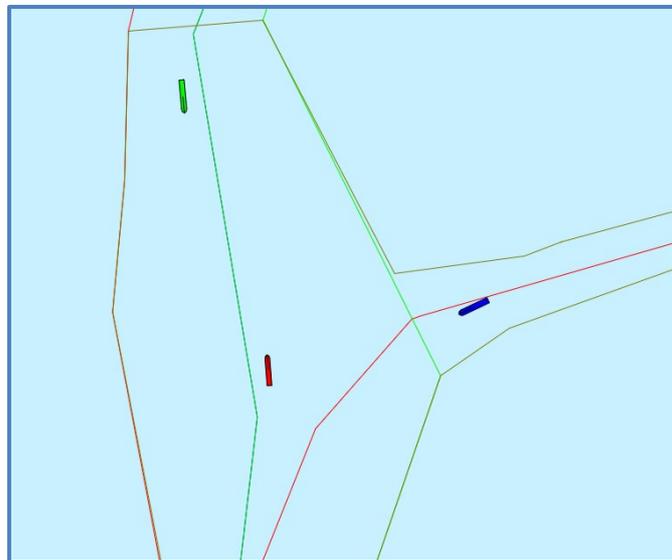


Figure 10 Three ships meeting outside Böttö - Phase 2.

In phase 3, see Figure 11 below, the container and the tanker are both steering back to the reference line after having completed the head on encounter. The RoPax vessel is steering behind the tanker and will eventually turn to port behind the tanker.

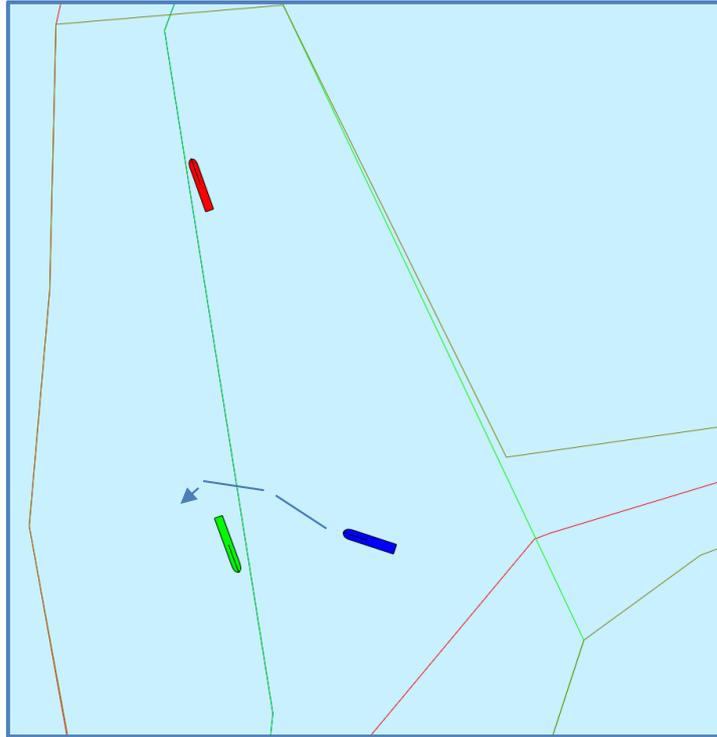


Figure 11 Three ships meeting outside Böttö - Phase 3.

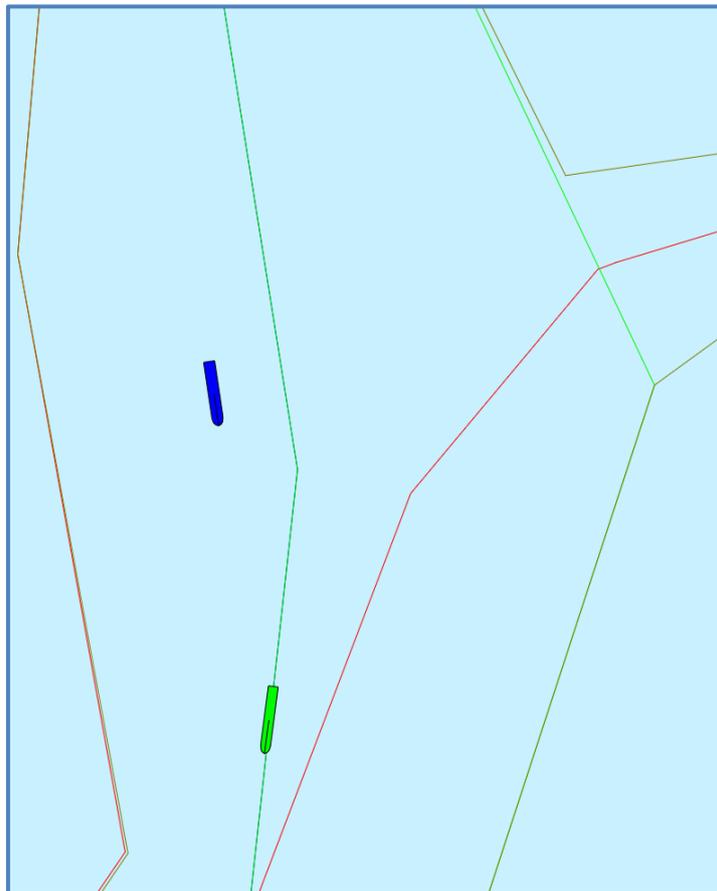


Figure 12 Three ships meeting outside Böttö - Phase 4.

## 2.4.4 Monte-Carlo simulations

As described in §2.3.1, the restricted fairway simulation scenarios were partially used to develop, test, and tune the autonomous steering algorithm.

In each simulation scenario, the RoPax ship had a *fixed* route and speed profile, forcing the ferry to take collision avoidance actions, and the road ferry was steered by the autonomous steering algorithm with slight variations on the parameters described in the previous sections governing its behaviour. The Monte-Carlo simulations were visualised to gain insights regarding the behaviour of the autonomous steering algorithm.

To verify that the autonomous steering algorithm produced realistic behaviour, the results from the simulations were compared against AIS data. The AIS analysis covered the Ljusterö ferry crossing during a period 30 days in the early spring of 2022. Figure 13 presents an aggregation of the location of the Ljusterö ferry and of ships larger than 50 meters. An overview and ship trajectories with the minimum passing distance are found in figure 14. Due to meeting traffic, ships over 50m deviated slightly from the fairway centre, but overall, each interaction was very predictable and only crossed the road ferry planned path.

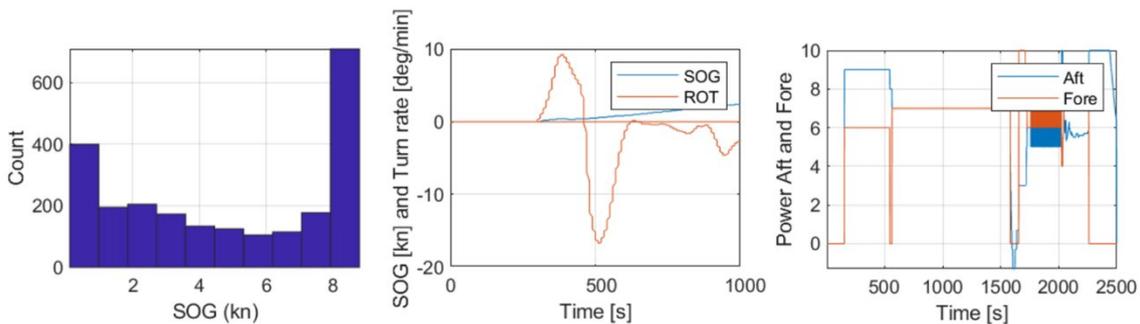


Figure 13 The figure shows a simulation result visualisation from one Monte Carlo run.

The Ljusterö ferry route area was used for the Monte Carlo simulation scenario as the area has good AIS coverage. It allows us to study real-life traffic behaviour and patterns to assist in defining normal behaviour for the track-keeping COLREG-compliant algorithm.

Additional to the road ferry, the most significant traffic volume observed was two large ships over 50 m simultaneously inside the observation area. The smallest distance between the road ferry and the other ship(s) was 116 m and an average passing distance of 418 m. From 272 situations where a ship over 50 m crossed the road ferry route, only in 76 situations did the road ferry stay docked. In all other cases, the road ferry was underway and either adjusted the speed or course to avoid the passing ship(s).

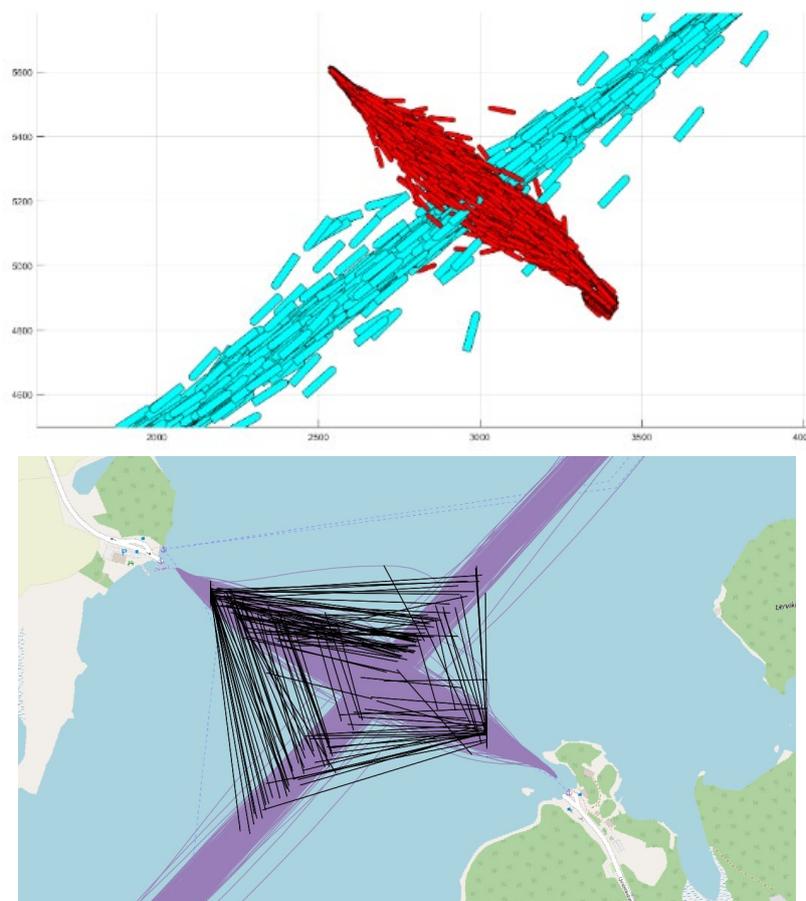


Figure 14 The figure shows on top the AIS positions of the road ferry in red and ships over 50m in blue. The bottom illustration shows the ship trajectories in purple and the minimum distances between the road ferry and passing ships in black lines.

Insight into the traffic pattern and behaviour around the road ferry assisted us in tuning the COLREG algorithm to a similar distance-keeping limits behaviour.

The AIS analysis is also an essential component in risk analysis as it gives insight into how often different traffic situation types occur and what vessel interactions are common. As the analysis shows, most ships over 50 m passing the road ferry are ships on regular traffic intervals. The area's geographical features allow only crossing situations with larger ships, resulting in a less complex traffic risk analysis than areas with longer routes and more open water.

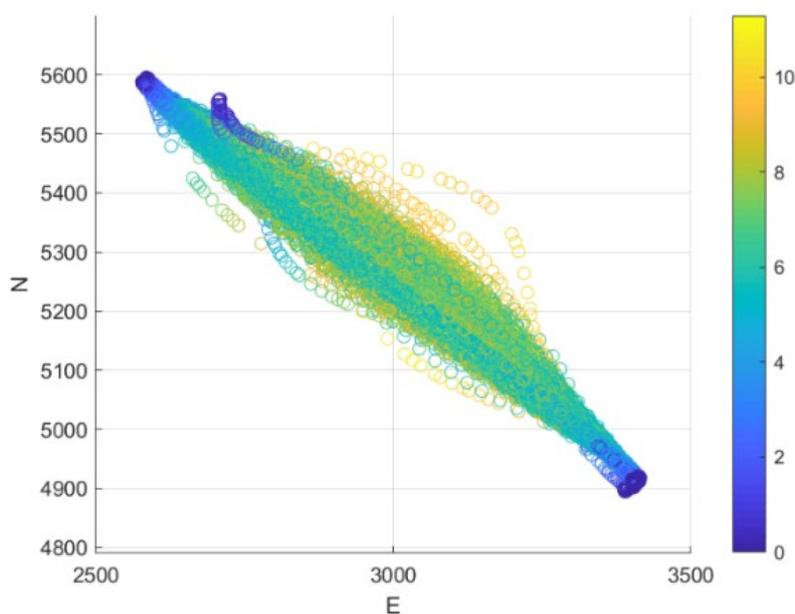


Figure 15 Road ferry positions and speeds from the Monte Carlo simulations. (Color scale: speed in meters per second; XY-axes: position in meters east and north from simulations origo).

## 2.5 Full Mission Bridge Simulator

In the simulations, Chalmers Full Mission Bridge Simulator was used. The simulator is based on Wärtsilä's Navi-Trainer Professional 5000 is certified by the classification society Det Norske Veritas as a Class A simulator that allows a complete simulation of the operations carried out onboard, including manoeuvring in confined areas. The simulator can simulate all the competence requirements of the international regulatory framework STCW95 and consists of three bridges with a cylindrical visual projection of 255, respectively 200 and 120 degrees.

The simulator layout is based on an integrated bridge philosophy and is provided with, and connected to, hands-on vessel equipment (Figure 16). Bridge layout conforms to the requirements of SOLAS Ch. V - Reg. 15, ref. MSC Circular 982 and IACS draft unified interpretation UI SE 181. The system interface software modules use normal and up to date data exchange standards such as e.g., NMEA standard via RS, CAN interface, Ethernet interface, etc. The Universal Exchange Data interface, covering a broad range of both digital and analogue input/output devices, expands the possibility to connect further hands-on equipment interacting with the simulator.



Figure 16 Inside of one of Chalmer's Full Mission Bridge Simulators.

## 2.6 Hybrid simulator

To enable the exchange of data between different simulation software i.e., Wärtsiläs Full Mission NTPro simulator and SEAMADE's SHIPMAN application, a standard protocol is used for communicating essential data. Chalmers Wärtsilä NTPro is already connected to the European Maritime Simulator Network (EMSN) by using the Standard for DIS (IEEE Std 1278.1-1995), while the DIS protocol has been implemented in SHIPMAN as part of this project.

DIS is a government/industry initiative to enable an infrastructure for linking simulations of various types at multiple locations to create realistic, complex, virtual worlds for the simulation of highly interactive activities.

IEEE Std 1278.1-1995 defines the format and semantics of data messages, also known as Protocol Data Units (PDUs), that are exchanged between simulation applications and simulation management. The PDUs provide information concerning simulated entity states, the type of entity interactions that take place in a DIS exercise, and data for management and control of a DIS exercise.

Each simulation application communicates the state (called ground truth) of the entity it controls/measures (location, orientation, velocity, articulated parts position, etc.) to other simulations on the network. IEEE Std 1278.1-1995 also specifies the communication services to be used with each of the PDUs.

The receiving application is responsible for taking this ground truth data and calculating whether the entity represented by the sending simulation is detectable by visual or electronic means. This perceived state of the entity is then displayed to the user as required by the individual simulation.

In the context of the project simulations only a subset of DIS PDUs used in the EMSN needed to be supported in order to achieve the goals. The mandatory PDUs are as follows:

Table 5 Mandatory PDUs.

PDU	Content
Entity State	speed, position, orientation, type, markings and entity appearance
Transmitter	For AIS-Exchange of messages 1,2,3 and 5
Receiver	For AIS-Exchange of messages 1,2,3 and 5
Signal	For AIS-Exchange of messages 1,2,3 and 5

The computer running the SHIPMAN simulator software, once configured with the DIS protocol and site ID IP address, was subsequently connected with Chalmers EMSN network card by a direct network cable. SHIPMAN and NTPro do not support a common synchronized entity model database. Each simulator site uses its own models to visualize external entities received from the DIS exercise. A simplified but sufficiently realistic impression can be achieved if there is an agreement about a set of entity models that shall be used for visualization in both simulators.

For the purpose of the simulations in the project, 3 suitable ship types as already used by Chalmers in the EMSN were identified and chosen:

Table 6 Suitable ship types.

Entity kind	Domain	Country	Category	Subcategory	Specific	Extra	Description
1	3	0	61	1	3	-	Generic Ship Container Class small (< 3.000 TEU, Feeder)
1	3	0	61	2	3	-	Generic Ship Tanker Class small (10.000 - 80.000 dwt)
1	3	0	61	3	9	-	Generic RoPax Vessel large (> 100 m)

Accordingly, SEAMADE developed 3 similar ship models to be used in their simulator and last but not least extensive testing was performed to verify the data exchange between the simulators.

# 3 RISK ANALYSIS

## 3.1 Introduction

The data obtained from the scenario simulations were used in the risk analysis and enable identification of risks not previously identified in the HAZID. The data obtained from the simulation scenario runs consists of recordings and interviews. A recording is a set of files describing the states of the vessels (position, speed, rudder angle, etc.), while an interview is a set of question answered by the navigators sailed the “crewed vessels” in the simulation. As shown in Figure 17, the recordings are processed through a numerical risk analysis. This analysis provides a “risk score” and a set of KPIs. Together with the interviews, the risk scores and KPIs are then used to identify new risks and provide further insights.

This chapter is organized as follows: section 3.2 presents the numerical risk analysis, section 3.3 presents the questionnaires given to the navigators after the simulations and the reasoning behind it; finally, section 3.4 presents a summary of the results from the simulations.

## 3.2 Numerical risk analysis

The numerical risk analysis quantifies the risk in the simulation scenarios. The output risk score of the analysis is calculated through several modules that evaluate different aspects of marine navigation. There are multiple navigation KPIs evaluated which were identified from a group interview with experts of marine navigation.

The situation risk varies depending on the operational environment, ship characteristics and other external influencing factors such as local customs and policies. The tracked KPIs each needs to be weighted with a factor that reflects the actual effect on the final aggregated risk quantification score. The weighted factors on the KPIs should also consider the aim of the risk analysis.

The different key performance indicators are grouped and combined into submodules. These submodules give aggregated insights for a performance area example geographic obstruction and traffic. The aggregated key performance indicators are named **risk index** in the evaluation model. Combining all submodules risk indexes will give the final risk score. The **risk score** is an aggregation of all risk indexes. An overview of the risk quantification model is seen in figure 17.

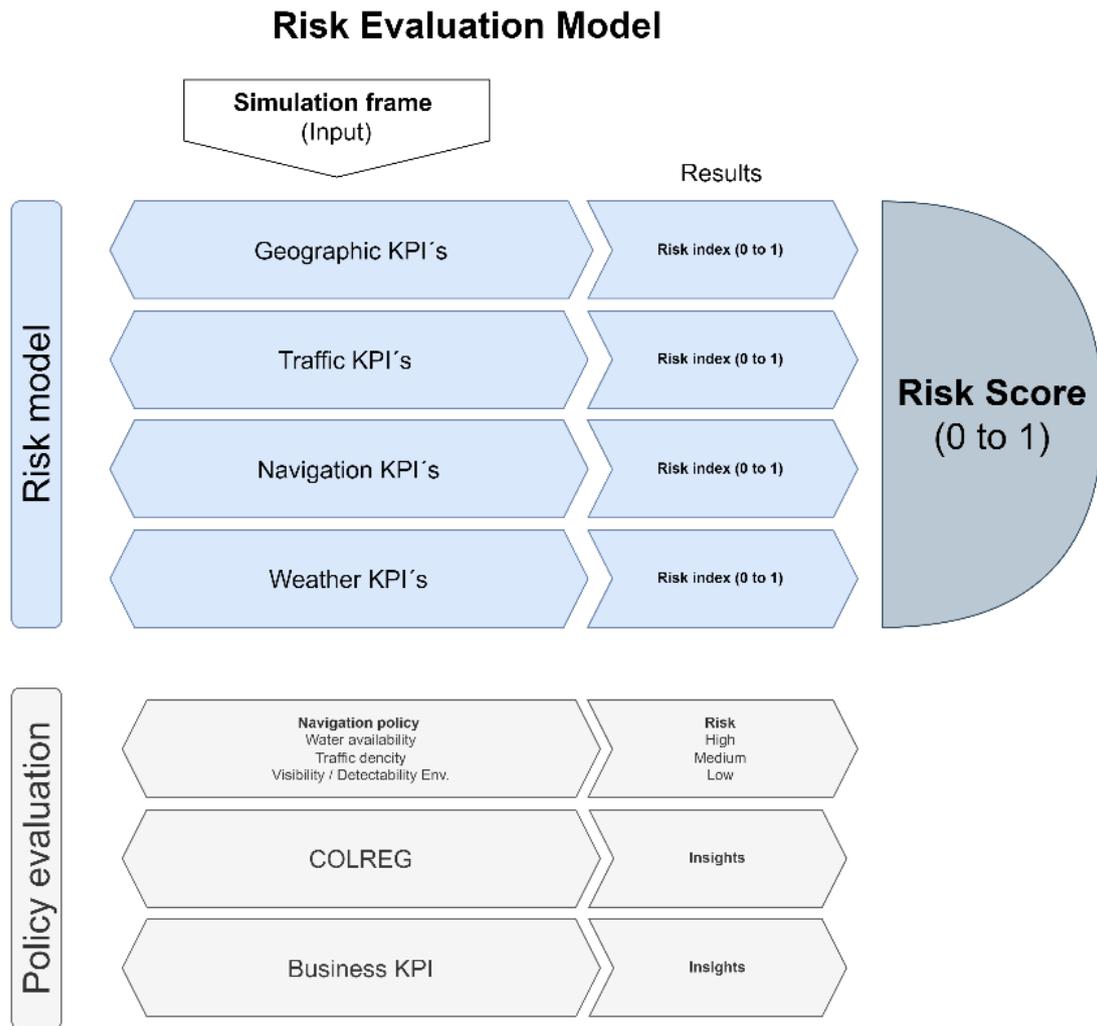


Figure 17 shows an overview of the risk evaluation model. The blue elements are the risk model, and the grey is the policy evaluation model.

The risk model describes the risk from a relative viewpoint for the own ship, which means all risk indexes are relative to the own ship. All other moving objects are targets, and all fixed or geographical features are seen as fixed obstacles.

The risk score from the risk model can assist in evaluating scenarios by providing an easily read index value. This allows for identifying events of interest related to increased risk in a large set of operational data from marine navigation. For example, plotting the risk score on a timeline for visual inspection. The risk score numerical format also allows for easy comparing scenarios.

This is especially useful when the analysis requires a high number of scenarios to be evaluated, whether manually going through the logged operational data or playback files is not feasible. This could also assist when marine navigation experts are not available to evaluate the scenarios. For example, developers with none or little maritime knowledge building marine navigation algorithms can get instant feedback on the algorithm's performance.

The overall risk evaluation model has a second module, Policy evaluation model, as seen in figure 17. This is because the ship may operate within its safe domain but not follow

the desired practice from the operator's perspective. Such events and limitations can be speed limits, no-go areas such as environmentally protected areas, timekeeping, fuel consumption, efficiency, or design constraints of the ship. These limits and contains are aimed to be tracked in the policy evaluation model as they do not increase the navigation risk.

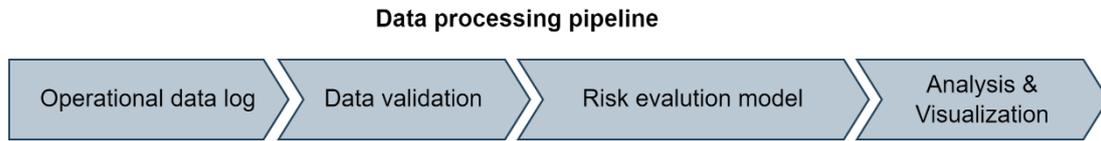
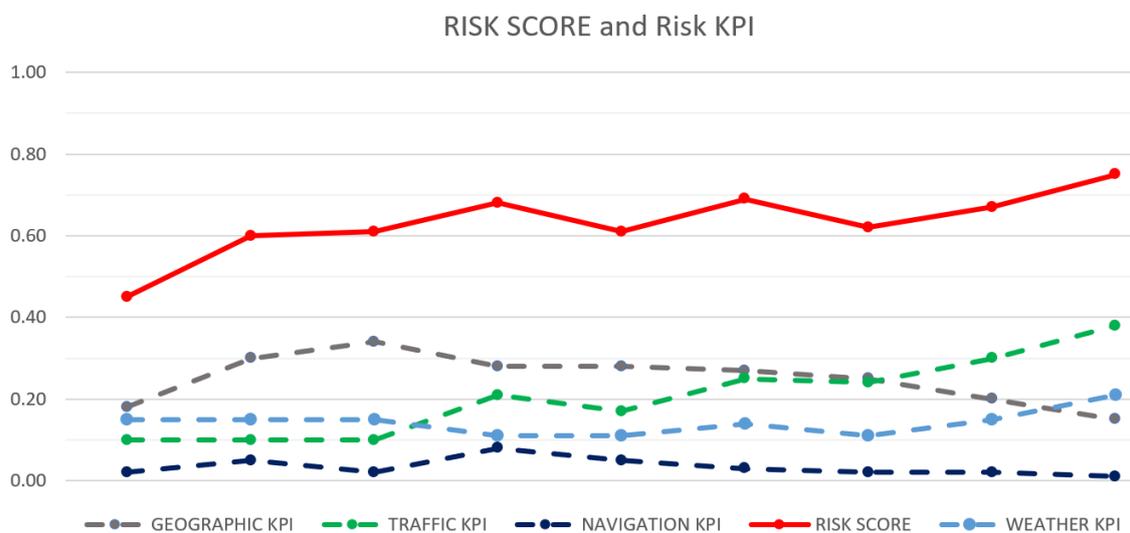


Figure 18 shows the risk evaluation model's primary processing steps.

The first step in the data processing sequence for the risk evaluation model is to obtain the operational data, either from simulation or real-life operation. The second step is validating the data parameter's trustworthiness and checking time synchronisation. As the risk model evaluates a frame or state for each specified time point in the scenario, the selected intervals between checked frames need to be selected based on how fast stats change so that the risk score captures and reflects the actual events for the scenario.

The third step in the data processing pipeline is to run the risk evaluation model. If a full risk evaluation is not desired, each submodule can be calculated independently. The fourth step is to process the result for comparison between scenarios by visualisation or numerical values giving insights. As the risk evaluation model is based on submodules, the risk score can be split up into the submodule's performance indexes, with can provide more insight into what is causing an increased risk score.



$$RISK\ SCORE = GEOGRAPHIC\ KPI + TRAFFIC\ KPI + NAVIGATION\ KPI + WEATHER\ KPI$$

Figure 19 shows an example of how the risk score is aggregated from the risk indexes.

### 3.2.1 Risk model

In this section, the risk model is described consisting of four submodules: Geographic KPI, Traffic KPI, Navigation KPI and Weather KPI. The risk module tracks performance indicators to objectively evaluate marine navigation risks for the own ship's operational domain. The output or result from the risk module is a risk score from zero to one based on the risk indexes. A score of zero is the lowest likelihood and smallest consequences, and one is the highest likelihood and biggest consequences. The submodules also return risk indexes from zero to one, with zero being the lowest likelihood and consequence and one being the highest likelihood and consequence.

The risk model uses a simplified reachability simulation for all moving objects. The reachability simulation allows finding the reachable area ahead of the moving object. The simulations consider external forces such as wind and current along with the moving object's characteristics to manoeuvre and stability performance. The reachability simulation starting point is the moving object's current position and environmental state. The reachability simulation time length is dependent on the submodule function aim. Most future positions reached within the set simulation time are combined into a polygon area describing the reachable region for the moving object. All fixed and moving object obstacles are ignored in the simulations; therefore, the reachability area will go beyond the grounding line.

An example of the environmental effects on the reachability simulation are visualised in figure 20. The illustration to the left has no wind or current, which creates a uniform reachability area. The middle and left illustration have strong wind and current pushing the own ship either south or north, as indicated by the blue area.

The geographical features are ignored, and moving objects are not affecting the reachability simulation area. These limitations will be managed in the submodules Geographic KPI and Traffic KPI.



Figure 20 shows the reachability area in blue and the crash stop area in red. The left illustration has no environmental effects. The centre illustration has a strong wind from the north and current to the south. The right illustration has a strong wind from the south and current towards the north.

The geographic KPI module is mainly for determining the grounding risk and has two KPI submodules: navigable water and available fairway. These submodules generate

each a risk index and together generate a geographic risk index. The geographic KPI is checking risks related to geographic features such as grounding lines, fixed objects and intended areas potentially used for navigation.

Both the submodules; navigable water and available fairway use reachability analysis to obtain the area ahead of the own ship.

The navigable water submodule checks how big the area inside the reachability area that has safe navigable water or in other words available water depth based on the current maximum draft. When knowing both reachable area and navigable area this area the risk index can be calculated by:

$$\frac{\text{reachable area}}{\text{navigable area}} = \text{navigable water risk}$$

The available fairway submodule can be described as the intended or planned water space that could be used for navigation in normal circumstances, including space for collision avoidance maneuverers and counteracting environmental forces. Emergency beaching places or anchorage areas are not included because they are not part of the intended operational voyage plan. A simplified approach to this could be to take the planned route safety corridor, but the borders to the corridor are often set by a constant value for each leg and do not accurately reflect the available fairway. Therefore, we are generating a custom area around the planned voyage track that includes optional parts, varying with availability along a leg based on available water, fairway, or other restrictions. When knowing both reachable area and reachable fairway area this area the risk index can be calculated by:

$$\frac{\text{reachable\_area}}{\text{reachable\_fairway\_area}} = \text{risk\_navigable\_fairway}$$

The traffic KPI is intended to identify risks associated with nearby traffic and moving objects around the own ship. Mainly it is other ships, but also including moving objects such as swimmers or floating objects. The traffic or objects in the vicinity of own ship are named targets for the modules. The main influencing factors on the traffic risk for the own ship are: target size, movement, ship or object type, navigation state, distance, detectability and predictability of movement.

To decrease the complexity of risk assessments associated with traffic the traffic KPI module is divided up into four submodules: Targets Reach, Traffic Density, Traffic Collision and Erratic Targets. The division also allows more insight into each performance index. The risk indexes are selected after discussions with marine navigation experts participating in the simulations.

The traffic KPI returns a result normalized from zero to one, where zero is lowest risk and one is the highest risk. To connect the resulting risk factor to perceived traffic risk impact a worst-case operational traffic intensity needs to be defined.

To determine collision risk in close-quarter situations, we use reachability simulations to obtain all moving object's reachable areas and then check if there is a possibility for

overlapping travel paths. The main objective of this submodule is only to quantify the risk associated with close-quarters and collision avoidance. The target reach area for close-quarters risk association is from the reliability simulation, which is effective for a maximum period it takes the target to return to the initial simulation start state. With a longer timeframe, the target's expected travel path gets to a large uncertainty as the target has the potential to travel in any direction making the reliability simulation the same effect as a distance calculation.

Where the own ship reachability area overlaps with a target reachability area is the area of where a potential collision can occur between the own ship and the target. The likelihood of a collision then depends on the area size. Suppose that there is no overlap of own ship and target reachability area, then the close quarters risk index is zero. If the overlapping covers the entire reachability area of the own ship, the risk index is one.

The following calculation is used for the close quarter risk index:

$$\frac{\text{obstacle\_free\_area}}{\text{navigable\_area}} = \text{close\_quarter\_risk}$$

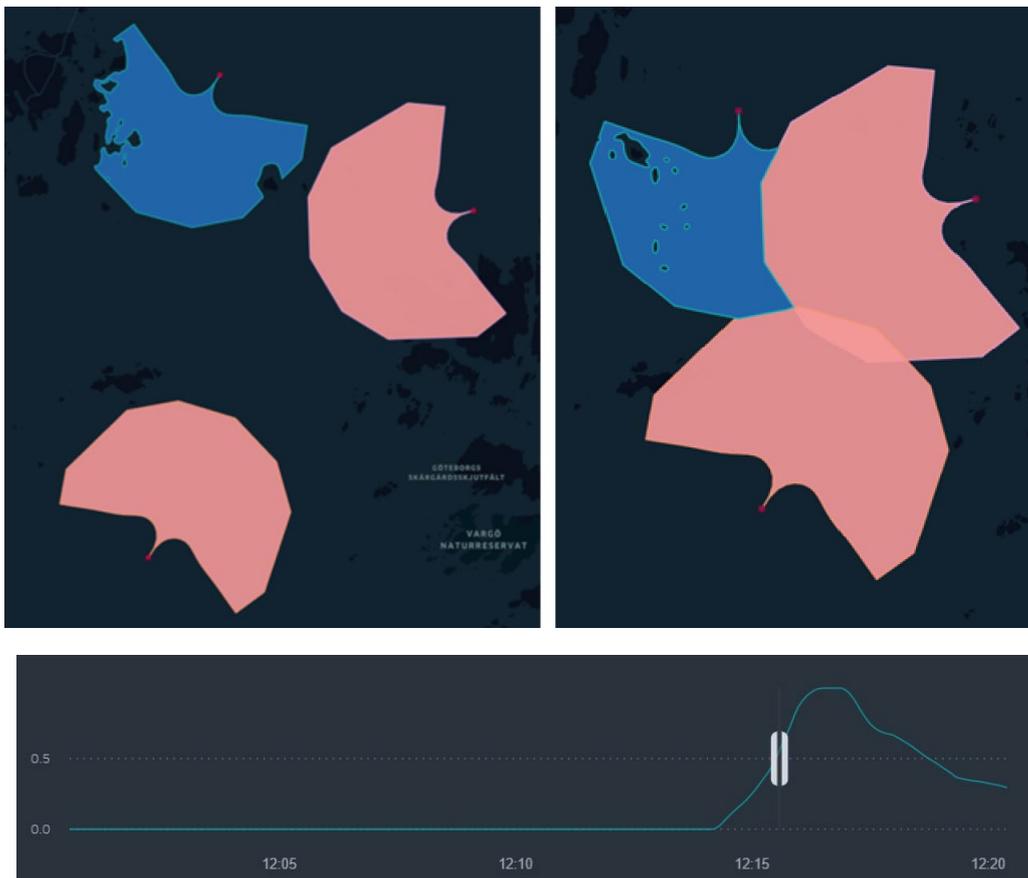


Figure 21 shows 3 min reachability simulations for own ship identified by the blue area and two targets with the red area. The left picture is before the close quarters situation, where none of the areas overlaps with the close quarters risk index at zero. The right picture shows that the reachability areas overlap with the close quarters risk index near 0.5 in the scenario. Below is a timeline of the simulation scenario risk index for each simulation frame. The risk indexes start to increase as the close-quarters situation takes effect. The index marker around 0.5 risk index is for the right picture.

The traffic density index estimates the risk based on how many targets are around the own ship and the targets' movements. As the traffic density increases, the complexity of navigation and collision avoidance tasks increases due to the potential of limiting manoeuvrability space as other targets occupy navigable water. The highest amount of traffic density needs to be defined for the operational area to allow the risk index to be normalized. The traffic density estimation should be the worst case. Historical AIS data could be utilised to estimate the worst-case traffic density, rely on input from navigators with experience in the operational area, or even system manufacturer's operational design limitations or guidelines if boundaries are set for operations.

Figure 22 shows the own ship RoPax vessel outbound in Gotenburg archipelago (Green track), with a tanker outbound in the northern fairway and an inbound container vessel from the south. The target's colour intensity is the individual target traffic density risk, and the own ships green track shows the colour intensity of the aggregated traffic density risk. As seen in the figure, the intensity increases until the close quarters situation occurs at the end of the scenario, and the traffic density risk decreases after the own ship passes the targets.



Figure 22 shows an example of traffic density index from the perspective of own ship RoPax ship outbound in the Gothenburg archipelago, identified by the green track and targets read track.

The traffic collision risk index aims to assess the actual risk of collisions from the current state of own ship and targets. The submodule mainly uses Closed Point of Approach (CPA) and Time to CPA (TCPA) values to assess the collision risk for likelihood and consequence based on target mass and relative speed.

The traffic monitoring area needs to be specified by a navigation policy to normalise the traffic collision risk index. The submodule required a CPA distance definition of when collision risk potentially starts occurring. This will mainly be dependent on the ship type and manoeuvrability characteristics.

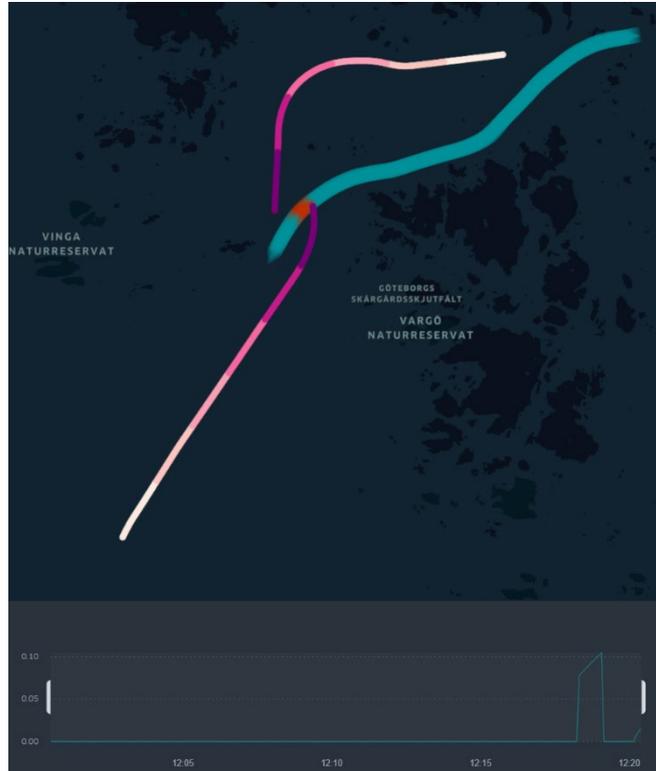


Figure 23 shows traffic collision risk index from the perspective of the RoPax ship. Blue and red zone indicate higher collision risk.

Erratic targets that show unusual behaviour are easily identifiable for a human operator but putting erratic behaviour categorization into logical statements has shown to be difficult. To demonstrate the concept in the project, we simplified it to check for a larger change in the rate of turn and speed on target ships. A larger action taken may indicate that a course or speed change was initiated too late. This concept is mainly intended for open waters, but to also include it under archipelago navigation, a lower limit of acceptable rate of turn are defined for each ship and navigation mode.

### 3.2.1.1 Navigation KPI

The navigation KPIs describe the management of own ship movement and performance based on navigation decisions related to increased risk both short time and long term. Depending on the ship type and cargo, ships are designed to operate within their design limits. Technical and structural limits of equipment and machinery require that the navigator avoids a high load on the ship's system under normal navigation conditions.

Suppose the ship is underway and the voyage plan is not stating a manoeuvre change. In that case, a larger change in speed or manoeuvring is classed as unexpected behaviour related to an increased risk for the situation. These can be any excessive unplanned actions due to collision avoidance, avoiding debris in the water or compensating for ice or other weather effects. As it would be too complex to individually check for all

unnatural event conditions, the Navigation KPI module is trying to identify these increased risk situations based on the own ship state changes.

### 3.2.1.2 Weather KPI

Weather and external forces affecting the ship's navigation are taken into consideration partly in the reachability simulation. The reachability simulation includes external weather effects such as wind and current. This is how far this project includes the weather risk into the risk score. All simulations carried out were under prevailing weather conditions.

Weather impacting the navigation of the ship will have a significant effect on the risk of the own ship. It is also important to consider risks related to navigating in heavy weather or how the ship operation manages severe weather forecasts. But the effect of weather on the ship construction should be determined from the ship's sea-keeping design capabilities, which falls outside of the scope for these simulations carried out in this project.

### 3.2.1.3 Submodule effect on risk score

Each submodule produces a risk index describing risk quantification and performance insights. All indexes return a value from zero to one where zero is the lowest risk, and one is the highest risk. Each submodule has a specified effect weight. An example of this can be seen in figure 35. All submodules risk indexes aggregated are the risk score.

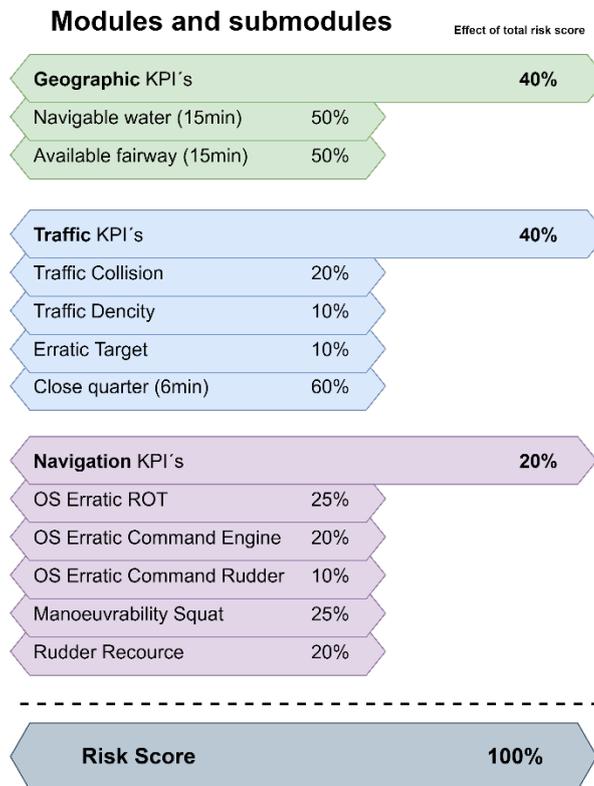


Figure 24 shows an overview of the submodule's weight effect on the risk score.

The weight is set based on discussion with navigation experts, and it was determined that the effect for each module should be as seen in figure 15; the Geographic KPI module

with an effect of 40%, Traffic KPI module with an effect of 40%, Navigation KPI effect of 20% and weather KPI effect of 0%. The submodules also affect varying dependent on the function relevancy to increased risk for the own ship.



Figure 25 shows different risk indexes plotted for each submodule with red indicating higher risk; the left picture is the Geographic KPI risk index, the centre image shows the navigation KPI risk index, and the right image shows the traffic KPI risk index.

As seen in figure 25, each module resulting risk index has been plotted on a map, with each position having a calculated risk index score. The Geographic KPI risk index can be seen in the east as a higher risk index due to the own ship future inside the archipelago compared to the west side, where the ship is closer to the open sea. The Navigation KPI risk index has lower risk on the straight and higher in the turns. For the Traffic KPI risk index, the actual ship meeting happened in the west area, reflecting the higher risk score. The total risk score is plotted in figure 26, where we can easily detect the high risk that occurs at the close quarter traffic situation.

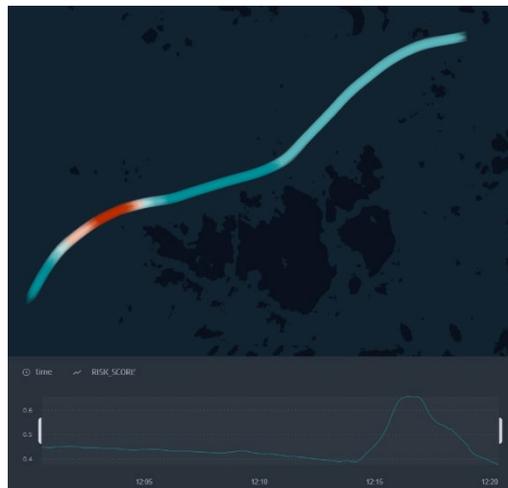


Figure 26 shows the risk score with red positions plots indicating the highest risk areas under a simulation scenario.

### 3.2.1.4 Validation of the risk quantification model

The hybrid simulation scenarios were conducted in the fairway and open sea areas. Manned ships and autonomous ships interacted in the same operational area. The impact of introducing autonomous ships is mainly made by comparing the hybrid simulations to the fully manned simulations. These allowed us to analyse the effects and

identify the risks associated with introducing unmanned ships into the same navigational domain as manned ships.

The experienced navigators who participated in the simulation scenarios with only manned ships perceived the risk score as shown in table 8. The scenario risk behaviour goal is low, normal, or high risk set for each simulation scenario. It is achieved according to the participant's average perceived risk score and reflected in the group interview debriefing feedback.

Table 7 shows the participant's perceived risk score for the simulated scenarios with only crewed ships. A score of zero is low, and ten is high.

		Scenario Risk level (0-10)	Own Risk level (0-10)
		Average	Average
Fairway	Low	1.33	1.00
	Normal	4.50	4.17
	High	6.33	6.33
Open sea	Low	1.00	0.67
	Normal	3.40	2.00
	High	7.00	7.00

The manned simulation scenarios with normal risks behavioural goals are where the navigation experts agree that the upper acceptable risk level under real-life situations with traffic would be around. Ideally, the risk level under normal conditions in real life should be preferable, close to the low-risk score of around two. Only under heavy traffic is the risk score expected to move up to five as the acceptable upper limit.

Long-term planning was not an option because the simulation scenarios were designed to create a close-quarters situation with the participant only having 20 min to the close-quarters situation. For example, the close-quarters traffic situation could have been avoided with long-term traffic management planning in the fairway scenario.

The high-risk behavioural goal with manned ships changed the navigation style towards a more stubborn driving style as the navigators kept their course and speed for longer and initialized the collision avoidance action at the last minute. The ship's track can be seen in figure 27 high-risk timeline position plot.

The risk score for the only manned simulations is shown in the figure 28 position timeline plot, where the scenario goals are high-, medium and low. The visualisation of each scenario ship track indicates the risk score with the colour intensity. The most notable behaviour changes are the distance between the vessels and the timing of the meeting.



Figure 27 shows ship tracks from the only manned ship's fairway simulation scenarios. The track colour intensity indicates a higher risk score.

As seen in figure 28 each scenario, the ship has a risk-level strategy:

In the **low-risk strategy**, the RoPax ship from the east speeded up, and the other slowed down to avoid a three ships close-quarters situation. The navigation experts agreed this approach was the most likely outcome for a real-world scenario. The timing of meeting or overtaking would have been communicated between ships.

In the **medium risk strategy**, all ships kept their initial speed, forcing a close quarters situation between the three ships, but maintained a good distance between them to the extent the geographical features allowed.

In the **high-risk strategy**, all ships stubbornly keep the fairway centre line and maintain the initial speeds resulting in a very close-quarters situation. The “driving style” resulted in all ships doing a last-minute collision avoidance action to avoid a collision.

The notable difference in the risk levels is that the highest risk score period is longer compared to a lower risk level scenario. In the risk score timelines, we can also see small bumps that are caused by an erratic engine or rudder usage. Especially noted on the ALPHA ship that was a large tanker with unresponsive manoeuvrability characteristics made it harder for the navigators to gain familiarity with the vessel characteristics under the short time period of the simulation scenarios.

## Fairway

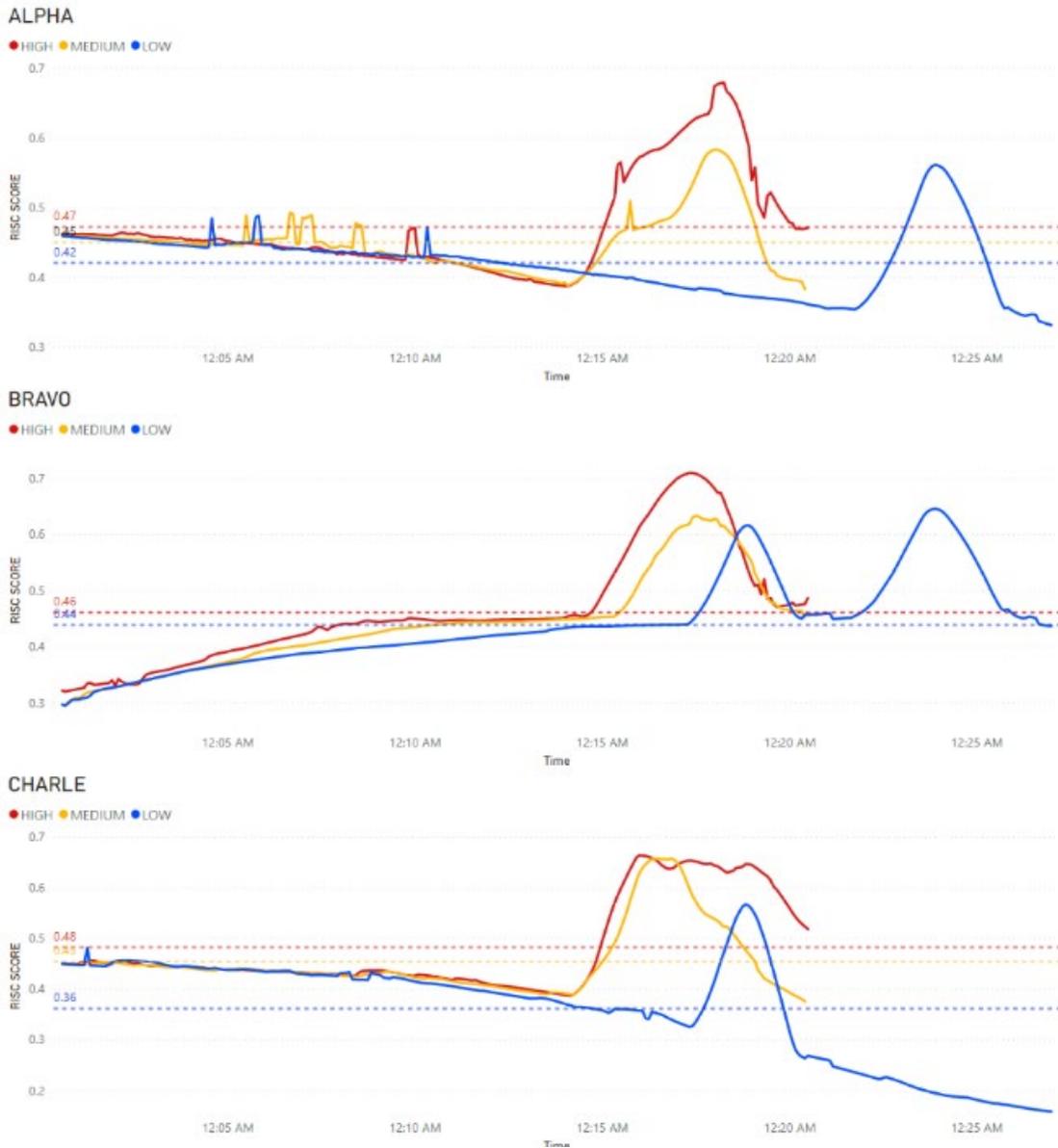


Figure 28 Timeline plot shows fairway scenarios with only manned ships with the risk scores for each simulation frame.

## Open Sea

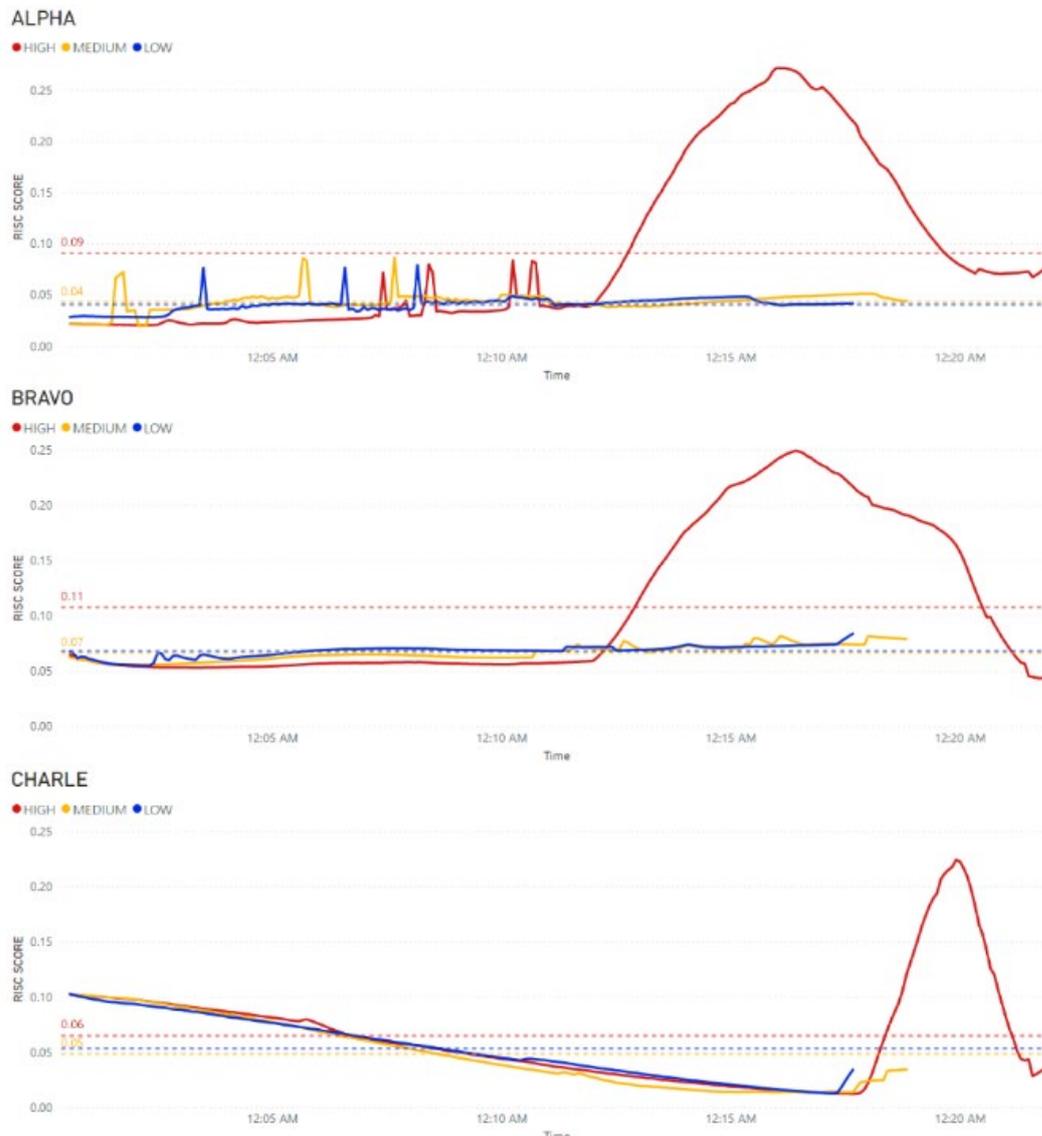


Figure 29 Timeline plot shows open sea scenarios with only manned ships with the risk scores for each simulation frame.

As the risk score is an aim to move closer to a more objective risk evaluation judgements, the open sea and fairway scenarios significantly differ in the maximum risk score. This is due to the geographical risk being almost non existing in the open sea scenarios.

### 3.2.2 Policy evaluation

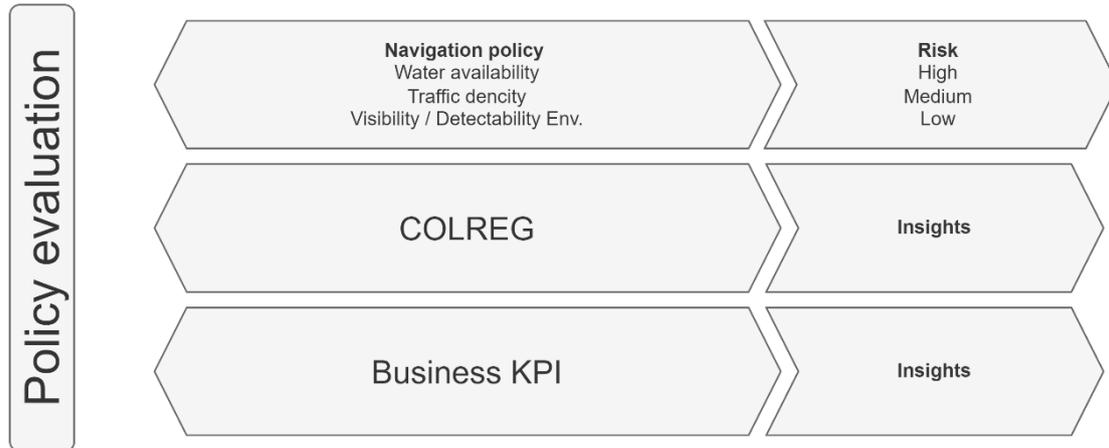


Figure 30 shows an example of how a policy evaluation module.

The primary purpose of the policy evaluation module is to provide insight into the performance that is not directly connected to increased risk but needs to be understood for containing the operation within the desired operational domain.

The policy evaluation model keeps track of operationally defined limits mostly coming from some form of policy, for example, operational limitations of engines, company navigation policy, no-go zones, regulations, or other guidelines on international-, national- or company level, even local customs and behaviour fall under this module.

The functions under policy evaluation are evaluated mainly by logical statements that are either true or false or categorise the operational state. Policy submodules functions output can also be index value or a flag highlighting that a limit is exceeded.

Submodules in the policy evaluation module are dependent on the target operational domain for the own ship. For the purpose of this project, the submodules selected are generic and just a base with include the following submodules Navigation policy, COLREG and Business KPI. In addition to the mentioned submodules, it was discussed with experts to include environmental policy covering emissions and other pollution, emergency procedures and redundancy level. These are not covered because they could also be included in the previously mentioned submodules which may even include the state of equipment onboard or available communication networks.

The COLREG policy evaluations intended to validate if the own ship complying with COLREG. Due to COLREG being very complex, we only cover a small part in this project, the work will be continued under “COLREG 2” project part of Trafikverkets Branchprogram Hållbar sjöfart.

Like the previous, the Business KPI provides insight on the navigation efficiency-oriented to business-driven goals. This can be requirements from a transport contract, timekeeping, fuel consumption, cargo environment conditions or passenger comfort.

### 3.3 Interviews

Each simulation scenario involving manned bridges had feedback and input collected from the participants through questionnaires and group interviews. The feedback collected was used for tuning the risk quantification model and identifying new potential risks related to the introduction of autonomous ships inside the operational domain of manned ships.

In total 6 participants were included in the project for manning simulation bridges and assisting with inputs and feedback on the risk quantification and identification. The navigation expert participants had in average 13 years of experience in analysing navigation scenarios and eight years working onboard ships with navigational tasks. The high number of years analysing navigation scenarios is due to the participants being or having been simulator instructors and teaching navigation at a simulation centre. Also, a few participants had experience in maritime accident investigations.

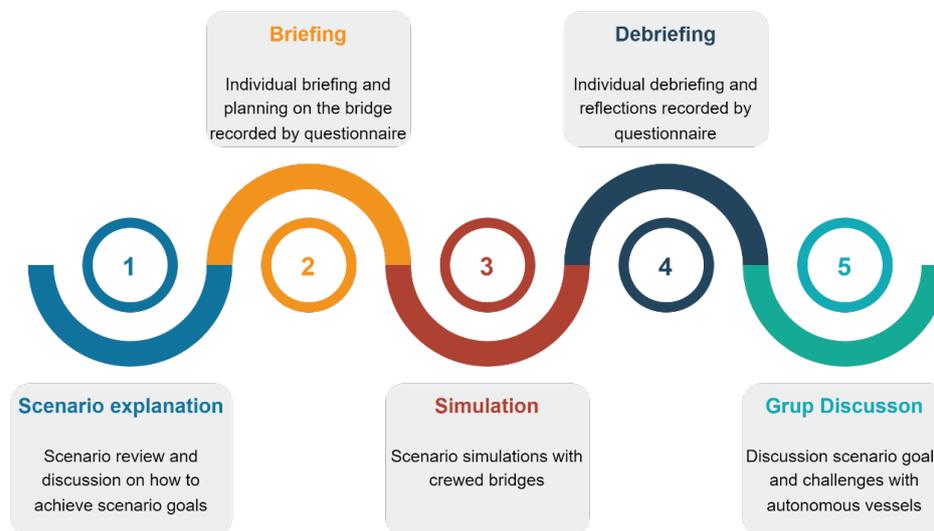


Figure 31 shows the simulation process with involved manned ships scenario to collect input and feedback from participants.

Feedback and expert opinions collected during the simulation sessions had the following steps, as seen in figure 31:

- 1) The scenario session started with an introduction of the area and scenario along with the bridge equipment and vessel model. Behavioural risk goals and scenario goals were stated to participants.
- 2) Before the scenario simulation, each participant got to familiarise themselves with the bridge, ship model and voyage plan. Feedback and input were collected from a participant about expectations of the other ship's behaviour, safety margins and own navigation strategy plan to achieve the scenario goal. Questionnaires were used for collecting feedback and input.
- 3) During the simulation, participants entirely concentrated on the navigation and scenario goal, and only simulation logs were collected during these periods.
- 4) After the simulation, participants individually answered a debriefing questionnaire to gather feedback on scenario events that unfolded as expected or

deviations occurred and assign risk scores for their own ship, targets and the whole scenario.

- 5) The session ended with a group discussion in the format of a debriefing of events and under the scenario and risk identified related to autonomous ships.

## 3.4 Lessons learned from simulations

This section will go over lessons learned from the simulations. Suggestions and highlights were selected from the interviews with navigation experts regarding the results from the simulations. Focusing on potential emerging risks, control measures and potential future outcomes with the introduction of unmanned ships within the same operational domain as manned ships.

Due to a small sample set of simulations and only mimicking fully autonomous ship capabilities with a track keeping and COLREG compliance algorithm, the quantified result should be interpreted as a guiding hand. The navigator expected the unmanned ships algorithm to behave like the navigator's "driving" behaviour. The navigators approached the autonomous ships with high expectations that they could keep their navigations style unchanged when interacting with the unmanned ships. But as early state prototypes showed, the unmanned vessels had a few unexpected behaviours that led to a grounding and a collision under the simulation's scenarios, allowing lessons to be learned.

### 3.4.1 Perceived risk

In the hybrid simulations scenarios, the navigation experts operated in the same traffic domain as unmanned ships. Based on the answers in the questionnaire, the following table describes the perceived average risk from the manned ships perspective, shown in table 8.

Two manned ships & one autonomous ship				One manned ship & two autonomous ships					
		Scenario Risk level (0-10)		Own Risk level (0-10)		Scenario Risk level (0-10)		Own Risk level (0-10)	
		Average		Average		Average		Average	
Fairway	Low	1.50	2.00	5.00	5.00	10.00	10.00	5.00	5.00
	Normal	6.50	4.50	10.00	10.00	10.00	10.00	5.00	5.00
	High	8.50	7.00	10.00	7.00	8.00	8.00	5.00	5.00
Open Sea	Low	2.00	1.50	5.00	5.00	5.00	5.00	5.00	5.00
	Normal	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
	High	6.00	5.00	8.00	8.00	8.00	8.00	8.00	8.00

Table 8 shows the participant's perceived risk score for the simulated scenarios with autonomous ships. A score of zero is low, and ten is high.

From a general perspective, we can see a slight increase in the perceived risk compared to the only manned vessel scenarios. Mainly increased risks are found in the fairway area due to a grounding and collision that can occur. Based on the risk quantification model, we identified a similar trend of increased risk with the introduction of unmanned ships into the same traffic domain as manned ships both for the fairway and open sea area. The increased risk score was identified by a higher risk score for a longer time compared to the only manned scenarios. An example of the increased risk score can be seen in figure 43 showing the scenarios with the own ship perspective from the RoPax ship.

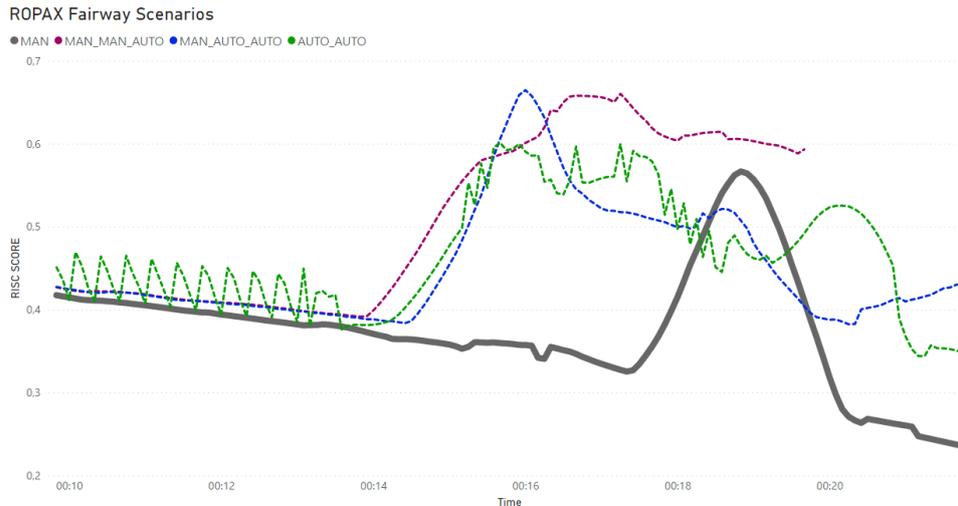


Figure 32 shows RoPax ship risk scores for each low-risk behaviour fairway scenario.

### 3.4.1.1 No communication

The autonomous ships used in the simulations for the projects had no functionality that enabled other vessels to communicate or exchange information. Neither implemented remote control operators that could assist in situations where autonomous vessel reached their operational limitations. This increased the reliance on pre-defined expectations based on COLREG and traffic patterns.

To gain an understanding of what the effects were with no communication capabilities between ships, we simulated fully manned ships on both open sea and fairway area scenarios with communication allowed and simulation with no communication allowed. The resulting tracks from the fairway area with speed profiles and risk scores can be seen in figure 34.

In the ship-to-ship communication test scenarios on the open sea area, no significant change in perceived risk or risk score were observed. The feedback from the navigators related to lack of communication on open sea indicated that lack of communication did not contribute to increased risk. With sufficient navigable water around and collision risk targets complying according to COLREG, there is no need for ship-to-ship communication.

In the fairway scenario where it is required to meet other ships in a restricted water space, the timing of the meeting point gains importance. This could be observed in the fairway scenarios when testing ship-to-ship communication effect by observing the timing of the meeting point in the fairway scenario in figure 34.

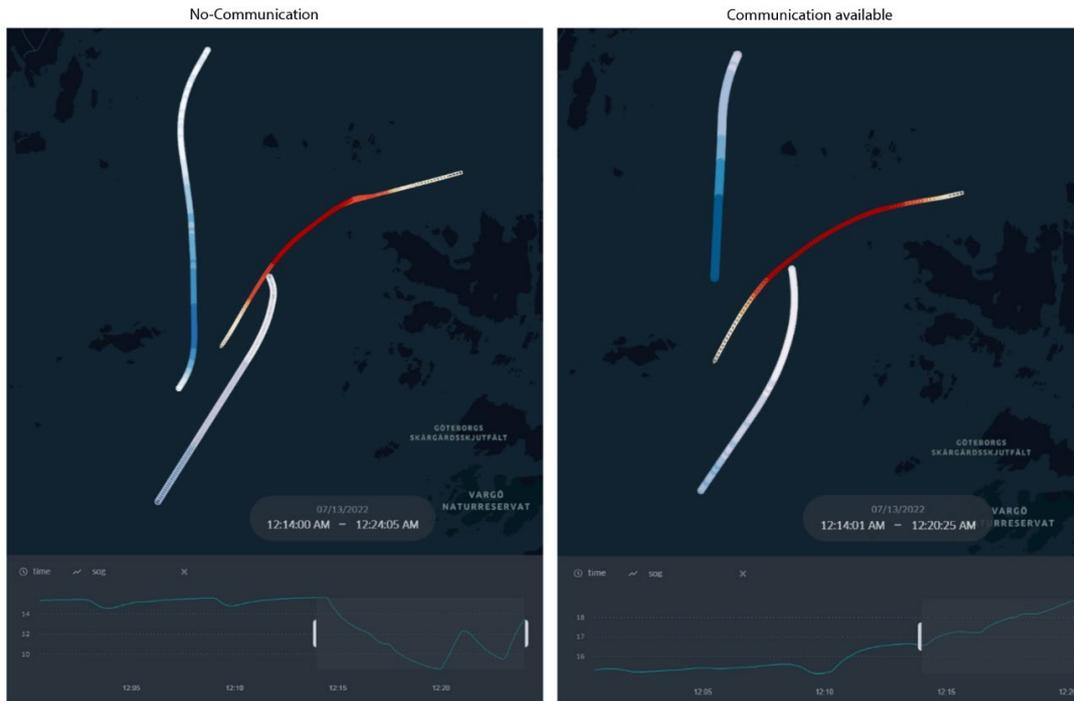


Figure 33 shows the ship tracks for communication effect scenarios with own ship (red) risk score change and target ships (blue) speed over ground change and below own ship speed over ground profile.

With no communication and only timing of the meeting point based on the observation of the target's position and speed and not knowing the route made the no communication scenario riskier than when having communication established between the ships. This was also observed in the risk quantification models where the maximum risk score was almost the same but the scenario with no communication had a prolonged period of higher risk score. The risk score from the ship-to-ship communication test can be found in figure 35.

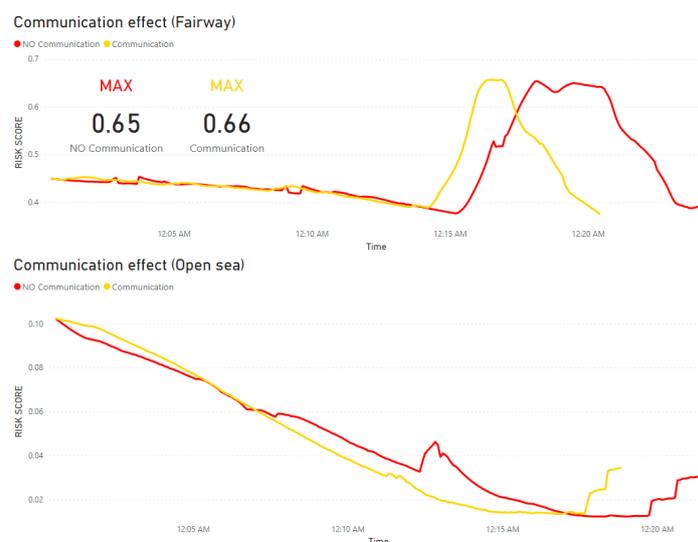


Figure 34 shows the simulation scenarios risk score of no-communication and communication for the fairway on the top and the open sea scenario on the bottom.

The main findings related to unmanned ship from the scenarios with no communication and communication:

- A ship should be capable of communicating its intention.
- A ship should be capable of communicating and establishing a plan of action with an external actor. For example, meeting point, who will go first or overtaking in restricted water.

Supposing external arrangements over VHF can be made with an unmanned vessel with an automated function to comply. In that case, this functionality could be vulnerable to hacking as the external input affects the unmanned ship navigation and such a function should be implemented with extra caution.

### 3.4.1.2 Interaction between manned and unmanned ships

This section focuses on the interaction between manned and unmanned ships within the same operational domain.

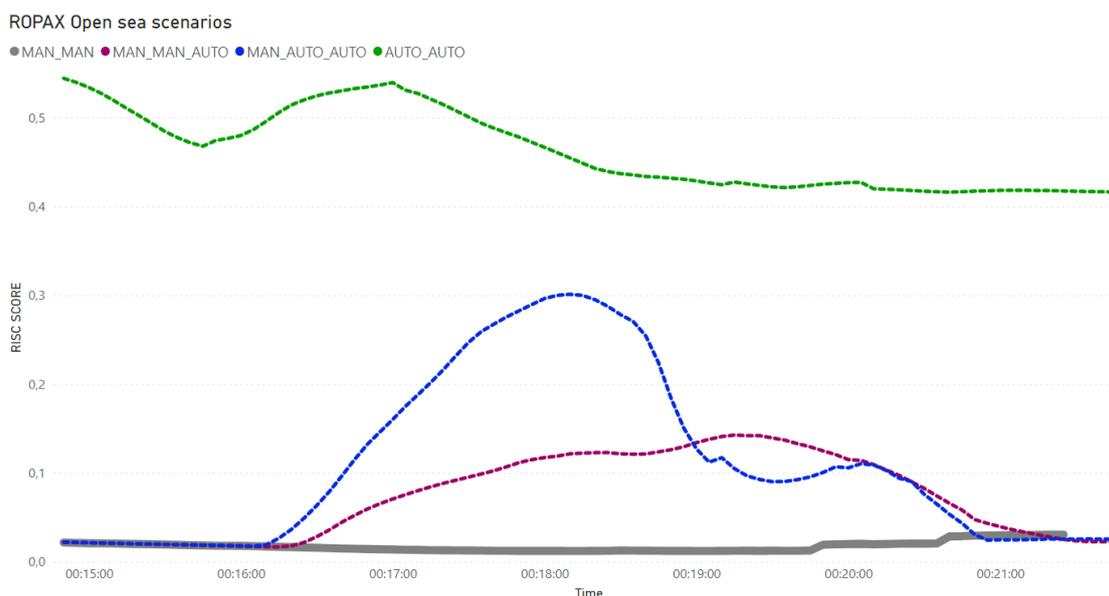


Figure 35 shows all low-risk open sea scenarios from the perspective of the RoPax.

In the open sea scenario, we can see that the safety boundaries or acceptable distances between ships in collision avoidance situations are smaller for unmanned ships than for manned ships. These are entirely dependent on the setting of the algorithm on the unmanned ships in the simulation. As the acceptable distances for the unmanned ships were smaller, the scenario with only unmanned ships had the highest risk score of the simulations on the open sea.

#### **Collision between manned and unmanned ship**

One medium-risk behavioural goal fairway scenario ended up in a collision between a manned and an unmanned ship. As seen in figure 47 the manned RoPax ship is outbound in the south fairway heading west and soon to turn south while an unmanned container ship is inbound and heading northeast and soon to turn north to follow the northern fairway.

The unmanned ship does not recognise the collision risks yet with the outbound RoPax ship and continues to follow its intended route by turning northward. The unmanned ship's turn to port is interpreted by the RoPax ship as if the unmanned ship is giving way on the east side of the fairway for the RoPax ship to head south and meet green to green. The RoPax appreciates these intended meetings as it does not require the RoPax ship to go ahead of the container ship and then turn south. This results in the RoPax ship starting to turn to port to keep the east side of the fairway.

The unmanned ship decreased its turn rate to port. However, only 2 minutes before the collision, the RoPax ship entered a high enough starboard bearing, which made the unmanned container ship reclassify the RoPax ship as a stand-on ship coming from the starboard. The low CPA and TCPA trigger the unmanned ship to initialize a hard starboard turn to give way for the RoPax ship. This resulted in the unmanned and manned ship colliding.

After the collision occurred, the unmanned ship did not stop. Instead, the unmanned ship tried by all means available to return to the route and continue the voyage.

The main findings related to unmanned ship and manned ship collision:

- Autonomous ships should not end up in such a situation at first, and if they do, they should try to minimise the damage.
- The intentions at a meeting should be standardised or confirmed by information exchange.
- The unmanned ship should proceed to a safe state configuration if an incident occurs. A safe state needs to be determined by the incident type.

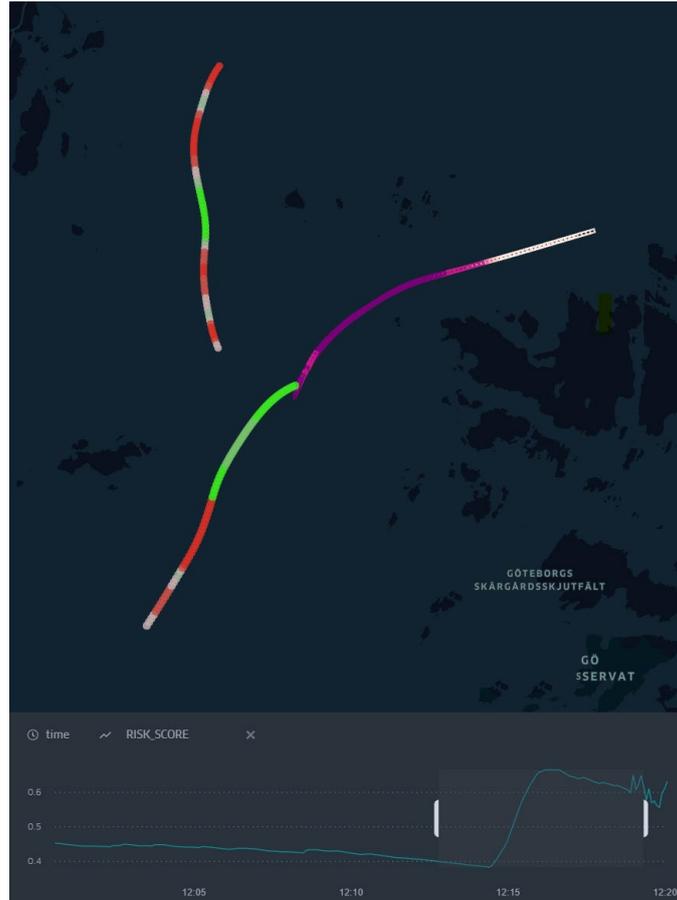


Figure 36 shows the ROPAX ship heading west in track shifting from with to purple.

### Traffic management and COLREG

The previously discussed collision between manned and unmanned vessels is one example of the challenges in traffic management and COLREG. With increased traffic density and a magnitude of options to manage complex traffic.

The navigation experts discussed the implementation of stricter traffic control to increase safety. If the traffic flow were pre-determined with fixed routes and traffic flow only directional, it would also be easier to develop navigation algorithms due to decreased unpredictability. But it also has negative aspects such as decreased efficiency due to voyages travel distance increase, more advanced traffic management and infrastructure needed to enforce and monitor the traffic flow.

### Time slots

Based on the restricted fairway simulations with a road ferry crossing the main fairway. The navigation experts discussed timeslot-controlled traffic. This would allow the unmanned road ferry to cross the main fairway if a large ship is not passing within a selected time window. As the logic is simple, it would be easily implemented into an algorithm, and with a good know behaviour pattern, other ships could quickly identify if the behaviour is deviating. Selecting a suitable time window would need careful consideration to not impede too much on timetable keeping for the road ferry or passing larger vessels.

### **Navigation expert's expectations of unmanned vessel navigation**

Under the group interview the navigation experts expressed their expectations on unmanned ships within the same traffic space as manned ships. The main expectations where they could see digitalisations and automation to improve information sharing for collective decision making that could potentially improve:

- Increased predictability of ships travel path
- Improved prediction of collision

As it boils down to increased predictability of ships movement and making available information about intended actions, they see that marine traffic safety could be improved.

# 4 RISK MITIGATION ACTIONS AND RECOMMENDATIONS

## 4.1 Introduction

This section reports identified risk mitigation actions and recommendations for decision making. Both risk mitigation measures and recommendation to the industry needs to be considered in the rule making process. IMO has taken the initiative to perform a scoping exercise to assess how Maritime Autonomous Surface Ships (MASS) might be addressed in IMO regulation. Further, a dedicated MASS Code will be developed, and a Correspondence Group (CG) has been established for this purpose. Results from this project will be put forward to this CG.

### 4.1.1 IMO MASS

The IMO scoping exercise was started in 2017 and ended in May 2021 at IMO's Maritime Safety Committee (MSC) 103. (MSC 103/21/Add.1, annex 8) and can also be found in circular MSC.1/Circ.1638 (Outcome of the Regulatory Scoping Exercise for the use of MASS). The following degrees of automation was considered:

- Degree one: manned ship with automated processes and decision support (A0)
- Degree two: remotely controlled ships with crew on board (A1)
- Degree three: remotely controlled ships without crew on board (A2)
- Degree four: fully autonomous ship (A3)

These definitions of autonomy levels was submitted MSC 100/5/6 [IMO 2, 2019] by Australia, Denmark, Finland, France, and Turkey.

The exercise analysed a high number of IMO regulations in order to identify rules which are applicable to MASS and MASS operations. Some regulations would need to be amended or clarified to admit MASS. Others have no bearing to MASS or MASS operations.

Some high-priority issues were highlighted which would be addressed at a policy level. Below some of these issues are listed: [IMO 2, 2019]

- MASS terminology and definitions
- Clarifying the term master, crew, and responsible person
- Requirements on remote-control stations
- Bridge functions and alarms
- Functions related to be performed by crew

MSC 103 noted that the best way forward for the technical parts were that they would be address in a goal-based MASS Code. This code will be an add on to the current technical

regulations. For the human centred parts (COLREG and STCW) the identified barriers can be treated as equal safety.

## 4.1.2 MASS Correspondents Group

The overall goal with the MASS Code is to consist of functional requirements and regulations for all four degrees of autonomy, addressing the identified gaps in the scoping exercise. The purpose of the CG is to give the opportunity for larger groups to put forward views and comments on the issues discussed. Lighthouse, which is a Swedish maritime competence center, coordinates these comments, and the Swedish Transport Agency represents Sweden in the CG. This CG can be used to put recommendations from this project forward to the decision making and rule making process.

## 4.2 Risk mitigation

### 4.2.1 Safety level

Putting new technology into operation and trying to predict safety outcome, is a complex task. Many factors are affecting maritime safety, and causal factors can be found in mainly technical failures, but also in Human Performance, Management, Marine Environment and Working Environment. Humans act in today's shipping as the main safety barrier for avoiding accidents and incidents to happen and limit the adverse consequences [Hüffmeier, 2018 ].

Automation has been traditionally seen as a safety measure in the shipping industry. At the same time, it is certain, that new risks will be imposed by automation. From discussions with the industry and findings from previous research, a joint agreement is that the introduction of the automated or autonomous system will require a safety and risk level equal to or better than today's operation with manned vessels. [HAZID, 2020]

The risk model developed in this project will not find the equal or normal risk tolerance but will give an objective risk score. In conclusion the basic principle used in this project is that:

Autonomous ship should have higher or the same safety level as manned ships.

The accidents and incident types are not expected to change on more automated and autonomous ships. This implies that risk reducing measures that are provided in today's ships by humans need to be covered by automated functions. These risks occur during all stages of the ship's operation and involves various technical systems. The HAZID performed in [HAZID, 2020] indicate that events with the most severe outcomes involve the categories collision, contact, fire, and weather damage, while the most frequent relating to machinery and equipment failures.

In order to assess the safety of an automated ship, the ship's functions need to be identified. This can be divided into two parts:

- **Technical functions**, this is functions that constitutes a ship's sub-system, which together makes up to a ship's system; and

- **Operational functions**, this is functions performed by the crew in a A0 and A1 ship. Hence, these are functions that needs to be replaced by autonomous functions for A2 and A3 ships. Examples on such functions are navigation control, search and rescue, firefighting, cargo stowage and security.

The ship's functions are identified by using the proposed outline of the IMO Mass Code part 2 "SOLAS SAFETY MEASURES" performed at MSC 105/7/2 and MSC 105/7/3:

- Structure
- Subdivision and stability
- Machinery
- Electrical
- Fire safety
- Life-saving appliances
- Navigation
- Communication
- Management of Safe Operations
- Ship Security

And in further in part 3 "OTHER SAFETY MEASURES":

- Collision Prevention
- Manning and Training
- Load Line
- Tonnage
- Search and Rescue
- Cargo

Based on the outcome of the [HAZID, 2020] performed in the project, focus has been put on the operational functions and in particular the navigation control in different geographical and traffic conditions.

## 4.3 Risk mitigation measures

In order to meet the criteria "equal or better safety level as manned ships" a number of risk mitigation measures are proposed. The input comes from three sources:

- The HAZID performed in this project, see [HAZID, 2020]
- SAFEMASS study, see further below
- Simulation results using the developed risk model, see chapter 3

In the European Maritime Safety Agency (EMSA) study SAFEMASS *Study of the risks and regulatory issues of specific cases of MASS* [SAFEMASS, 2020]. The study made by Det Norske Veritas on behalf of EMSA was divided into two parts. Part 1 addressed emerging risks associated with autonomous vessels with qualified operators onboard (A3-B1 level of autonomy and control, as proposed by IMO MSC 100/5/6). Part 1 also looked at regulatory gap associated with the A3-B1 category. Part 2 addressed emerging risks with unmanned, remotely supervised/operated vessels (A2-B0 level of autonomy

and control). Both studies included a HAZID, fault tree analysis, and recommended risk control options and measures (RCO and RCM).

Part 1 of the study developed descriptions of three different vessel types designed to operate according to the A3-B1 MASS level, as a basis for the risk analysis. These included a short route domestic passenger ship, a short-sea cargo ship, and an ocean-going cargo ship. The study identified several emerging risks associated with the operator's situational awareness, and risks related to "mode confusion and (dis-)trust in automation".

The potential risks include, for example: [SAFEMASS, 2020]

- *“Alarms not being generated or incorrectly communicated by the system due to boundary parameters, alarms not perceived by the operator, alarm device failure, etc.*
- *The operator intentionally or unintentionally not mustering to the bridge or other location where controls are available even if successfully informed due to overreliance on the MASS system automation, the operator prioritizing other tasks or being located too far away from the bridge, etc.*
- *If the operator is able to muster to the bridge, there are threats against the required situational awareness within the time available to act on the notified/alarmed event. Threats may come from the design of human-machine interfaces (HMI) and other displays not supporting quick analysis and decisions by the operator.*
- *While advanced automation with redundant functions can be a highly reliable system, it can however introduce some new risks driven by increased system complexity, such as alarm fatigue due to increased number of sensors and difficulty for the operator to interpret how a combination of failures can be critical.”*

The study for Part 1 concludes that future efforts to increase automation should use human-centered design and apply established Human Factors Engineering standards. Automation should be focused on a task and system function level.

Regarding Part 2, the study looked at potential risks associated with "the use of unmanned vessels operated with a relatively high level of automation, combined with supervision by human operators located in a Remote-Control Centre (RCC)", the A2-Bo level of autonomy and control. As the basis for risk analysis, descriptions of a generic MASS fleet of three identical vessels were developed with simultaneous operations performed by one bridge and one engine operator located in the RCC. In a similar way as for Part 1, a team of industry experts took part in a workshop to identify potential hazards as a basis for making a fault tree analysis model for a ship collision scenario.

The study identified several emerging risks with the use of remotely controlled and unmanned operations. Some of the main concerns are: [SAFEMASS, 2020]

- Navigation failures not alerted to or not detected by the RCC operator due to, for example, the MASS system not being aware of its own failures, and poor alarm prioritization and categorization by the RCC operator.
- Operator's response to navigational failures is not made feasible, even if successfully detected, because of limitations or degradations in the system (cameras, sensors, etc.). The "operator's chance of success is relative to the system's capabilities, or lack thereof".

- More limited time to obtain situational awareness when supervising several MASS at the same time, particularly in complex traffic situations.
- Other risks such as loss of communication and power, excessive workload, absence of operator due to acute illness, etc.

Part 2 of the study concluded that "the need for supervision is directly related to the degree of system reliability (or unreliability)". The demands on the RCC operator in various scenarios must be taken into consideration when designing a remotely controlled system. More active supervision is required if the system is less reliable.

Risk mitigation measures have been summarized below for the technical and operational functions.

Table 9 Risk mitigation measures for different levels of automation.

Level of automation	Function	Measure
A1		
	Structure/hull	As today
	Machinery/electricity	As today
	Cargo management	Autonomous and manual override
	Manoeuvring	Autonomous and manual override
	Navigation and anti-collision	Autonomous and manual override  Autonomous functions need to be evaluated based on expected traffic scenarios and geographical areas.  Crew needs to be able to discover risk situations and have time to act.
	Communication	Manual
	Safety and fire management	As today
A2		
	Structure/hull	As today
	Machinery/electricity	Redundant
	Cargo management	Autonomous / remotely controlled
	Manoeuvring	Autonomous / remotely controlled
	Navigation and anti-collision	Autonomous functions need to be evaluated based on expected traffic scenarios and geographical areas.  Most risk discover needs to be automated onboard, near or long time risk prevention can be remote.

Level of automation	Function	Measure
	Communication	Autonomous / remotely controlled
	Safety and fire management	Autonomous / remotely controlled
A3		
	Structure/hull	As today
	Machinery/electricity	Redundant
	Cargo management	Autonomous, redundant
	Manoeuvring	Autonomous, redundant
	Navigation and anti-collision	Autonomous, redundant <ul style="list-style-type: none"> <li>Autonomous functions need to be evaluated based on different traffic scenarios and geographical areas.</li> <li>Autonomous functions need to discover risk situations.</li> </ul>
	Communication	Autonomous, redundant
	Safety and fire management	Autonomous, redundant

For all cases (A1 – A3) operational measures have been added in the table below.

Table 10 Operational risk mitigation measures for different levels of automation.

Level of automation	Function	Measure
A1		
	Navigation and anti-collision	System or crew discovers that a risk situation is developing. Actions to be taken depending on situation: <ul style="list-style-type: none"> <li>360 degrees turn</li> <li>Stop engine</li> <li>Crash stop engine</li> <li>Emergency anchoring</li> <li>Beaching</li> <li>Position keeping</li> </ul>

Level of automation	Function	Measure
A2		
	Navigation and anti-collision	<p>System or remote control discovers that a risk situation is developing. Actions to be taken depending on situation:</p> <ul style="list-style-type: none"> <li>• 360 degrees turn</li> <li>• Stop engine</li> <li>• Crash stop engine</li> <li>• Emergency anchoring</li> <li>• Beaching</li> <li>• Position keeping</li> </ul>
A3		
	Navigation and anti-collision	<p>System discovers that a risk situation is developing. Actions to be taken depending on situation:</p> <ul style="list-style-type: none"> <li>• 360 degrees turn</li> <li>• Stop engine</li> <li>• Crash stop engine</li> <li>• Emergency anchoring</li> <li>• Beaching</li> <li>• Position keeping</li> </ul>

The operational measures listed in table 11 puts requirements on the fairway. There needs to be a safety margin in the fairway between the safety corridor and no-go areas. This safety margin needs to be ship-dependent based on characteristics and system performance and include the human response time in order to detect, react and act. Hence, the safety margin size depends on accident consequences, reaction/detectability time/event horizon, decision time and time to perform a successful corrective action.

## 4.4 RECOMMENDATIONS FOR DECISION-MAKING

The main purpose of the project was to develop a risk analysis methodology that can evaluate safety impact of technology, especially automation and possible automation scenarios. A risk evaluation model has been developed that classify the risk and safety level from a relative norm. The risk evaluation model can analyse the outcome of actions from future navigators or control algorithms. Actions from a navigator will affect the vessel's movement, impact on nearby traffic and relative vessel position to geographical restrictions or danger.

The project puts forward the following recommendations for the national and international rule making process.

### **General recommendation:**

It is recommended that regulations take a holistic view on the whole ship's system, including issues on the reliability, ship-to-shore communication, maintenance, collision scenarios and emergency response actions, risks directly related to increased automation, and remote control. These last points include especially HMI and rules and regulations. Most of the frequent risks identified includes technical failures of systems onboard ships due to reliability issues, redundancy, installation, ship design, maintenance and interface to other systems. This includes machinery damage and black-out and engine failure.

Below follows a list of detailed recommendations (R).

#### **R 1: Navigation control**

The navigators in the simulation expected the unmanned ships algorithm to behave like the navigator's "driving" behaviour. The navigators approached the autonomous ships with high expectations that they could keep their navigations style unchanged when interacting with the unmanned ships. But as early state prototypes, the unmanned vessels had a few unexpected behaviours that led to a grounding and a collision under the simulation's scenarios, allowing lessons to be learned.

It is recommended to use an objective navigation control validation method as part of system validation as has been demonstrated in this project.

#### **R 2: System reliability**

Major technical challenges are identified as the reliability of integration and redundancy of engines. The lack of possibility to manually override a system including emergency repairs while underway, lack of continuous engine manning is challenges that needs special attention at level A2 and A3.

#### **R 3: Anti-collision**

The main findings related to unmanned ship and manned ship collision:

- Autonomous ships should not end up in such a situation at first, and if they do, they should try to minimise the damage.
- The intentions at a meeting should be standardised or confirmed by information exchange.
- The unmanned ship should proceed to a safe state configuration if an incident occurs. A safe stat needs to be determined by the incident type.

#### **R 4: COLREG**

Traffic situations were identified as technically difficult to solve when following today's COLREG. Looking in more detail on the collision scenarios, there is a wide interpretation of what appropriate distances are in a close quarter situation and partly even on which factors steer the decision making of humans on the bridge. In line with the COLREG regulations, a clear and precise definition of good seamanship is a basis. This needs to be further studied.

**R 5: Fairway**

There needs to be a safety margin in the fairway between the safety corridor and no-go areas. This safety margin needs to be ship-dependent based on characteristics and system performance including the human response time in order to detect, react and act. Hence, the safety margin size depends on accident consequences, reaction/detectability time/event horizon, decision time and time to perform a successful corrective action.

**R 6: Technical breakdown**

Major challenge for crews/ operators with autonomous navigation are given by regaining controls of the vessel after breakdown/ blackout. This needs safe mode operations and specific control operations.

**R 7: Maintenance**

Functions done by today's crew that are the most difficult to replace by automation/ digitization/ remote control are continuous maintenance and control (incl. alarms). This also includes the main and auxiliary engine (daily and hourly) as well as fixing small problems and breakdowns. The situation with electrical motors can be different due to less need of maintenance.

**R 8: High density traffic**

High density traffic issues including reacting to other ships erratic behaviour and anchoring has been brought up as navigational functions difficult to replace. On a high-level taking action on the spot when it becomes unavoidable, decision making and the interaction between human and machine are challenging. This needs extra attention at level A2 and A3.

**R 9: Security**

Secure communication between ship – ship and ship -shore is of great importance.

**R 10: Communication**

No communication is needed between ships for situations with clear policies, such as COLREG or customs in the traffic area. However, clarifying intentions is a good seamanship. Therefore:

- A ship should be capable of communicating its intention
- A ship should be capable of communicating and establishing a plan of action with an external actor. For example, meeting point, who will go first or overtaking in restricted water.

**R 11: Information sharing**

Digitalisations and automation can improve information sharing for collective decision making that could potentially improve:

- Increased predictability of ships travel path
- Improved prediction of collision

An increased predictability of ships movement and making available information about intended actions, marine traffic safety could be improved.

**R 12: Time slots**

Timeslot-controlled traffic would allow the unmanned road ferry to cross the main fairway if a large ship is not passing within a selected time window. Selecting a suitable time window would need careful consideration to not impede too much on timetable keeping for the road ferry or passing larger vessels.

**R12: Traffic management**

Implementation of stricter traffic control in the context of autonomous shipping could increase safety. If the traffic flow were pre-determined with fixed routes and traffic flow only directional, it would also be easier to develop navigation algorithms due to decreased unpredictability. But it also has negative aspects such as decreased efficiency due to voyages travel distance increase, more advanced traffic management and infrastructure needed to enforce and monitor the traffic flow.

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