SEPTEMBER 2021
AARHUS HAVN

BILAG 16

UDVIDELSE AF AARHUS HAVN - YDERHAVNEN

BESEJLINGSIMULERINGER

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Bilag B Port of Aarhus. Port Expansion 'Yderhavnen'. Navigation simulations, dredged channel. March 2021

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1 Indledning

Aarhus Havn planlægger en ny stor havneudvidelse der benævnes ‘Yderhavnen’. Der skal i den forbindelse etableres et nyt havnebassin, et svajebassin og en sejlrende til den nye havn.

Havnen besejles af store skibe, som Mærsk Triple E containerskibe, samt af mindre feederskibe.

De besejlingsmæssige forhold under sejlads i sejlrenden, manøvrering, anløb og afsejling er undersøgt og rapporteret, som en del af den igangværende Miljøkonsekvensvurdering.

Besejlingsforholdene og de besejlingssikkerhedsmæssige forhold er undersøgt på en workshop i februar 2021, hvor der med deltagelse af Aarhus Havns lodser blev gennemført besejlingssimuleringer i COWIs desktop simulator i Lyngby.

Nærværende notat indeholder en sammenfatning på dansk af konklusioner og anbefalinger fra de to besejlingsstudier af henholdsvis havne- og svajebassin og sejlrende, der er vedlagt som henholdsvis Bilag A og Bilag B.

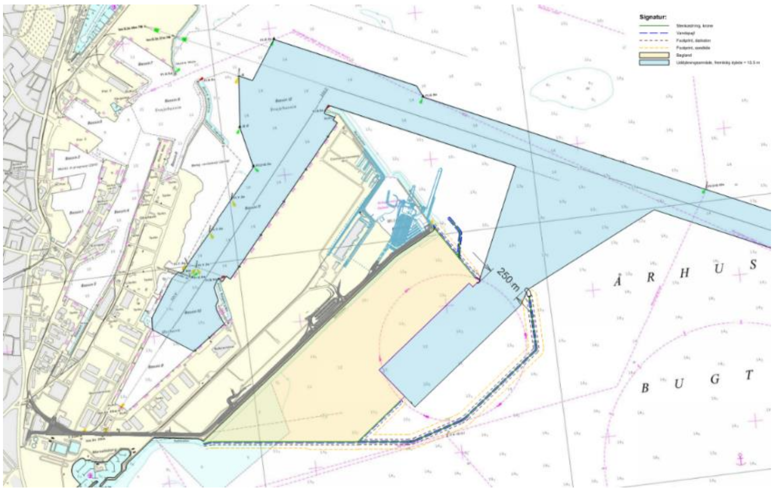
2 Besejlingssimuleringer, Havneudformning

Der er udført 16 besejlingssimuleringer med besejling, manøvrering og anløb til den nye containerkaj i Yderhavnen. Simuleringerne er foretaget med de største skibe der i dag besejler havnen, nemlig Mærsk Triple E containerskibe (400 m længde og 15m dybgang). Endvidere er der også undersøgt et større containerskib på 440 m længde og 16 m dybgang samt tillige mindre feeder skibe (190 m længde). Besejlingssimuleringerne er foretaget under vindforhold på op til 15 m/s fra forskellige retninger, og rapporteret i notatet "*Port of Aarhus. Port Expansion 'Yderhavnen'. Navigation simulations, port layout. March 2021*", der er vedlagt som Bilag A til nærværende notat.

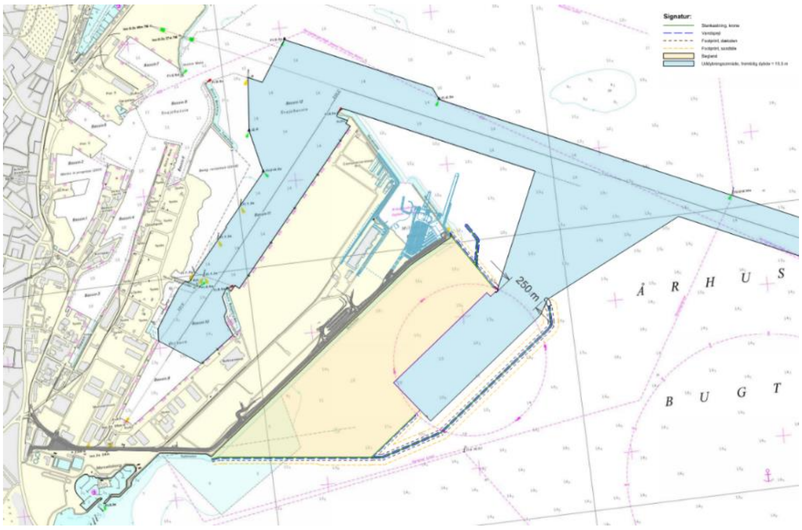
Besejlingssimuleringerne er foretaget med både hovedforslaget og den alternative udformning med indrykket ydermole. De to udformninger er vist i hhv. Figur 2-1 og Figur 2-2.

Det konkluderes af besejlingssimuleringerne, at udformningen og størrelsen af havne- og svajebassin giver tilstrækkelig plads til besejling, manøvrering og anløb, og at den besejlingsmæssige sikkerhed er ens for de to forskellige layouts.

Dog har hovedforslaget en stor fordel i forhold til alternativet, da det i hovedforslaget vil være muligt at vende ('svaje') selv større skibe i læsområdet bag ydermolen, hvor der i hovedforslaget er en naturlig indre svajecirkel på ca. 500 m i diameter og en vanddybde på over 12m. I besejlingssimuleringerne er der kun undersøgt anløbs- og afgangsprocedurer hvor der svajes i det ydre svajebassin udenfor indsejlingen.



Figur 2-1 Yderhavnen: Hovedforslag.



Figur 2-2 Yderhavnen: Alternativ udformning med indrykket mole.

Simuleringerne vist at de største containerskibe kunne vende i svajebassinet og manøvrere sikkert ind og ud af havnen i vind op til 15 m/s. Anløb og afgang til/fra kaj var dog med den benyttede slæbebådskonfiguration begrænset til vindhastigheder på 8-10 m/s. Det mindre feeder skib kunne også manøvrere sikker og vende inde i havnebassinet i vind optil 15 m/s, dog med slæbebådsassistance under kraftige vindforhold.

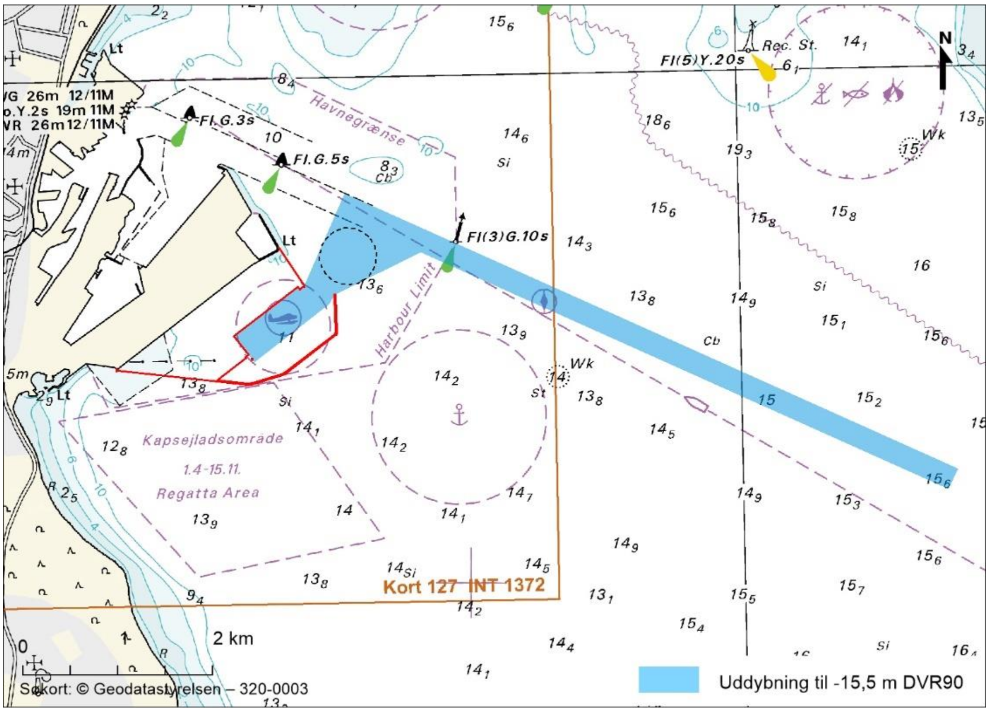
Workshopdeltagerne konkluderede, at der potentielt er mulighed for en mindre optimering af svajebassinets udformning, dvs. en reduktion af uddybningsområdet, hvilket evt. kan undersøges nærmere i forbindelse med supplerende besejlingssimuleringer.

Konklusioner og anbefalinger for så vidt angår besejlingssimuleringer i sejlrenden ("*dredged channel*") er gengivet i afsnittet herunder.

3 Besejlingssimuleringer, Sejlrende

Der er udført 16 besejlingssimuleringer med besejling igennem sejlrenden ind til havnen for de største skibe, som Mærsk Triple E containerskibe og 440m containerskib under vindforhold op til 15 m/s fra forskellige retninger. Der er endvidere foreslået og drøftet en afmærkning af den nye sejlrende. Besejlingssimuleringer er rapporteret i notatet "*Port of Aarhus. Port Expansion 'Yderhavnen'. Navigation simulations, dredged channel. March 2021*", der er vedlagt som Bilag B til nærværende notat.

Besejlingssimuleringerne er foretaget på grundlag af den foreslåede udformning af sejlrenden ("*dredged channel*"), som fremgår af Figur 3-1. Besejlingssimuleringerne er foretaget for henholdsvis en 240 m bred og en 320 m bred sejlrende.



Figur 3-1 Uddybet sejlrende i forbindelse med Yderhavnen.

Det konkluderes af besejlingssimuleringerne, at den foreslåede og simulerede bredde af sejlrenden på 240 m er for smal til besejling med de største skibe under vindforhold op til 15 m/s. Der er således ikke tilstrækkelig sikkerhed for at blive i sejlrenden under besejlingen. Det anbefales, at sejlrendens bredde forøges til minimum 320 m, hvilket efterfølgende er implementeret i projektet.

Det konkluderes endvidere, at besejling er mulig og sikker med maximal dybgang (fuld last) under rolige vindforhold, op til 5 m/s, med den undersøgte vanddybde på 15,5 m. Vindforhold, op til 15 m/s, udfordrer besejlingen i såvel sejlrende som i svajebassinet, da de største skibes bevægelser i vandet (krængning ved vind ind på siden) kræver mere frigang (afstand mellem skibets bund og havbunden). Ved besejling under disse kraftige vindforhold med maximal dybgang (skibslast) vil der være behov for en vanddybde på ca. 17 m. Alternativt anbefales det, at skibenes nominelle dybgang ved besejling kun må være

13,5 m (delvist lastet), i stedet for den nominelle dybgang på 15 m (fuldt lastet).

På baggrund af disse resultater af besejlingssimuleringerne er det valgt at uddybe svajebassin, sejlrende og bassiner i Yderhavnen til en garanteret vanddybde på 15,3 m, der inkl. 0,3 m overuddybning svarer til en reelt uddybet vanddybde på 15,6 m. Til sammenligning er vanddybden i eksisterende containerterminal i dag 14 m. Således vil man i Yderhavnen kunne modtage skibe med over 1 m større dybgang end ved den nuværende containerkaj (under sammenlignelige vejrforhold).

Ved kraftig vind (15 m/s) på tværs af sejlrenden er de store containerskibe nødt til at have en fart på op over 6 knob når de anløber svajebassinet. Det anbefales, at der foretages yderligere undersøgelser af betydningen af den større fart, for så vidt angår sikker manøvrering i svajebassinet, eller om man er nødt til at begrænse de operationelle forhold til mindre vindhastigheder for anløb med mindre frigang under skibet.

Bilag A Port of Aarhus. Port Expansion 'Yderhavnen'. Navigation simulations, port layout. March 2021

MARCH 2021
PORT OF AARHUS

PORT EXPANSION 'YDERHAVNEN'

NAVIGATION SIMULATIONS, PORT LAYOUT

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PORT OF AARHUS

PORT EXPANSION 'YDERHAVNEN'

NAVIGATION SIMULATIONS, PORT LAYOUT

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1 Introduction

1.1 Background

The port of Aarhus is planning a new major port expansion called 'Yderhavnen', as shown in Figure 1-1. Environmental impact assessment, EIA (in Danish "Miljøkonsekvensvurdering") for the project is currently being carried out and as part of this the navigational safety need to be addressed by navigation simulations.

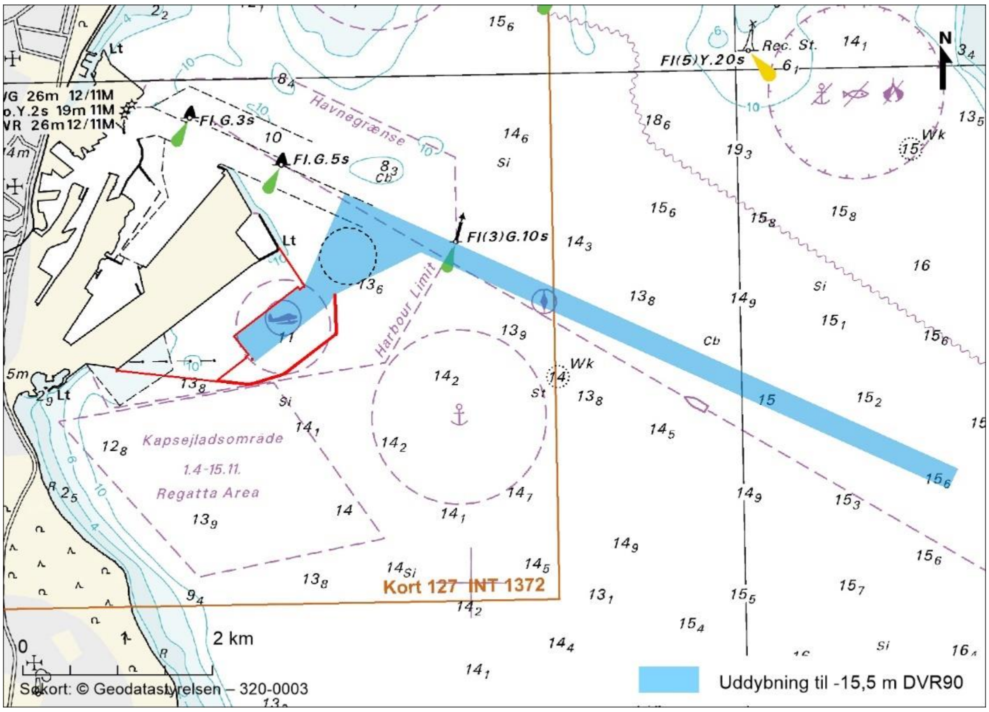


Figure 1-1 Port expansion 'Yderhavnen'.

1.2 Objectives of the report

The main purpose of the study is to provide input to the EIA in terms of navigational safety of the new port expansion. The navigational safety is evaluated through a workshop involving two Aarhus Havn pilots, Poul Pedersen and Thomas Sillesen. Both the base layout ("hovedforslaget") and the alternative layout with relocated outer breakwater is evaluated.

As a secondary purpose, the workshop and report shall evaluate the ship manoeuvring conditions at the future terminal, including a comparison of the two layouts and recommendations on the preferred layout.

Another purpose is to investigate potential optimization of the layout in order to improve the navigation conditions.

Finally, the workshop will give the pilots the opportunity to test also the navigation through the dredged access channel and draw some preliminary conclusions/recommendations regarding the channel width and depth prior to a separate desktop navigation study on the channel alone (reported in separate report no. A104076-PD-74, Ref [2]).

2 Basis

2.1 Layout

2.1.1 Current layout

The current port layout is shown in Figure 2-1.

Figure 2-1 Current port layout ENC chart

2.1.2 Future – Base layout

The future base layout of the port expansion in shown in Figure 2-2. The new container terminal has the following general geometrical characteristics:

- Quay length: 850 m
- Quay orientation: 233°-53° rel. to North
- Dredged depth relative to CD: -15.5 m
- Turning circle diameter: 700 m
- Port entrance width: 250 m
- Dredged Basin width: 350 m

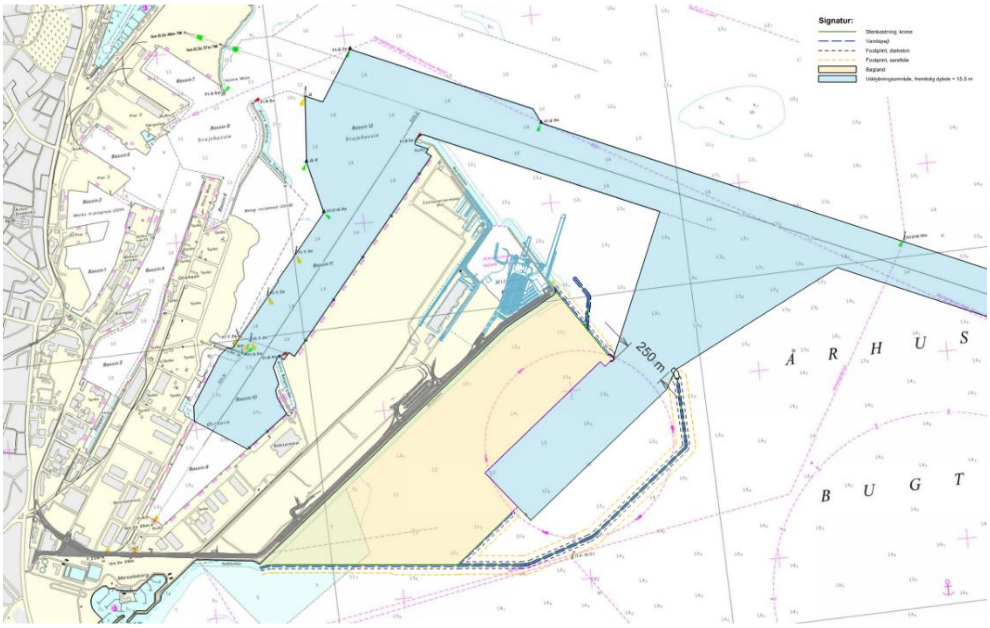


Figure 2-2 Future port – base layout.

A preliminary navigation aids layout has been prepared in coordination with Aarhus port pilots as shown in Figure 2-3.

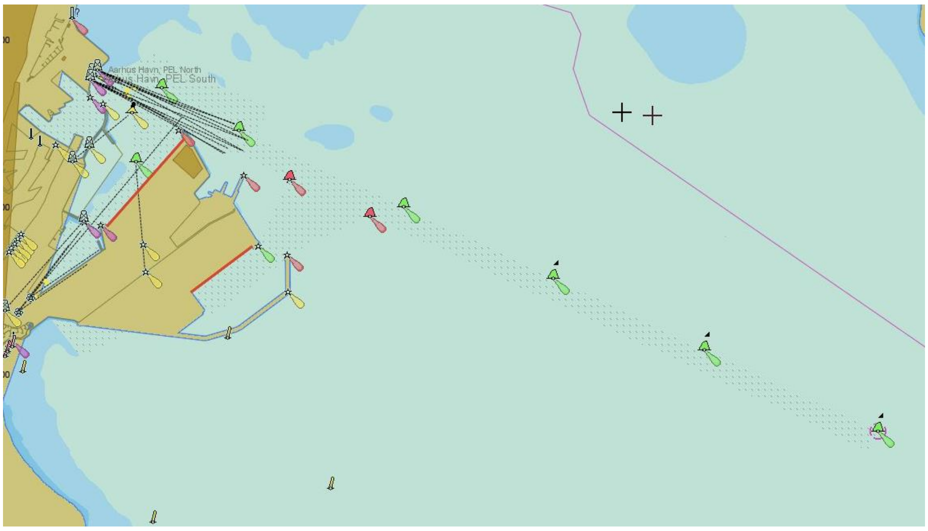


Figure 2-3 Navigation aids/marks and lights proposed (Base layout shown).

2.1.3 Future - Alternative layout

The geometrical characteristics listed in the above section for the base layout, as well as the navigation aids, also apply to the alternative layout.

The difference between the two layout lies in the location of the outer breakwater, which has been moved further towards the new harbour basin in the alternative layout. From a navigational point of view, the two layouts are equivalent.

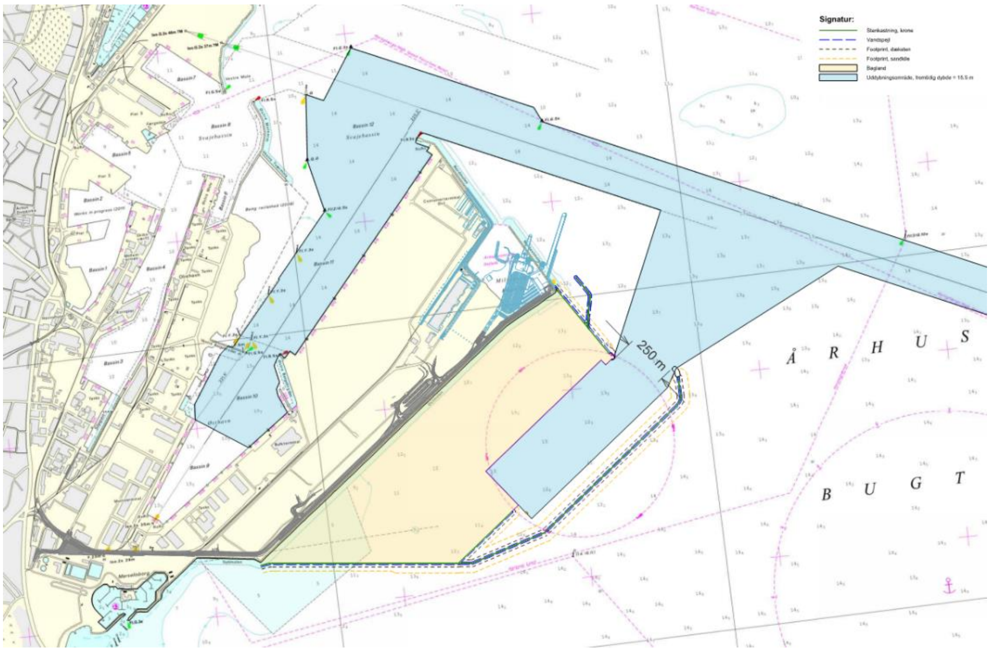


Figure 2-4 Future port - alternative layout

2.1.4 Dredged access channel

The channel is initially planned to be 240 m wide, oriented 295.1° (same are existing orientation), and dredged to -15.5 m DVR90 as opposed to the existing 14m water depth.

The preliminary navigation aids layout includes a racon at the channel entrance (relocated from its existing position) and lateral marks and lights (starboard green) placed on the Northern side of the channel every nautical mile.

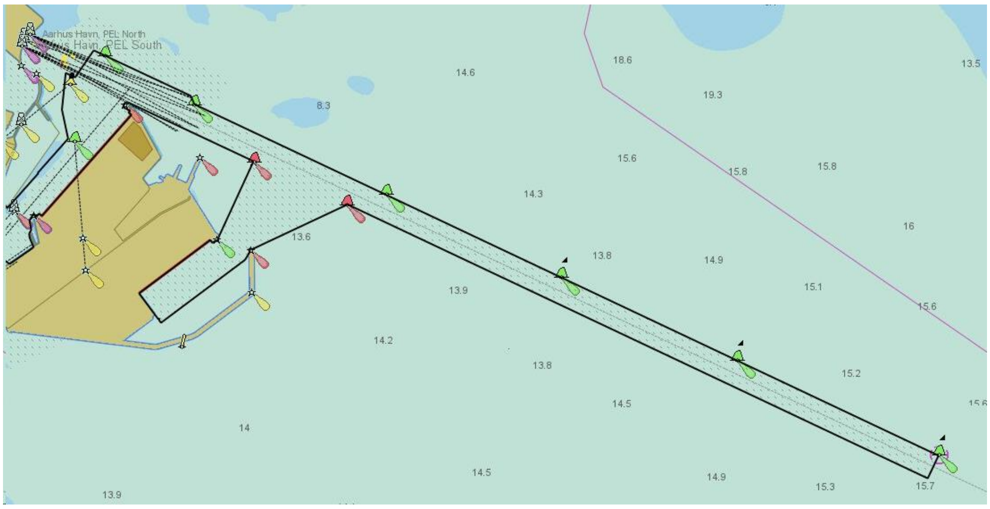


Figure 2-5 Navigation marking and layout of dredged access channel.

Further detailing shall be made to the marks and lights in the subsequent phases of the project to ensure compatibility and coherence with the neighbouring marking system and local preferences/requirements.

2.2 Design vessels

The new container terminal shall welcome the largest container vessels, therefore the navigation simulations consider the Mærsk Triple E (400 m LOA, 15m design draft) which corresponds to the largest container vessels currently in service. An even larger vessel model of 440 m long 60m wide with a 16m draft was available in the FORCE vessel library and is also considered in the simulations. Furthermore, in order to test the possibility to turn inside the basin, the simulations include runs with a smaller feeder vessel (190 m LOA).

The details of the vessel models are listed in Table 4-1.

2.3 Met-ocean conditions

The met-ocean data considered in this navigation study is based on Ref [3] and Ref [4]. The extraction points for the met-ocean conditions are shown hereafter on Figure 2-6.

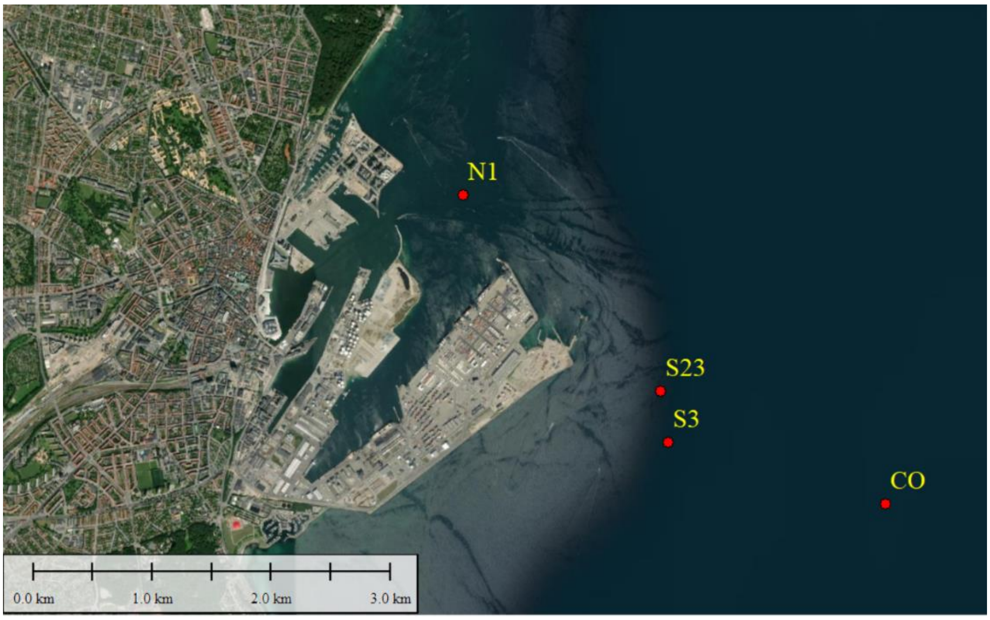


Figure 2-6 Wind and wave Extraction point locations.

2.3.1 Wind

Wind is assumed to be the governing effect on the vessel manoeuvrability, considering the very large windage area for loaded container vessels and relatively benign current conditions at the location.

The wind comes predominantly from Westerly and Southerly directions, see wind rose in Figure 2-7.

The approach and departure simulations consider the most adverse directions for berthing/unberthing, i.e. from 135° and 315°.

The simulations including navigation in the channel consider beam-on wind, i.e. from 25° and 205°.

Initially, the wind speed considered was 15 m/s, hourly average. This speed was selected based on a request from the Port pilots and is also in line with recommendations from PIANC WG 121 Ref [1]. However, this wind speed was reduced in some cases following the outcome of the first simulations, see the simulations run-matrix in Table 4-2.

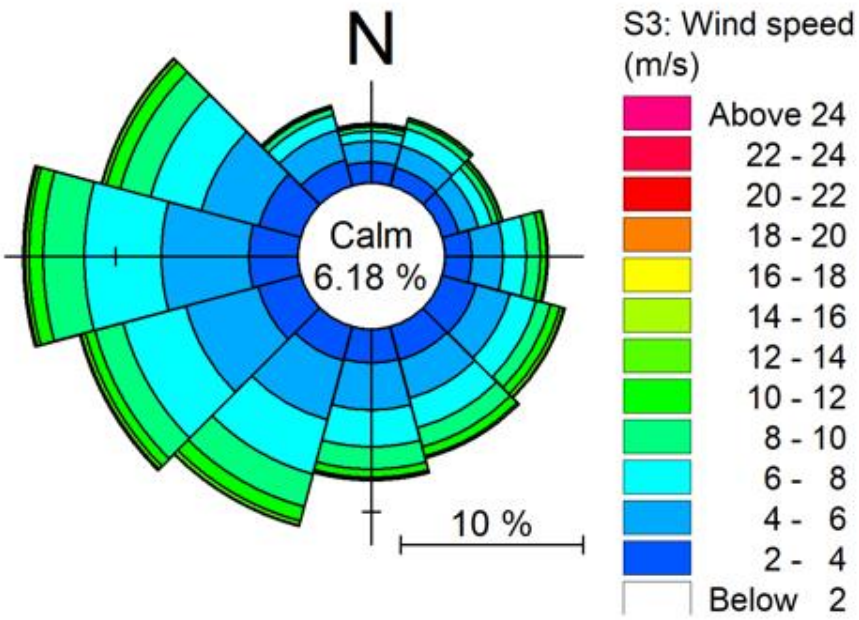


Figure 2-7 Wind rose, Ref [4].

2.3.2 Waves

At the port entrance, waves come predominantly from South Easterly directions, Figure 2-8. This is in line with the wind direction selected for approach and departure simulations.

In the channel, the Southern direction is predominant, Figure 2-9. However, the most adverse direction – in line with the wind direction selected – is considered for channel simulations, i.e. beam on from 25° and 205°.

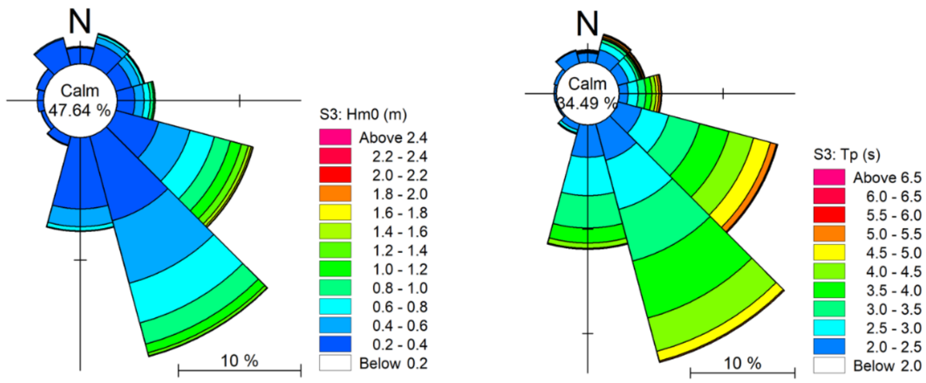


Figure 2-8 Wave rose - Future conditions at the Port, Ref [4].

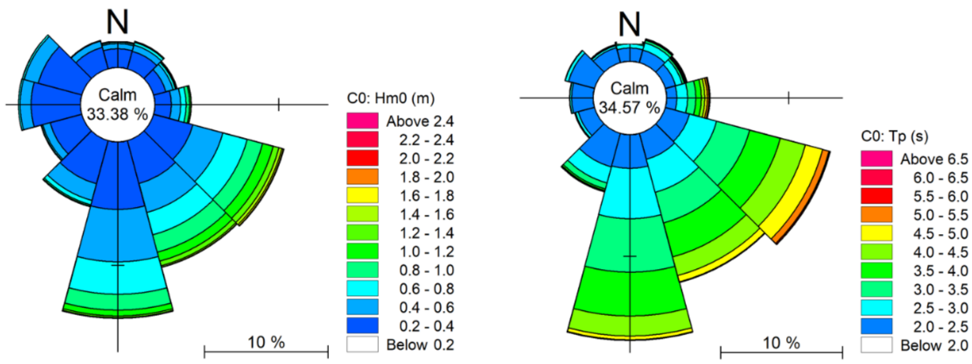


Figure 2-9 Wave rose - Future conditions in the channel, Ref [4].

For the approach and departure simulations, the wind generated wave heights and periods considered in the simulation are derived from the SW model, Ref [4], for a wind speed of 15 m/s from 135° and 315°.

For the channel simulations, it is estimated that the waves for the wind speeds and directions tested can be considered in the order of 0.5 m high, for the purpose of the navigation simulation study.

It shall be noted that the waves are not considered as a governing effect on the vessel's manoeuvrability.

2.3.3 Current

The current in the area is quite low (see Figure 2-10) and therefore not considered having a significant effect on the vessel's manoeuvrability. Therefore, current is neglected in the navigation simulations.

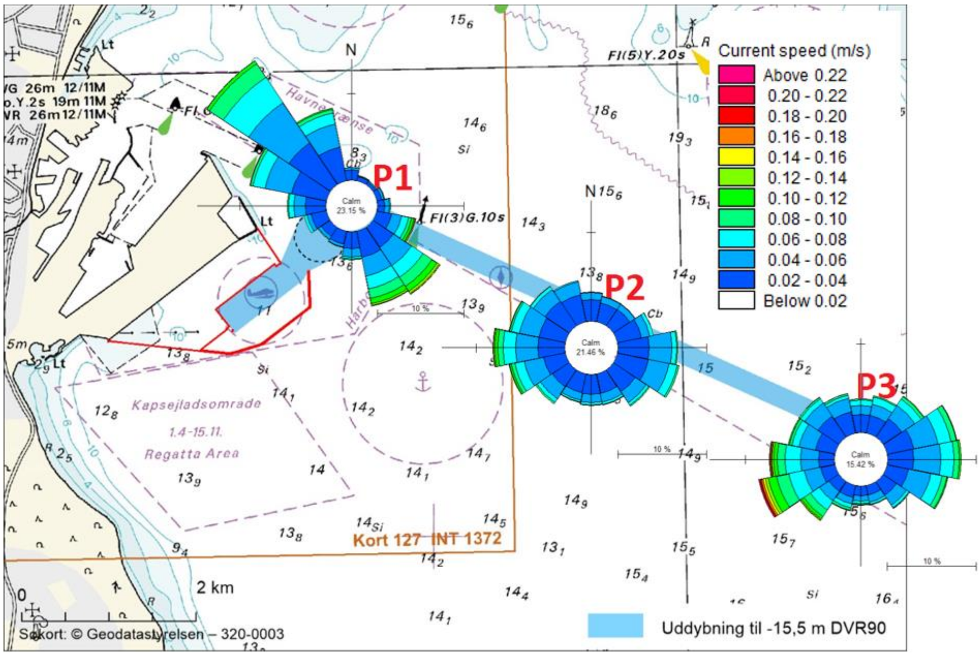


Figure 2-10 Current rose, future conditions, Ref [3].

3 Assessment of navigational layout

3.1.1 Turning area

The turning circle in both the base and alternative layouts has a diameter of 600 m (see Figure 1-1), but considering that part of the access channel can also be used, the actual diameter is in the order of 700m, which corresponds to 1.75 times the Triple-E LOA (400 m). This diameter is slightly lower than the 2 LOA starting value recommended by the PIANC WG-121, Ref [1]. Considering the manoeuverability of container vessels in general, and of the tug assisted Triple-E in particular, the value of 1.75 LOA can be considered adequate. The turning circle diameter of the existing container terminal is also 600 m and considered comfortable enough for standard manoeuvres, even for the largest vessels calling. The diameter of the turning area is further evaluated during the simulations.

3.1.2 Port basin

The port basin is 250 m wide, i.e. approx. 4 times the Triple-E's beam. This leaves 190 m (or 3 times the Triple-E beam width) for navigation if a Triple-E is berthed at the port. This corresponds to 7.6 times the beam of a smaller feeder such as the Clifford Mærsk used in the simulations. This space is deemed quite comfortable for standard manoeuvres of smaller vessels inside the port basin. The navigation simulations investigate this aspect.

3.1.3 Access channel

The future access channel width is currently planned as 240 m wide. The PIANC WG-121 2014 report "Harbour Approach Channels, Design Guidelines" Ref [1] provides a methodology for calculating the basic manoeuvring lane width according to the largest design vessel, the met-ocean conditions and foreseen navigation speed in the channel. Following this methodology with preliminary assumptions, the recommended width is calculated to be in the excess of 320 m. The channel of 240m is therefore considered too narrow. This is investigated during the simulations.

The future depth of the channel is currently considered as -15.5 m, similar to the future port and turning area dredged depth, which provides a residual under-keel clearance of 0.5 in case of 15m draft. This seems low considering the potential movements of the ship under high cross winds and due to squat effect as well as other hydrodynamic ship movements during manoeuvres. This aspect is investigated if possible, during the simulations, but will be further evaluated through the dedicated navigation simulation study for the access channel reported in Ref [2].

4 Navigation simulations

4.1 Hardware and software

The navigation simulations are based on two separate software packages, which are part of Simflex V4.11.06 The "Area Engineer" which is used to design the layout and the "Operation Control Centre (OCC)" which performs the actual real time simulation. Both software packages are developed by FORCE Technology, one of the market leaders for this type of software.

The 2D and 3D environments developed as part of this study are fully compatible with FORCE own simulators for future training/full mission bridge studies.

4.1.1 Area engineer

To run the simulations, a numerical layout model is set up by use of the software "Area Engineer". The model includes:

- 2D geometric definition of i.e. bathymetry, fenders and other physical objects.
- 3D definition of surrounding jetties, buildings, tanks, etc.
- Visualization tools for monitoring of environmental effects.
- Aids to Navigation such as marks and light descriptions.

4.1.2 Operation control centre

The real time simulations are performed by the Operation Control Centre (OCC). It is a state-of-the-art numerical navigation model, which simulates the effect and interaction between met-ocean conditions, and ship models and link to other external sources affecting the model ship such as push and pull tug operations. The effects are specific to each individual ship model and include:

- Wind forcing
- Current forcing
- Wave forcing
- Tug selection and handling
- Visibility conditions

4.1.3 Hardware

The simulator equipment operated is composed of three stationary PC in network, three 21" monitors displaying instructor screen (OCC), the ship instruments, and ship chart plotter (ECDIS). Furthermore, three 55" screens displaying the 3D visual environment, providing a 180°-panoramic view of the area.

Figure 4-1 Simulator screen and commands set-up.

The ship main controls (main rudder, main engines, thrusters, visual orientation) are provided via a hardware console as shown in Figure 4-2 below.

Figure 4-2 Ship main control hardware console.

4.1.4 2-D environment

The 2D environment consist of planar representation of the physical elements of the layout, in the format typical of official electronic navigation charts. It presents also the layout of navigation aids (buoys, lights, recommended navigation tracks, and dredged area) as well as the seabed natural or dredged elevation relative to Chart Datum.

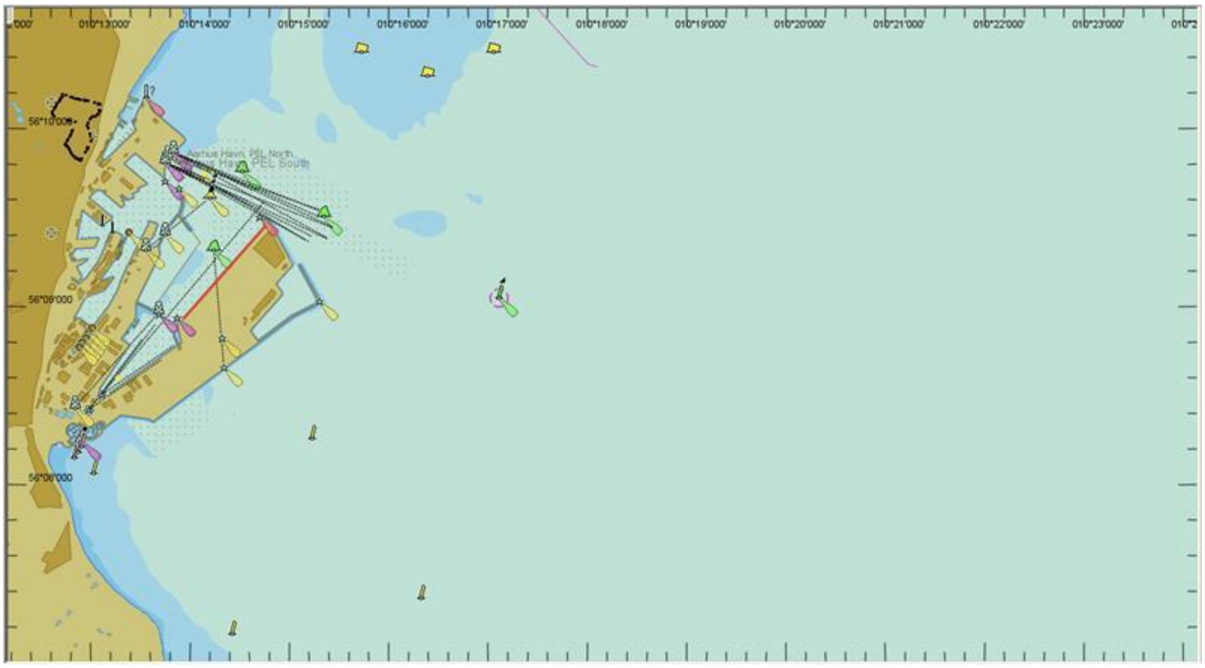


Figure 4-3 2D environment - Current port layout.

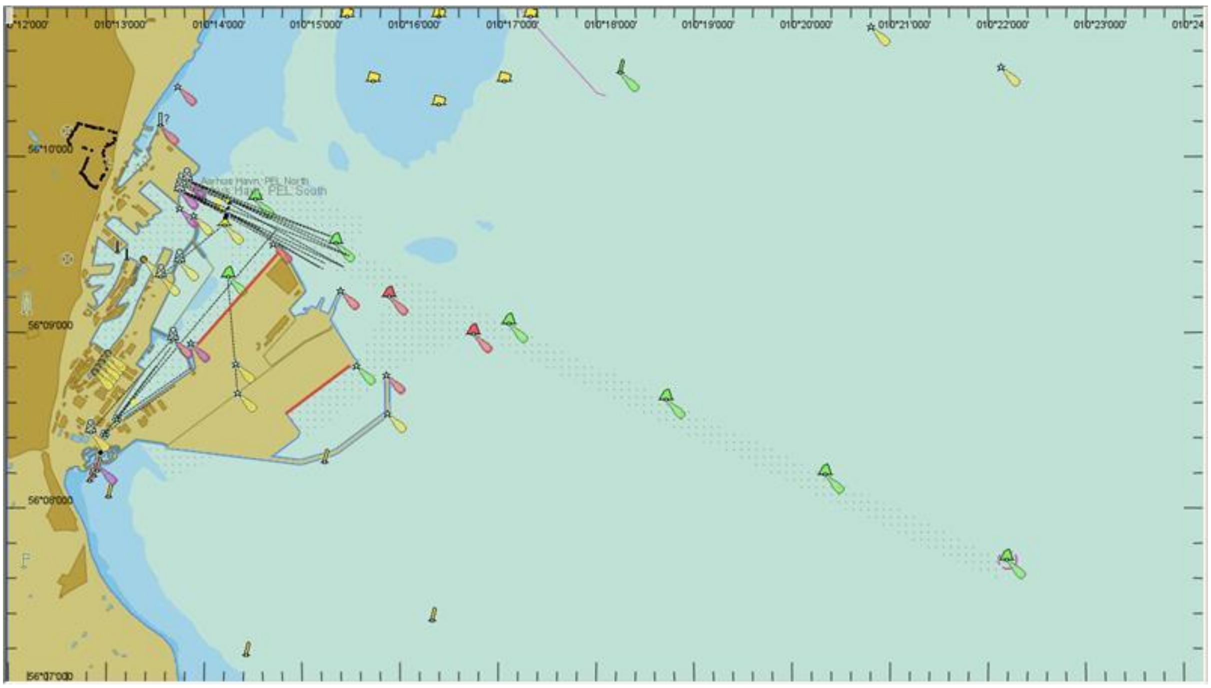


Figure 4-4 2D environment - Future port – Base layout.

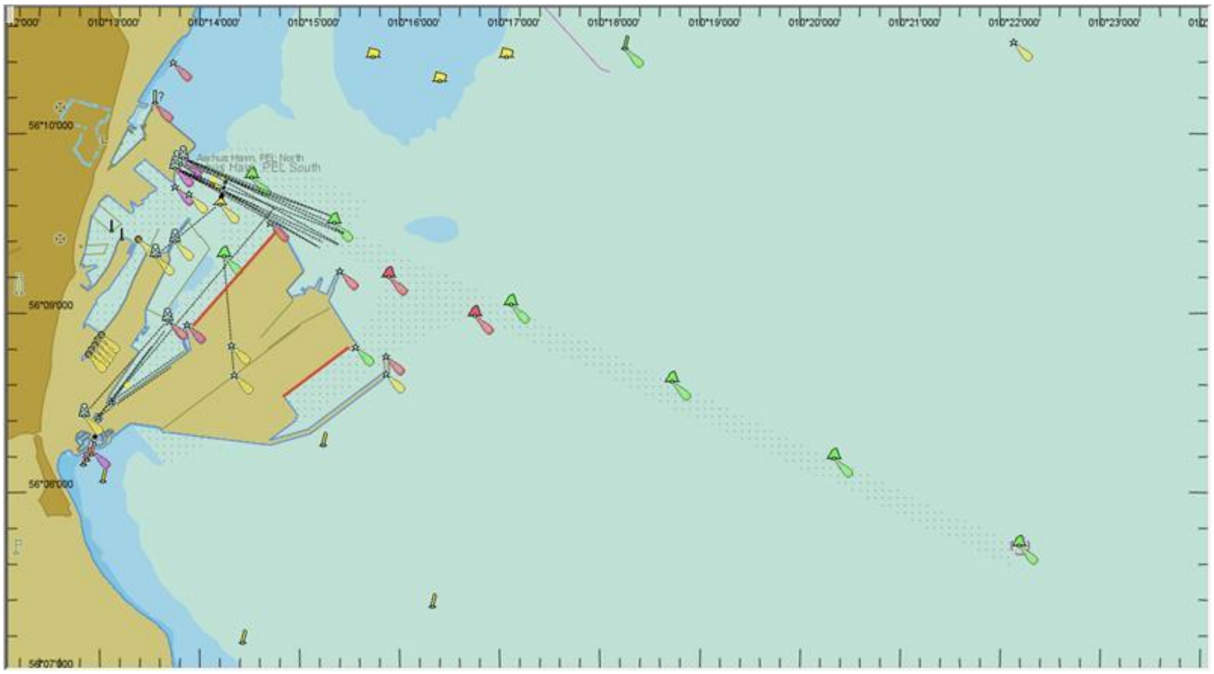


Figure 4-5 2D environment - Future port – Alternative layout.

4.1.5 3-D environment

3-D visual environments are created to offer a realistic perspective to the operator during the simulations. An example of the 3-D visualization is provided in Figure 4-3 to Figure 4-5.

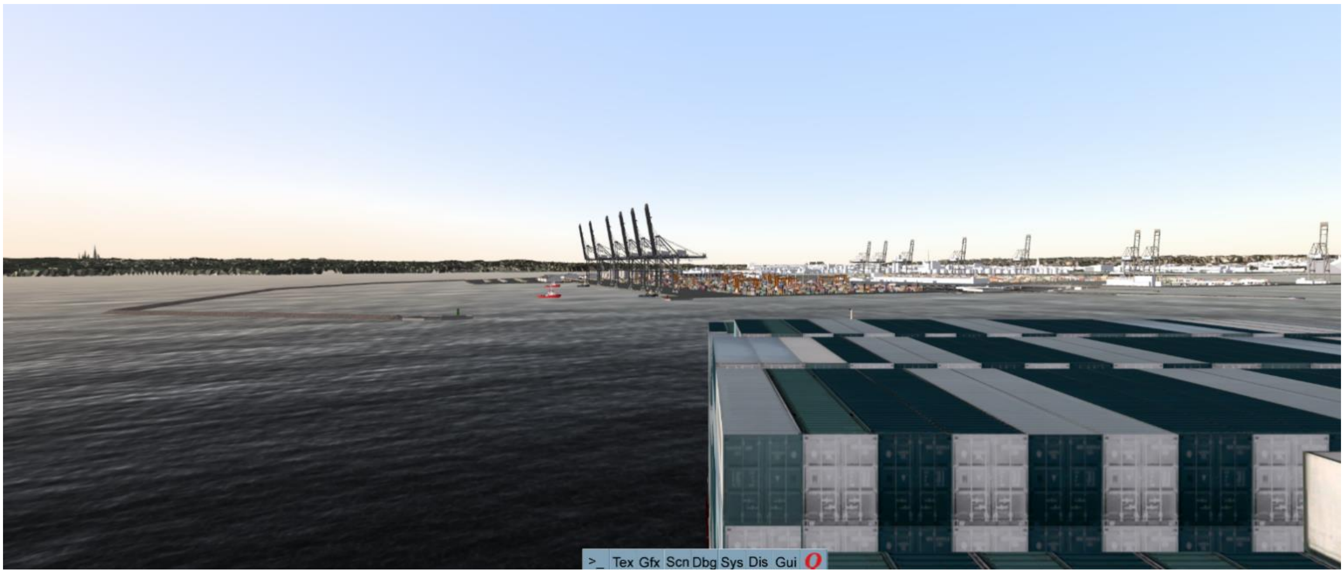


Figure 4-6 3-D model view from Triple-E bridge - Future port - Base layout.

Figure 4-7 3-D model view of Triple- E - Future port - Base layout.

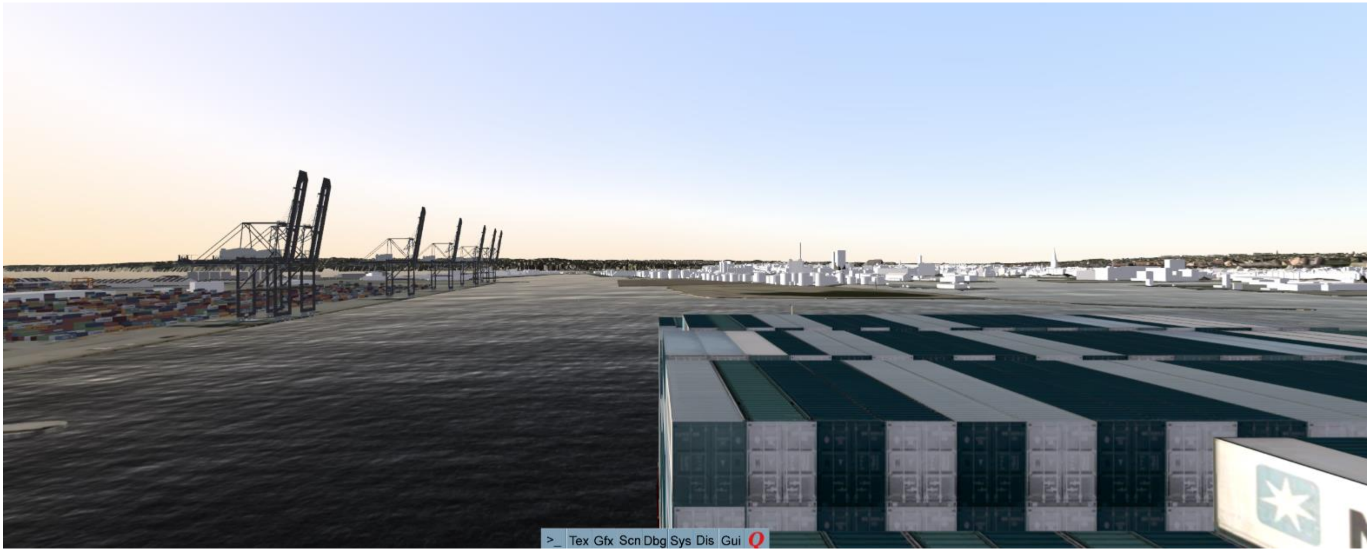


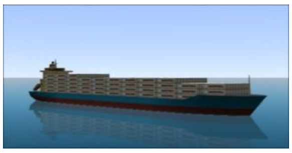
Figure 4-8 3-D model view from Triple-E bridge - Existing port.

4.1.6 Ship models

Ship models with dimensions as close as possible to the design vessels were selected for the simulations.

Ship models nos. 3663, 3058 and 3749 in FORCE's library were used for the simulations.

Table 4-1 Ship models particulars.

Ship no.	Type	Description	Loading condition	LOA [m]	LBP [m]	B [m]	D [m]	Model visualisation
3663	Container	Mærsk Triple E 18,000 TEU	Loaded	399	376.21	59	16	
3058	Container	Clifford Mærsk 1,500 TEU Feeder	Loaded	186.7	180.15	25.3 83	10.3	
3749	Container	Golden CMS 22,000 TEU	Loaded	440	418	60	16	

It shall be noted that the drafts of the Triple-E and Golden CMS are maximum design drafts, corresponding to a maximum number of containers, and thus a maximum windage area. This design loading case has been discussed among the participants of the navigation workshop and was deemed unrealistic, as the vessels calling at Aarhus port will not be loaded to this extent. Therefore, there is some conservatism in the effect of wind (which is higher in the simulations than what can reasonably be expected) and on the general manoeuvrability of both vessels. However, for the general purposes of this workshop, the models are deemed realistic enough.

4.2 Main assumptions

The following main assumptions were considered for the navigation simulations:

- In general, vessels will arrive loaded, and will depart loaded.

- The basin and channel are not deep enough to allow for the navigation of the loaded Triple-E and Golden CMS vessel models. Therefore, to simulate the navigation of the loaded vessels in the most realistic way, some adjustments are made to the water depth in the basin and channel to maintain a minimum UKC, see 4.3.3.

- Vessels are assumed to be berthed with the bow pointing towards the entrance of the port (port alongside). However, some departures have been simulated with the bow pointing inwards (Starboard alongside) in order to simulate having to turn when departing.

- The power of the tugs is only utilized typically up to 75% for all normal operations. If the degree of utilization is above 75% the operation is considered above safe limits unless it is done intentionally under controlled conditions to speed up the manoeuvres.

4.3 Methodology

4.3.1 Tugboat configuration

The originally envisaged tugboat configuration was:

- 2 x 55t towing tug at fore and aft
- 2 x 65t push/pull tugs at quarter points

However, the first runs performed with this configuration demonstrated that the available power was not sufficient to control the large vessels under the met-ocean conditions simulated. The following configuration was therefore adopted for the remaining simulations:

- 2 x 55t towing tug at fore and aft
- 2 x 90t push/pull tugs at quarter points

4.3.2 Standard manoeuvres

The standard manoeuvre procedures considered are described in the following sections.

Approach manoeuvres

- At the simulation start, the vessel is navigating in the channel at approximately 0.5 NM from the turning area entrance at a speed of 5 knots. The tugs are connected to the vessel.

  - The two large vessels (Triple E and 22,000 TEU): The vessel is turned using tugs and own engine/thrusters in the turning area. Once the vessel is position with the stern pointing to the port entrance, it is brought backwards into the port basin. The vessel is brought parallel to the quay and pushed onto the fender with a maximum berthing speed of approx. 0.1-0.2 m/s using four tugboats.

  - Small 1,500 TEU: The vessel enters the port with the bow pointing towards the port entrance and navigates towards the target berth. The vessel is turned inside the port basin using the tugs. Once the vessel is positioned parallel to the berth, it is pushed towards the fenders with a max berthing speed of approx. 0.2 m/s.

Departure manoeuvres

The vessel is lift off from the berth with tugboats.

- Large vessels (Triple E or 22,000 TEU): The vessel is then brought out of the port basin, at the centre of the turning area. Assisted by tugboats, the vessel is turned towards the channel exit and starts picking up speed.

- Smaller 1,500 TEU: The vessel is turned using tugs inside the port basin. Once in the correct orientation, bow pointing towards the entrance of the port, the vessel can navigate out of the basin, through the turning area and to the channel.

4.3.3 Adjustment of water level

The ship models for the Triple E and Golden CMS are provided with a design maximum draft of 16.0 m instead of the 15m design draft for the project. Therefore, in order to simulate a UKC of at least 0.5 m during the navigation (i.e. considering the vessel movements), the water level has been increased by 1.5 m.

Furthermore, it was noticed during test runs prior to the workshop that when navigating inside the access channel under high winds, the UKC is reduced due to roll/squat. Therefore, the water level had to be further increased by 2.5 m total.

4.3.4 Run-matrix

The run-matrix of the simulations performed as part of this navigation study is shown hereafter. A total of 16 simulations were performed with 10 approaches and 6 departures.

Table 4-2 Navigation simulation run-matrix.

Run No.	Ship			Tug Assistance	Other Traffic	Manoeuvre			Wind		Waves - in the channel			Current		Water level	Safety Level	Debrief Remarks
	No.	Type	Loading condition	No. tugs / BP	(Yes/No)	Type	Orient.	Berth	Speed (m/s) hourly	Direction from (deg)	Height (m)	Period (s)	Direction from (deg)	Speed (kts)	Going towards (deg)		1-5	
AarhusPort_01	3663	18,000 TEU	Loaded	2 / 55t + 2 Switzer Mars	yes	Approach	Stbd	Existing	15	315	0.8	4	315	-	-	MSL+1.5 (to allow sufficient UKC)	4	Unable to handle ship to halt. Recommend in-creasing tug capacity to 90t
AarhusPort_02	3663	18,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Approach	Port	New - Basis	15	135	1.7	5	135	-	-	MSL+1.5 (to allow sufficient UKC)	4	Manoeuvre until at berth was good and control was maintained. At the berth more power was needed to control the fender impact speed. Ap-proach channel and turning basin were ade-quate for this manoeuvre.
AarhusPort_03	3663	18,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Departure	Port	New - Basis	15	315	0.8	4	315	-	-	MSL+1.5 (to allow sufficient UKC)	2	Plenty of power. No particular issue for this manoeuvre.
AarhusPort_04	3058	1,500 TEU	Loaded	2 x 55t	yes	Approach	Port	New - Basis	15	135	1.7	5	135	-	-	MSL	2	No particular issue to turn the vessel inside the basin, most power used to stop the ship before getting in the berth.
AarhusPort_05	3058	1,500 TEU	Loaded	2 x 55t	yes	Departure	Stbd	New - Basis	15	315	0.8	4	315	-	-	MSL	1	No particular issue to turn the vessel inside the basin. It would however be difficult for feeders to manoeuvre themselves without tug assis-tance in these conditions
AarhusPort_06	3749	22,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Approach	Port	New - Basis	15	135	1.7	5	135	-	-	MSL+1.5 (to allow sufficient UKC)	4	Manoeuvre until at berth was good and control was maintained. At the berth more power was needed to control the fender impact speed. Ap-proach channel and turning basin were ade-quate for this manoeuvre.
AarhusPort_07	3749	22,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Departure	Stbd	New - Basis	15	135	1.7	5	135	-	-	MSL+1.5 (to allow sufficient UKC)	2	Started with 15m/s going down to 10m/s to be able to lift the vessel. The turning area is suffi-cient and gives enough alternatives depending on the wind directions.
AarhusPort_08	3058	1,500 TEU	Loaded	2 x 55t	yes	Approach	Port	New - Alter-native	15	135	1.7	5	135	-	-	MSL	1	No particular issue to turn the vessel inside the basin. It would however be difficult for feeders to manoeuvre themselves without tug assis-tance in these conditions
AarhusPort_10	3663	18,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Approach	Port	New - Basis	12.5	135	1.7	4	135	-	-	MSL+1.5 (to allow sufficient UKC)	3	Approach and turning manoeuvre well under control. However the power required for the berthing manoeuvre is high.
AarhusPort_11	3663	18,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Departure	Port	New - Basis	10	135	1.7	4	135	-	-	MSL+1.5 (to allow sufficient UKC)	2	Wind taken down to 10m/s in order to take off the berth. Turning in the outside was carried out only using 2 55t tugs

Run No.	Ship			Tug Assistance	Other Traffic	Manoeuvre			Wind		Waves - in the channel			Current		Water level	Safety Level	Debrief Remarks
	No.	Type	Loading condition	No. tugs / BP	(Yes/No)	Type	Orient.	Berth	Speed (m/s) hourly	Direction from (deg)	Height (m)	Period (s)	Direction from (deg)	Speed (kts)	Going towards (deg)		1-5	
AarhusPort_12	3663	18,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Departure	Stbd	New - Basis	12.5	315	0.8	4	315	-	-	MSL+1.5 (to allow sufficient UKC)	1	Enough power to control the ship in the port basin. Manoeuvring was well under control with little tug power used during turning.
AarhusPort_13	3663	18,000 TEU	Loaded	2 x 55t	yes	Departure	Stbd	New - Basis	8	135	1.7	4	135	-	-	MSL+1.5 (to allow sufficient UKC)	1	Two tugs provide sufficient power for manoeu-vring under 8m/s wind.
AarhusPort_14	3663	18,000 TEU	Loaded	2 x 55t	yes	Approach	Port	New - Basis	8	135	1.7	4	135	-	-	MSL+1.5 (to allow sufficient UKC)	1	Two tugs provide sufficient power for manoeu-vring under 8m/s wind.
AarhusPort_15	3749	22,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Approach	Port	New - Basis	15	25	0.8	4	35	0.5	205	MSL+2.5 (to allow sufficient UKC)	4	Either too narrow or not deep enough. Turning of vessel with only two tugs pushing. Turning performed almost within the circle without going into the channel. Full power on all tugs was not sufficient to con-trol the vessel
AarhusPort_16	3749	22,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Approach	Port	New - Basis	15	205	1.7	5	205	0.5	25	MSL+2.5 (to allow sufficient UKC	4	Either too narrow or not deep enough. Turning of vessel with only two tugs pushing. Turning performed in the turning area on the channel side - very close to the edge of the dredged area. Full power on all tugs was not sufficient to con-trol the vessel
AarhusPort_17	3749	22,000 TEU	Loaded	2 x 55t + 2 x 90t	yes	Approach	Port	New - Basis	10	205	1.7	5	205	0.5	25	MSL+2.5 (to allow sufficient UKC)	4	Better control over the vessel in the channel. The speed still needs to be high in the channel, therefore the speed is too high when entering the turning basin.

4.3.5 Safety level mark

Each simulation is (as shown in Table 4-2) evaluated by safety level marks as follows:

1 High, run proceeded without problems.

2 Good, run occurred without excessive use of available internal forces to carry out planned manoeuvre.

3 Acceptable, internal forces may have once been used to near or full capacity to carry out the planned manoeuvre.

4 Not acceptable, the use of 100 % internal forces was necessary at several occasions to carry out planned manoeuvre.

5 Fail, ship grounded, collided, loss of control.

4.4 Results of simulations

4.4.1 General

The turning area and port basin geometry provided enough space for all simulations performed, see Figure 4-9 and Figure 4-10 presenting the density plots of all the workshop simulations. The tracks are well within the boundaries of the area and overall, the pilots deemed the area comfortable enough in terms of available space. No difference in terms of navigational safety was observed between the two future layouts - base layout and alternative layout.

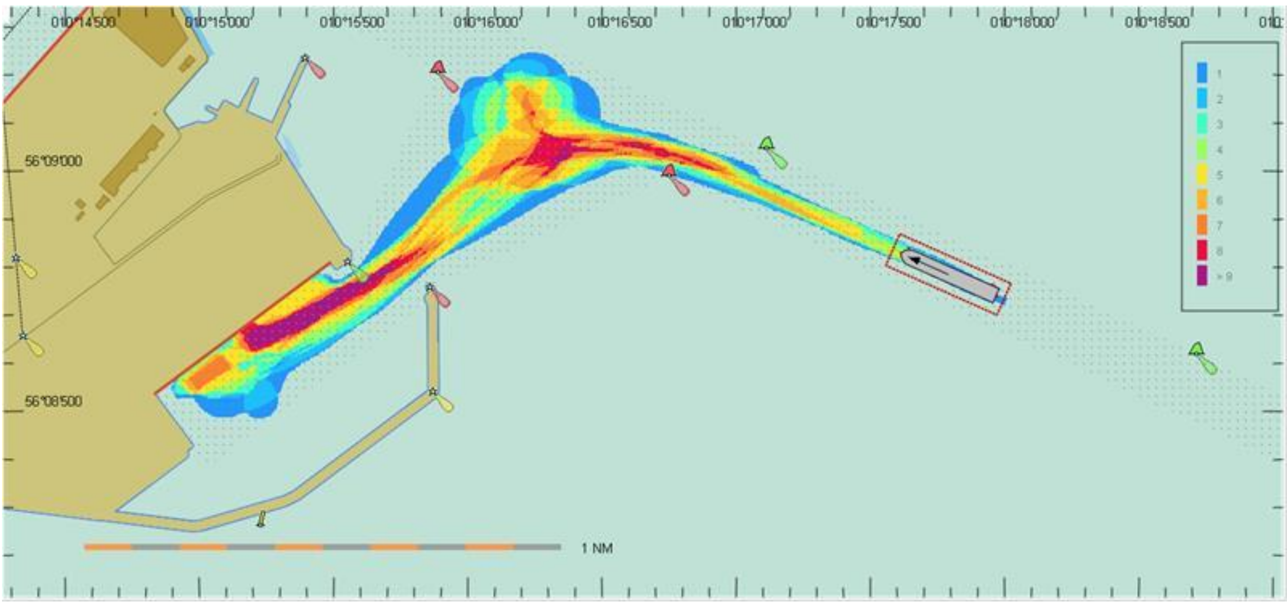


Figure 4-9 Density track plot of all workshop simulations (excluding channel runs 15, 16 and 17).

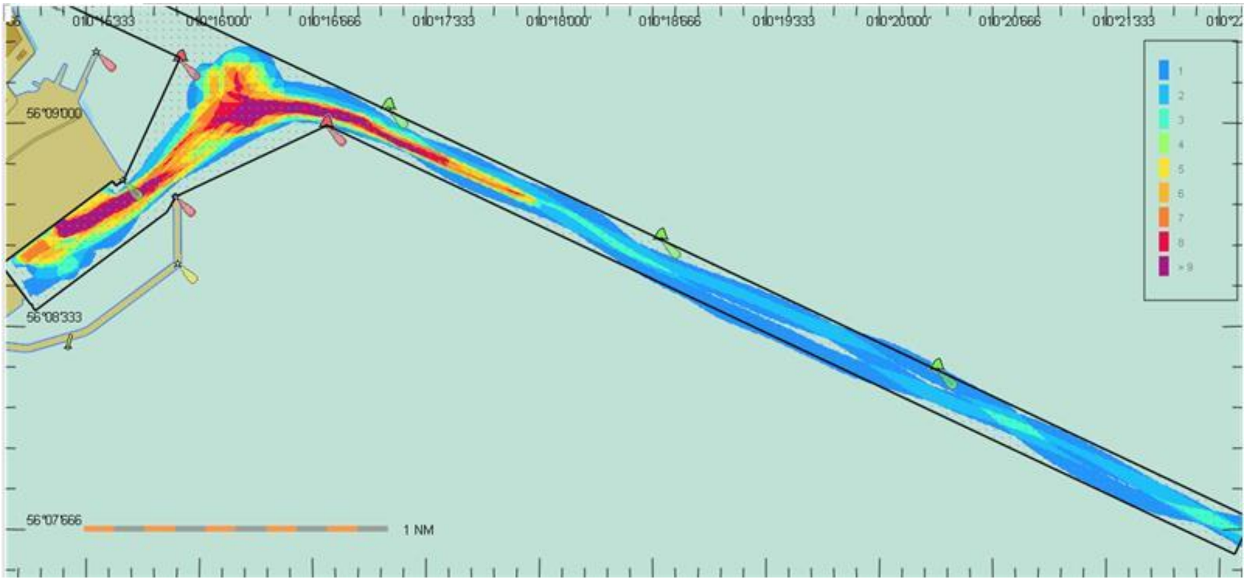


Figure 4-10 Density track plot of all workshop simulations.

The small vessel was easily turned into target position inside the port basin without difficulties even under high winds. No difference in terms of navigational safety was observed between the two future layouts.

Generally, for both approaches and departures, it was demonstrated that the largest vessels (Triple E and Golden CMS) cannot be controlled by the selected tugs under the conditions initially chosen for the simulations. With an increased tug power of 2x55 towing + 2x90 push/pull, 15 m/s wind still proved to be too high for a controlled and safe manoeuvre inside the basin. With this tug configuration, the operational wind speed limit was found to be 10 m/s.

4.4.2 Approaches

Under 15 m/s winds, the manoeuvres until the berth were controlled for all vessels. The turning area and port basin geometry provided enough space for safe turning and aligning with the port entrance.

Triple-E and Golden CMS

However, for the simulations with the largest vessels, the power available, from tugs and thrusters, was not sufficient to ensure a safe berthing speed once at the berth – see simulations 02 and 06 Figure 4-11 and Figure 4-12.

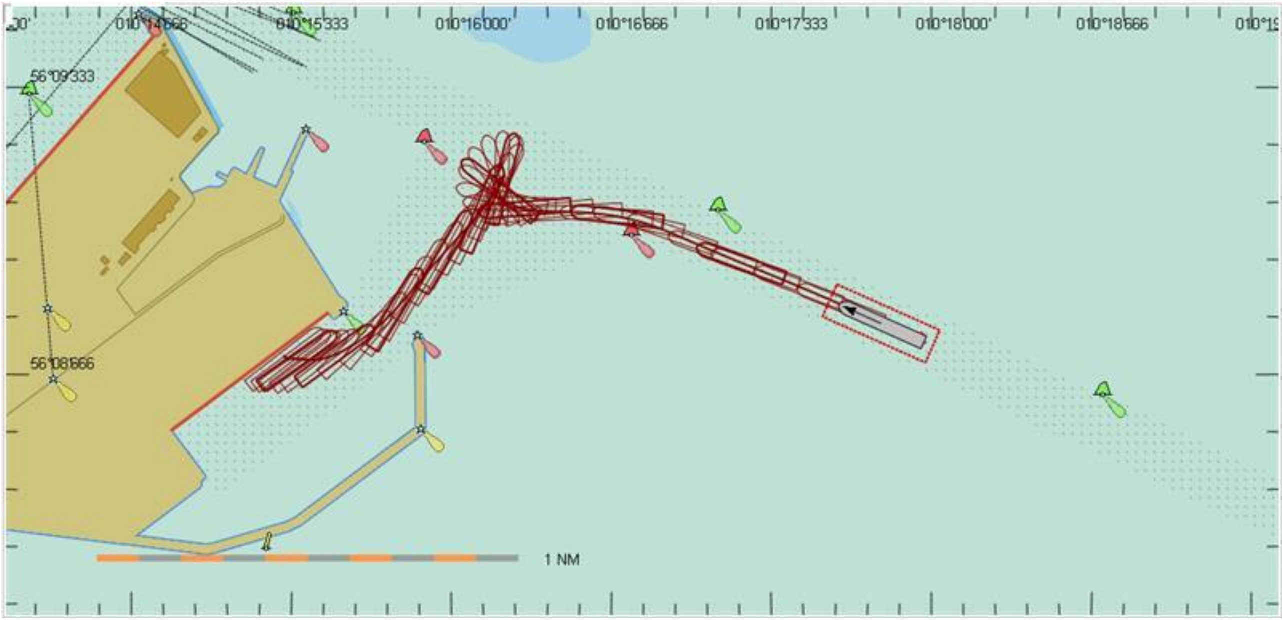


Figure 4-11 Simulation 02 - Triple-E Approach - Future Port base layout - 15 m/s wind from 135°.

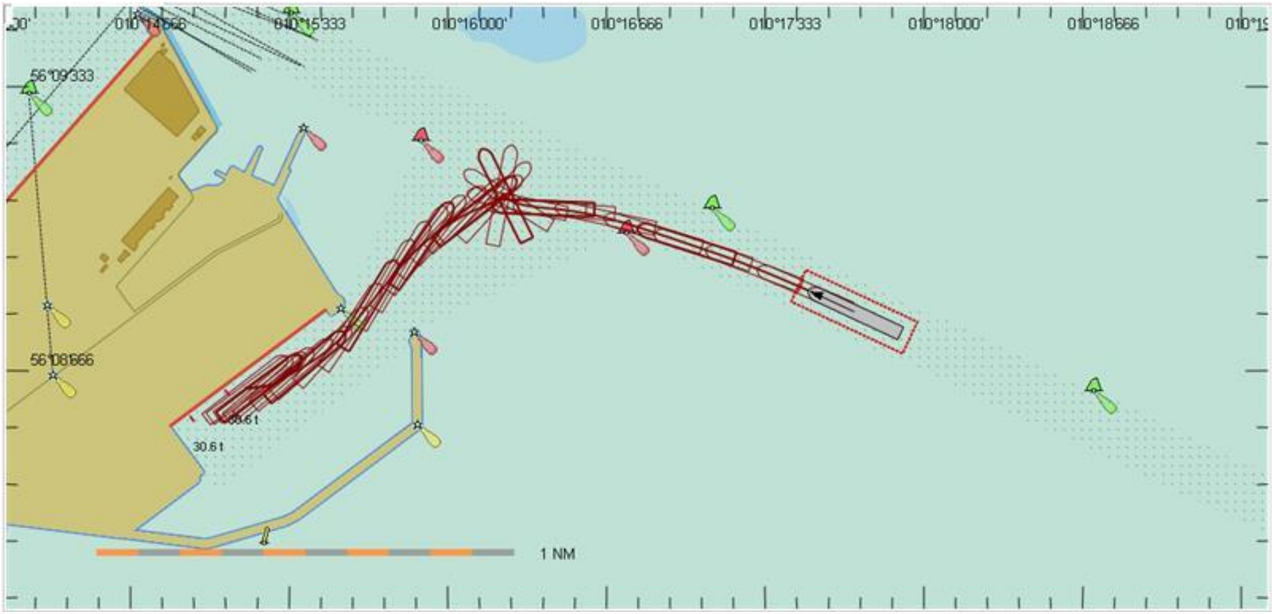


Figure 4-12 Simulation 06 - Golden CMS Approach - Future Port base layout - 15 m/s wind from 135°.

The wind speed was lowered to 12.5 m/s to be able to safely berth the Triple E with 4 tugs (2x55t + 2x90t), see simulation 10 in Figure 4-13. The simulation was rated as a 3 – 'Acceptable, considering the high power required for berthing'.

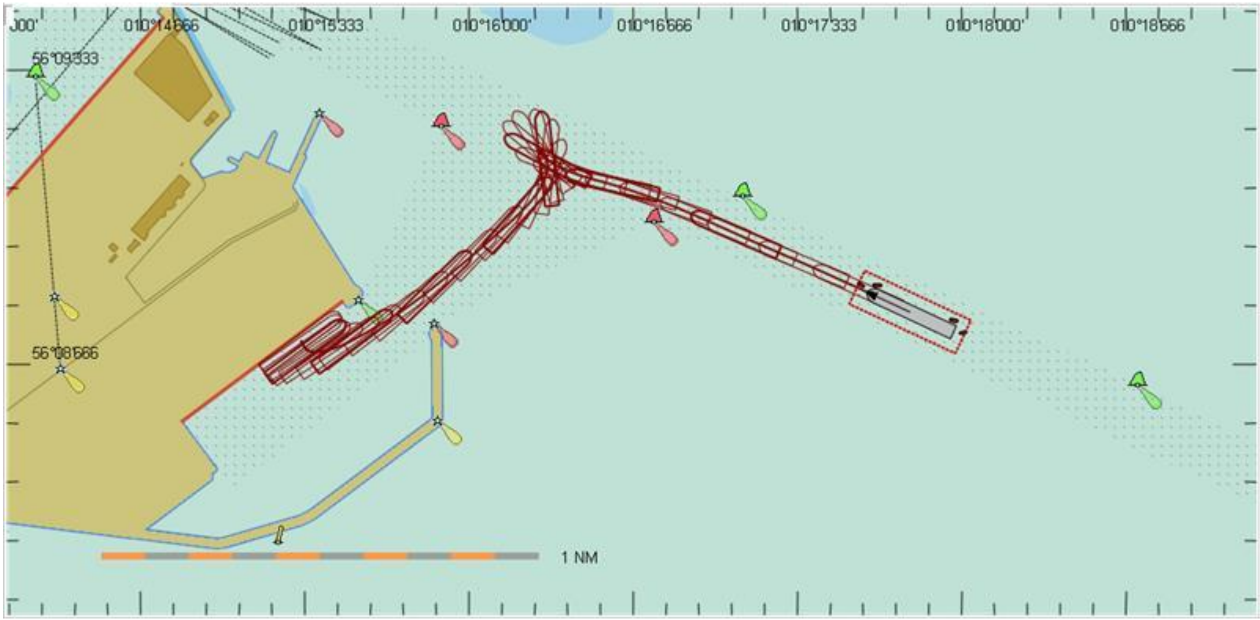


Figure 4-13 Simulation 10 - Triple-E Approach - Future Port base layout - 12.5 m/s wind from 135°.

Clifford Mærsk

The simulations with the small vessel did not raise any difficulties and were rated 1 or 2, although a lot of power was used to stop the vessel motion at the berth, see simulations 04 and 08 Figure 4-14 and Figure 4-15. It was noted that tug assistance was required for the small feeder under these conditions. No difference was noted between the two layouts, and the feeder could be turned inside the basin in both cases.

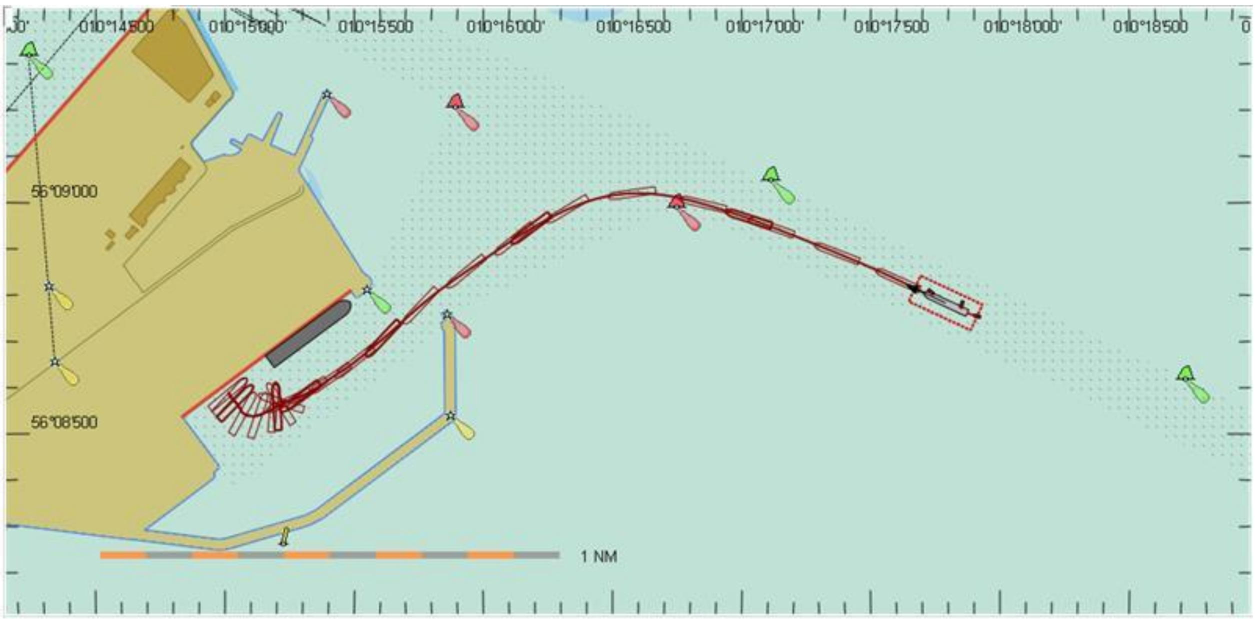


Figure 4-14 Simulation 04 – Clifford Mærsk Approach - Future Port base layout - 15 m/s wind from 135°.

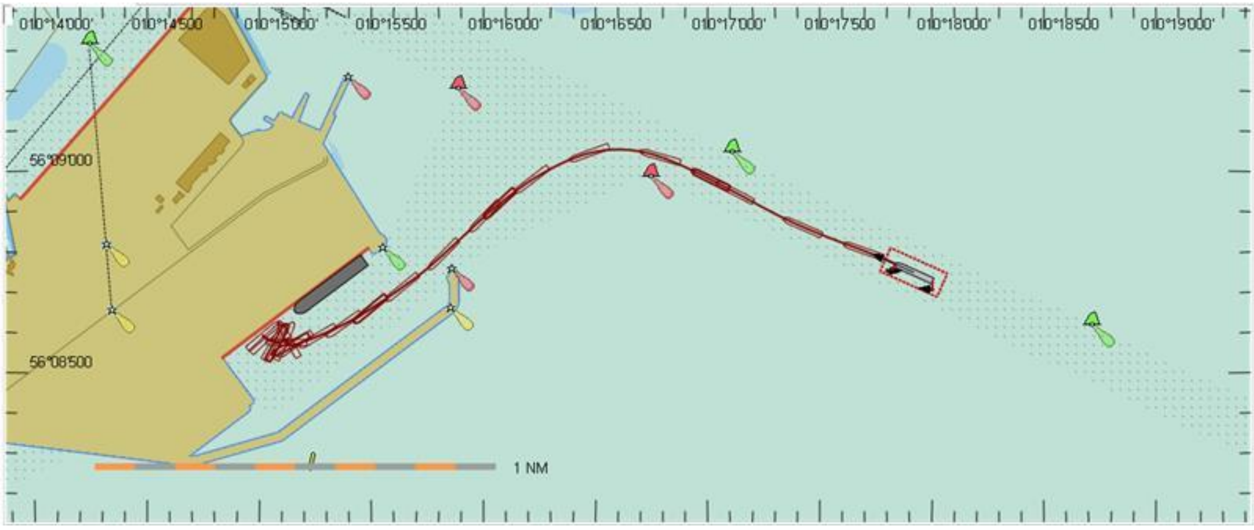


Figure 4-15 Simulation 08 – Clifford Mærsk Approach - Future Port alternative layout - 15 m/s wind from 135°.

Approaches including navigation in the access channel

Three simulations included navigation from outside the start of the access channel with the largest vessel Golden CMS – simulations 15 to 17 in Figure 4-16 to Figure 4-18. The navigation in the channel showed to be very challenging. The heading was difficult to maintain under high cross winds (15 m/s from 25° and 225° in simulations 15 and 16 respectively) and the width of the channel appeared not sufficient under these conditions, see Figure 4-19 where the total sweep for course correction reached about 270m.

Control of the ship was maintained by requiring to keep a relatively high speed (around 6 kts). Therefore, when entering the turning area, the vessel's speed is too high leading to not ideal conditions for making fast with tugs and plan the turning manoeuvres. When the wind speed is lowered to 10 m/s in simulation 17 (Figure 4-18), the vessel is found to be easier to control in the channel however. The speed at the entrance of the turning area still needs to be quite high and does not allow a safe and optimised turning manoeuvre.

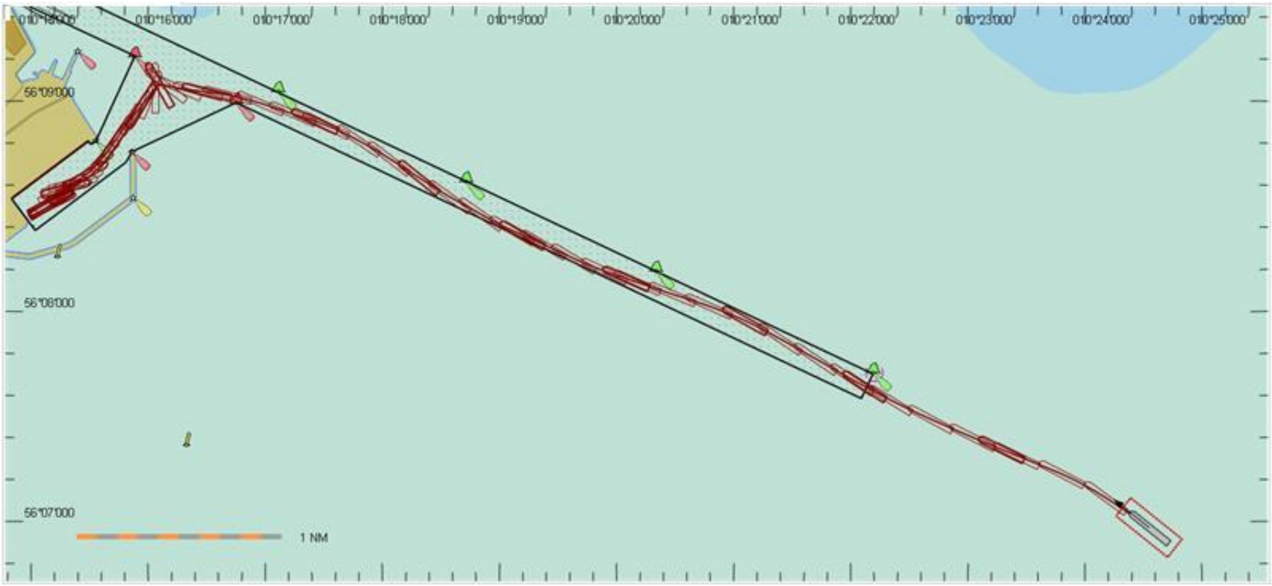


Figure 4-16 Simulation 15 – Golden CMS Approach - Future Port base layout - 15 m/s wind from 25° - Full channel.

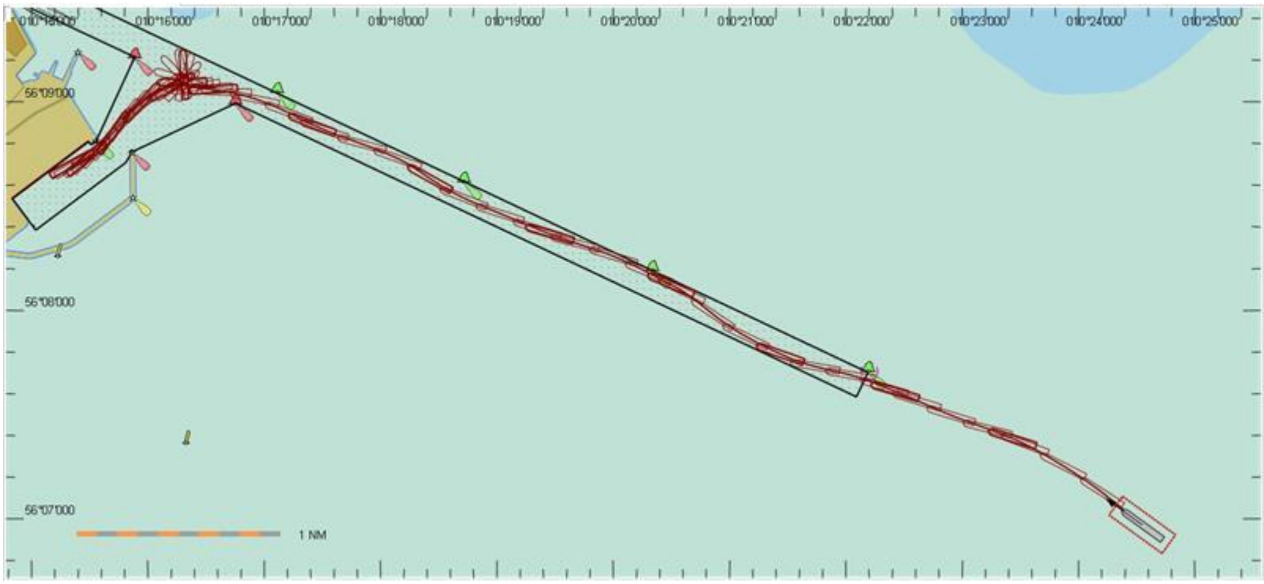


Figure 4-17 Simulation 16 – Golden CMS Approach - Future Port base layout - 15 m/s wind from 205° - Full channel.

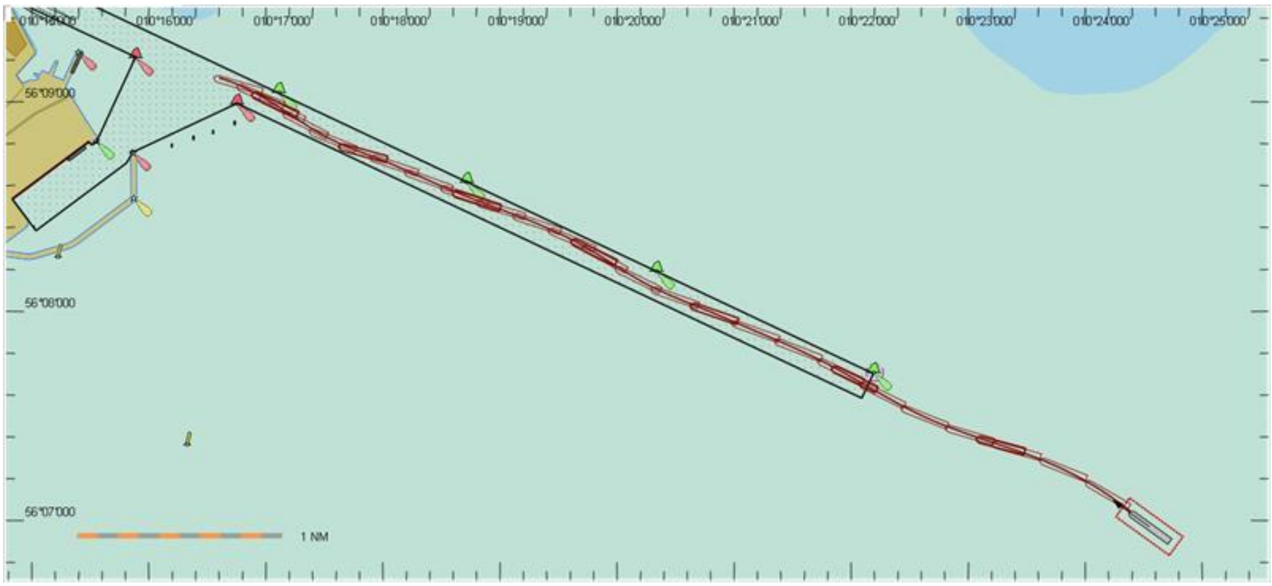


Figure 4-18 Simulation 17 – Golden CMS Approach - Future Port base layout - 10 m/s wind from 205° - Full channel.

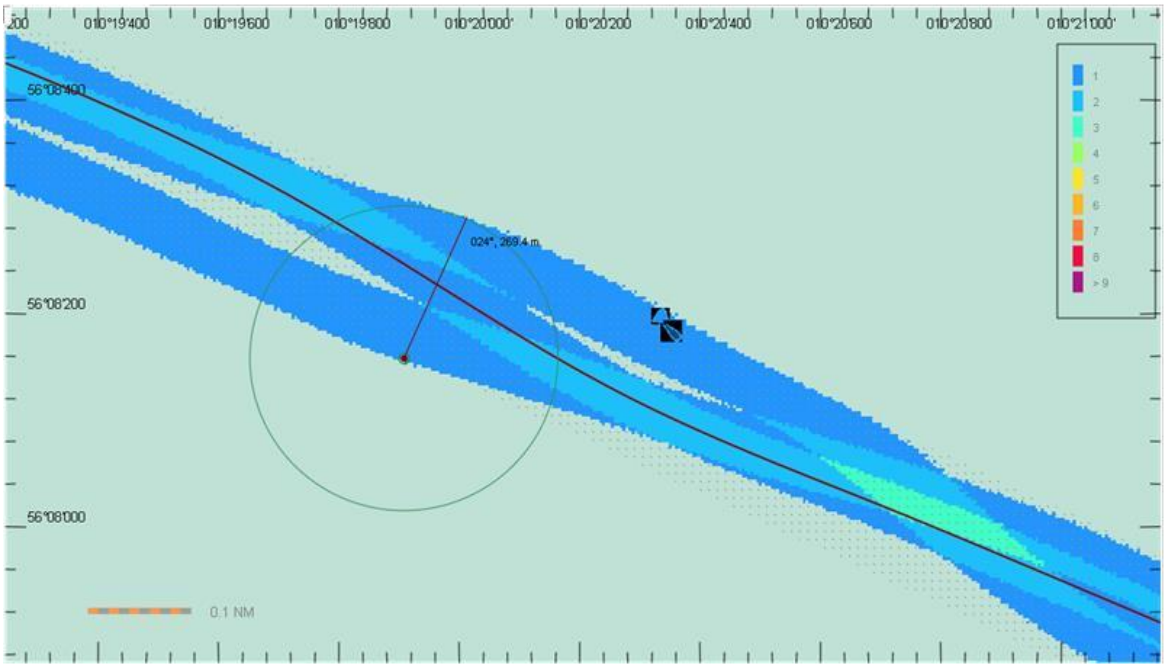


Figure 4-19 Close up of density track of channel simulations 15, 16 and 17.

4.4.3 Departures

Triple E & Golden CMS

Under 15 m/s wind coming from 315° (pushing the vessel away from the berth), the Triple E was able to be lift off from the berth and manoeuvre to the channel without difficulties and with some comfortable margin in terms of available power, see simulation 03 in Figure 4-20. With 12.5 m/s from 315°, the manoeuvre was well under control and little tug power was required during the turning, see simulation 12 in Figure 4-21.

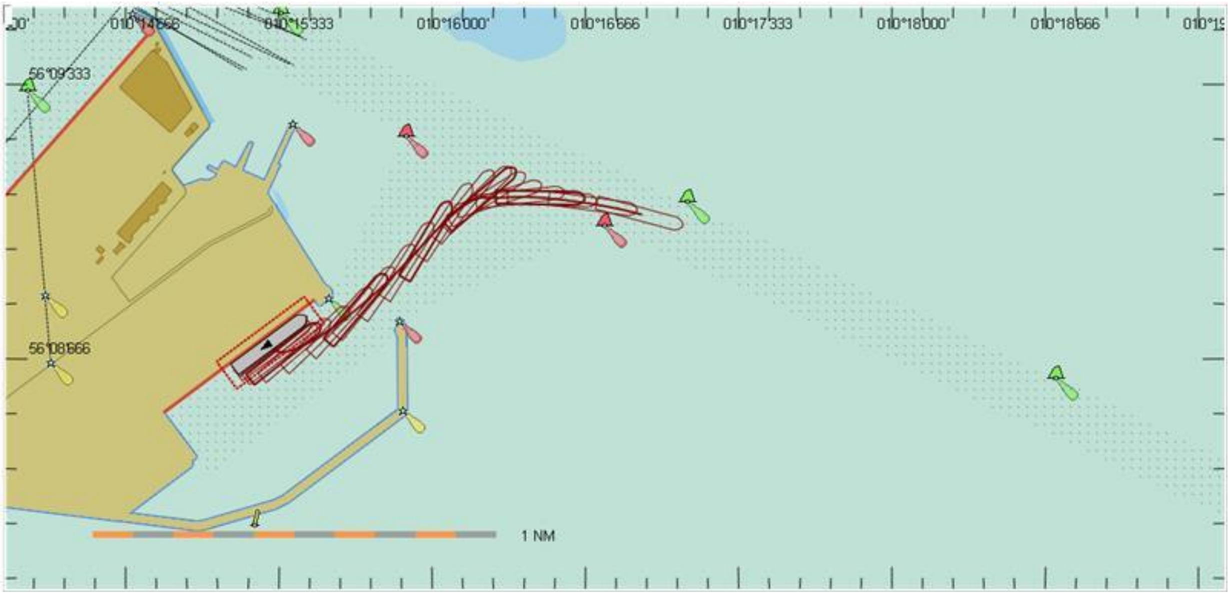


Figure 4-20 Simulation 03 – Triple-E Departure - Future Port base layout - 15 m/s wind from 315°.

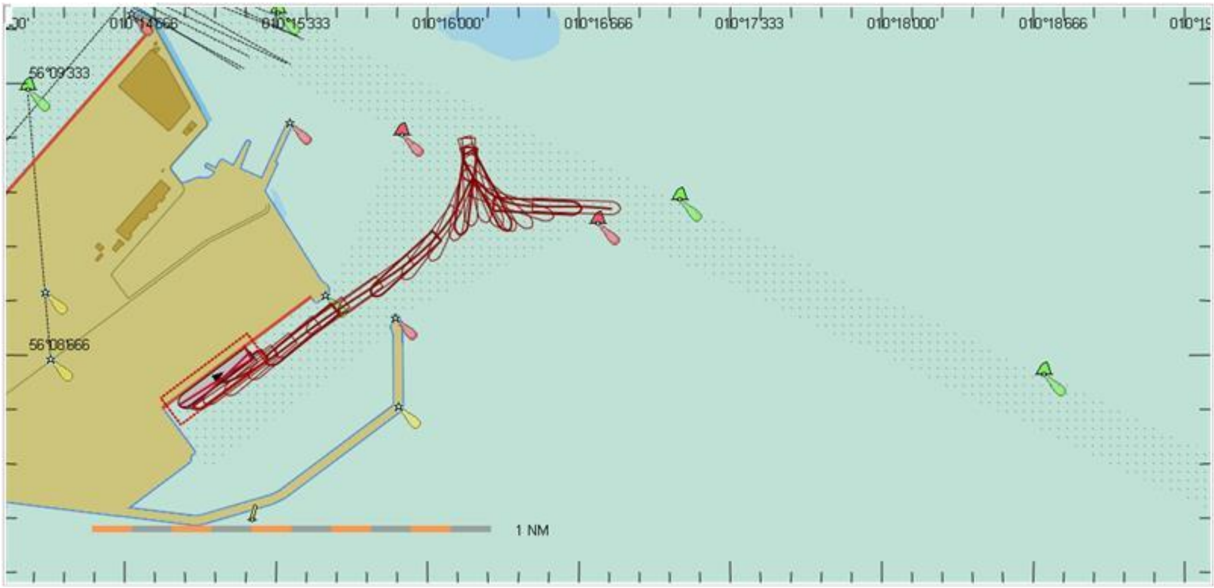


Figure 4-21 Simulation 12 – Triple-E Departure - Future Port base layout - 12.5 m/s wind from 315°.

However, with slightly lower wind (12.5 m/s) coming from 135°, the power available was not sufficient to lift the vessel off the berth. The wind was lowered gradually to define the maximum wind speed which allows to lift the vessel with available tug power. The limit was found to be 10 m/s wind. With this wind speed, the rest of the manoeuvre was controlled, the vessel was then turned with only 2 tugs inside the turning area, see simulation 11 in Figure 4-23. Based on this the layout was found adequate. Similar conclusion was drawn for the

Golden CMS departure with wind coming from 135°, see simulation 07 in Figure 4-22.

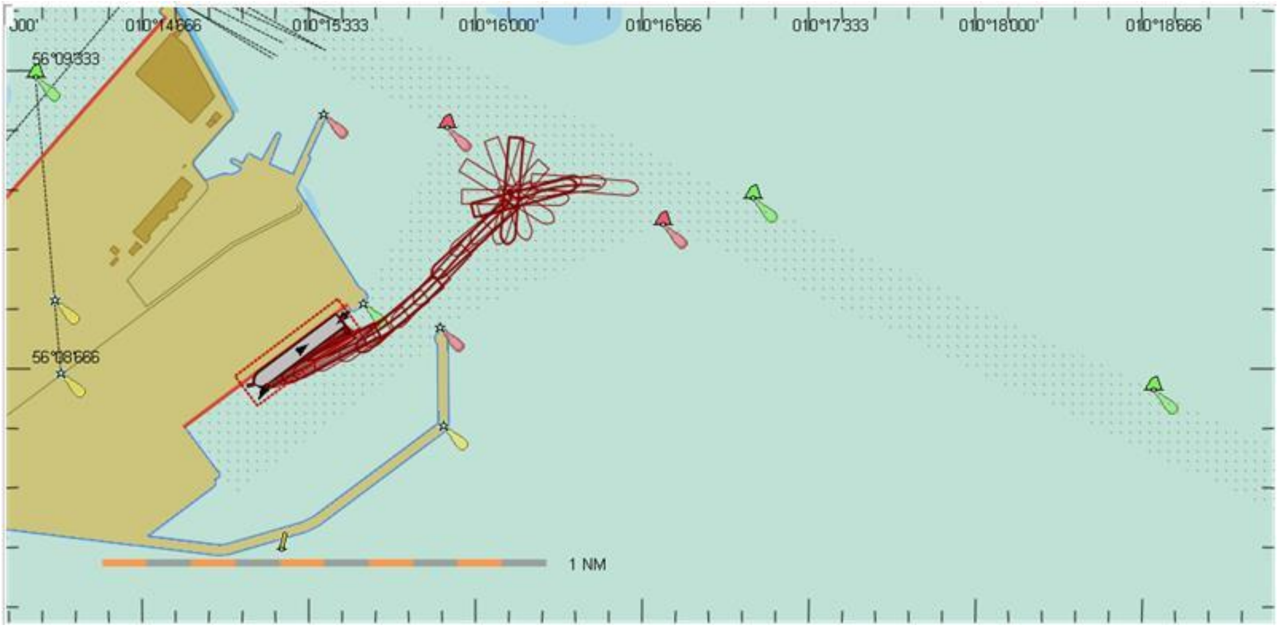


Figure 4-22 Simulation 07 – Golden CMS Departure - Future Port base layout - 10 m/s wind from 135°.

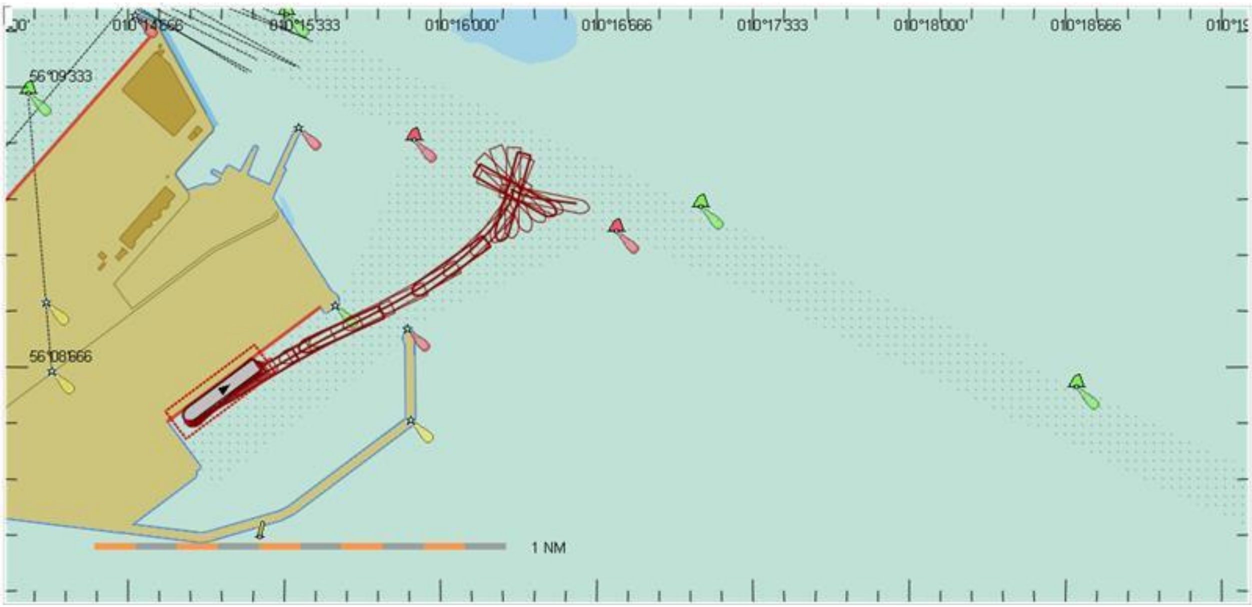


Figure 4-23 Simulation 11 – Triple-E Departure - Future Port base layout - 10 m/s wind from 135°.

Clifford Mærsk

With the feeder Clifford Mærsk, the departure manoeuvres were successful with even high winds (up to 15 m/s), and the vessel was easily turned inside the port basin, see simulation 05 in Figure 4-24. It shall be noted however that tug assistance is necessary for the feeder vessel manoeuvres.

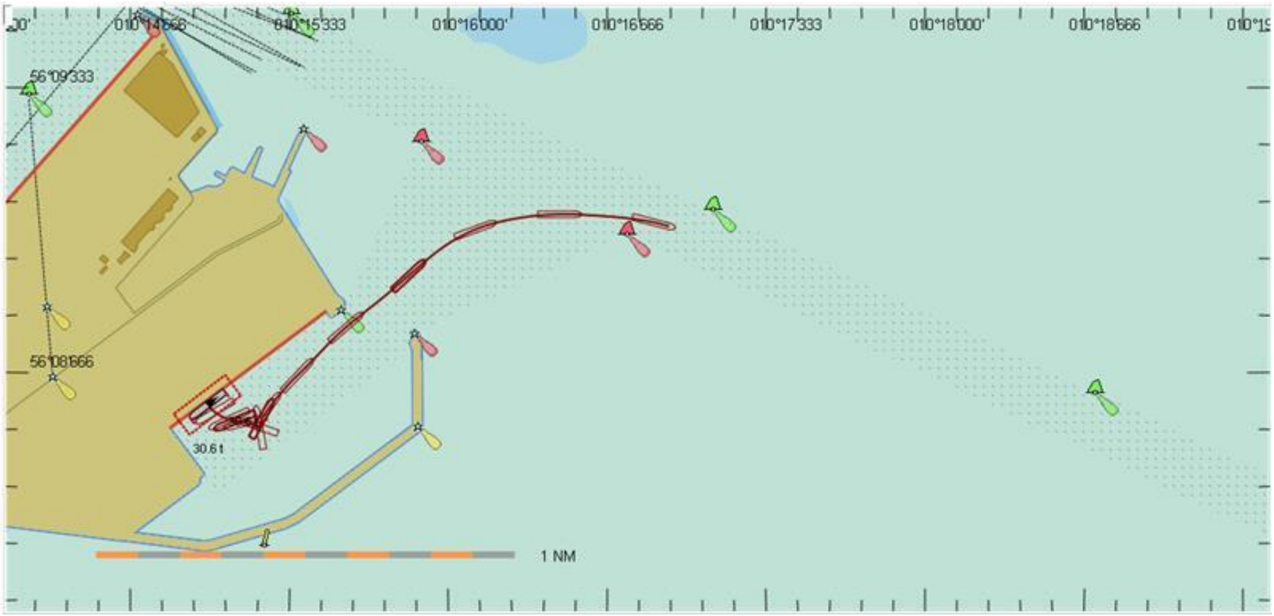


Figure 4-24 *Simulation 05 – Clifford Mærsk Departure - Future Port base layout - 15 m/s wind from 315°.*

4.5 Conclusions and recommendations

4.5.1 General

It was found that the base and alternative future layout are identical in relation to the navigation area geometry. Therefore, it should be assumed that the present recommendations apply equally for both future layouts.

4.5.2 Turning area and inner basin

Based on the simulations carried out, it was found that the geometry of the turning area (including the part in the channel) is generally adequate for manoeuvring all vessels up to Triple E and Golden CMS in both approach and departure manoeuvres in winds up to 15 m/s. Berthing manoeuvres for the last approach to place the vessels alongside the berths were too difficult for the tug fleet used due to high lateral forces from wind and it was unsafe or impossible to attempt berthing and de-berthing of the large container vessels with winds at 15 m/s. See section 4.5.5 below.

It was assessed that the inner basin offers sufficient space for smaller feeder vessels (1,500 TEU, 190 LOA) to turn inside the port basin. This is possible for both configurations, basis or alternative, and neither configuration is preferable to the other from this point of view.

All participants concluded that there is a potential for slight optimization (reduction of dredged area) of the turning area layout which may be further investigated at a later stage through additional navigation simulations.

4.5.3 Channel width

Based on the 3 initial simulations carried out starting out in the Aarhus bay and attempting to engage in the access channel under severe wind conditions, it is assessed that the channel is too narrow, not leaving room for any course correction for navigating the largest vessels Triple E and Golden CMS.

The channel dimensions and operating conditions are further investigated in a separate navigation simulation study focusing on this aspect, reported in Ref [2].

4.5.4 Channel depth

Initial simulations showed that with a combination of moderately high sailing speed (6-8 knots) required to maintain efficient steering and high wind speed (up to 15 m/s beam-on) with largest container vessels result in a reduced draft due to a combination of the squat effect with a heave movement of up to 0.4m, and roll angles of up to +/- 0.9° resulting in a loss of UKC of approximately 1m adding up to a total reduction of residual UKC by about 1.5m.
A final residual UKC of 0.5m after all effect accounted for is recommended.

This leads to a recommendation, for operating with 15 m/s wind to either dredge the channel 2 m below the rated draft of the triple-E calling at the port or limiting the draft/loading condition of the vessel to 13.5m.

Alternatively, reduced operating conditions may be assumed to allow the sailing speed to a minimum (reduce squat effect) and reduce the roll, by allowing only operation in the channel at lower wind speed operational limits. See section 4.5.5 below.

4.5.5 Operational limits for tug operations and access channel

Tug capacity and limit operational wind speed

Apart from the inherent limitations and reduction of efficiency of tug driven by wave conditions at the site, it was found that the tug configuration tested with 2 x 55t BPC and 2 x 90t BPC was not sufficient to control the berthing speed, and de-berth the largest container carriers.

Simulations 13 and 14 were carried out to demonstrate that a limit of 8m/s beam on wind (perpendicular to berth alignment) was acceptable for the above-mentioned tug configuration and provide sufficient forces to control the vessels (Triple-E). As this occurs inside the port basin, reduced efficiency of tugs due to waves is not relevant.

Channel depth and limit operational wind speed

In calm conditions (wind < 5m/s or head-on) and at relatively low sailing speed (<5 knots) in the channel, a small residual UKC of 0.5m relative to rated (static) draft may be assumed leading to the allowable draft in the channel of 15m. This shall be tested and planned carefully and ensure that wind/wave condition do not worsen during the channel transit which may take up to 1 hour.

In severe conditions (beam-on wind 15 m/s) as tested, due to the required high sailing speed (typically >6 knots) and high roll angle and heave movement, a large residual UKC compared to rated (static) draft of 2m is recommended.

Further analysis of the channel width and depth for various environmental conditions are analysed in a specific separate report, Ref [2].

5 References

Ref [1] PIANC WG-121, 2014 report "Harbour Approcah Channels, Design Guidelines"

Ref [2] COWI, March 2021, A104076-PD-074 "Navigation simulations, Dredged channel"

Ref [3] COWI, January 2021, A104076-PD-013 "Numerisk modellering af strømforhold"

Ref [4] COWI, January 2021, A104076-PD-013 "Numerisk modellering af bølgeforhold"

Bilag B Port of Aarhus. Port Expansion 'Yderhavnen'. Navigation simulations, dredged channel. March 2021

MARCH 2021
PORT OF AARHUS

PORT EXPANSION 'YDERHAVNEN'

NAVIGATION SIMULATIONS, DREDGED CHANNEL

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MARCH 2021
PORT OF AARHUS

PORT EXPANSION 'YDERHAVNEN'

NAVIGATION SIMULATIONS, DREDGED CHANNEL

PROJEKTNR.	DOKUMENTNR.
A104076	A104076-PD-74

VERSION	UDGIVELSESDATO	BESKRIVELSE	UDARBEJDET	KONTROLLERET	GODKENDT
1.0	17-03-2021	Rapport	MADO	GUAL	THGI

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1 Introduction

1.1 Background

The port of Aarhus is planning a new major port expansion called 'Yderhavnen', as shown in Figure 1-1. Environmental impact assessment, EIA (in Danish "Miljøkonsekvensvurdering") for the project is currently being carried out and as part of this the navigational safety need to be addressed by navigation simulations.

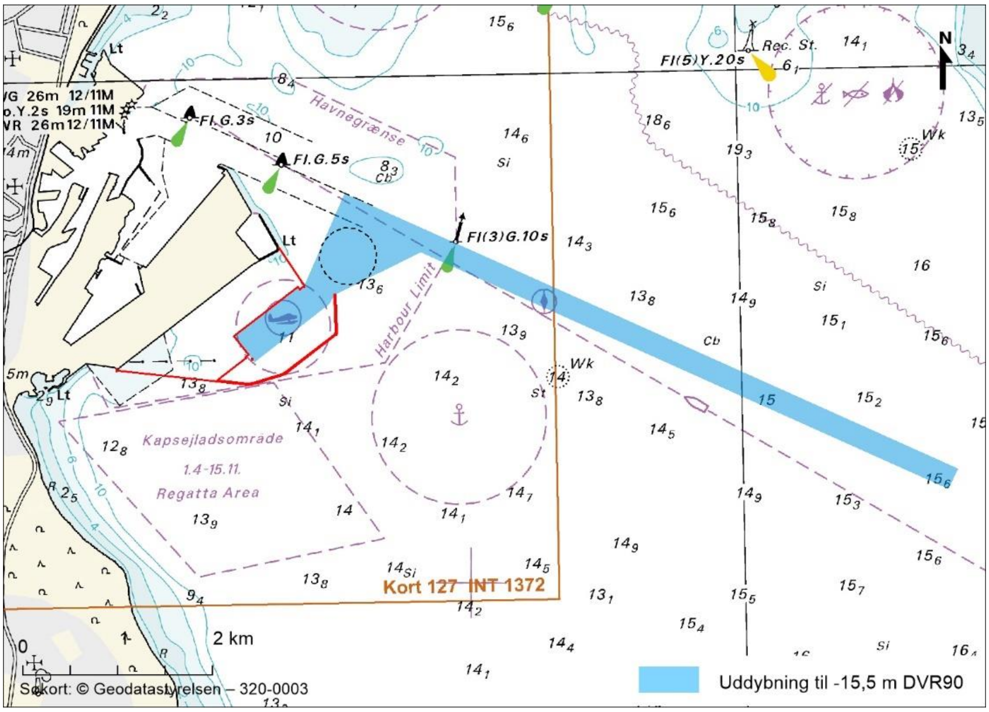

Figure 1-1 Port expansion 'Yderhavnen'.

1.2 Objectives of the report

The main purpose of the study is to verify the suitability of main navigation channel of the port of Aarhus in the context of the port expansion for larger container vessels, and to provide recommendations for future improvements if any.

A Navigation workshop took place in February 2021 and focused on the port layout in the context of the EIA. During this workshop, which was attended by two pilots from Aarhus Havn, three simulations were conducted in the channel. These simulations and the observations associated with them are also considered part of this study.

2 Basis

2.1 Dredged access channel layout

The channel is considered as 240 m wide, oriented 295.1° as straight extension of the existing heading and recommended track, and dredged to -15.5 m relative to CD.

The preliminary navigation aids layout includes a racon at the channel entrance (relocated from its existing position) and lateral marks and lights (starboard green) placed on the Northern side of the channel every nautical mile.

The port confirmed that they would not prefer adding also port side red marks in order to allow vessels with adequate draft to navigate outside of the channel as needed.

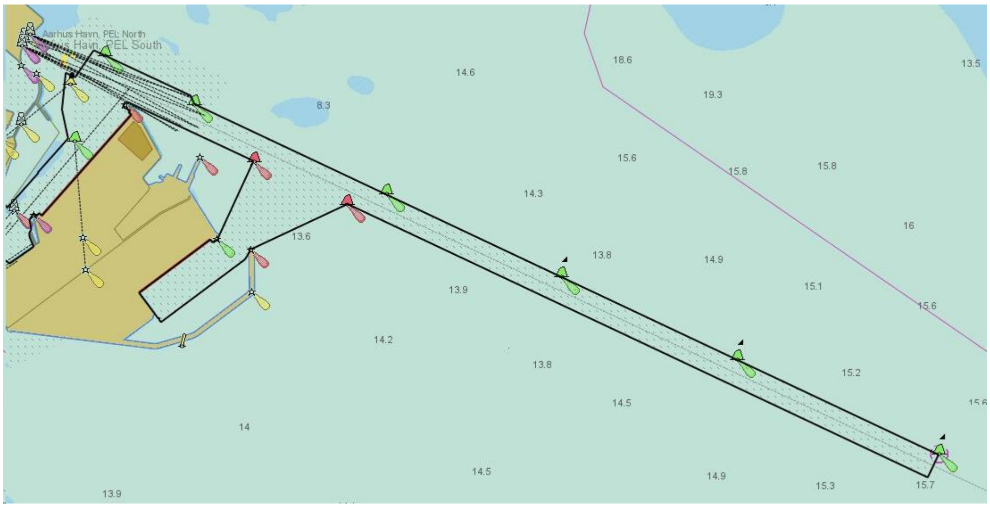

Figure 2-1 Navigation marking and layout of dredged access channel

Further detailing shall be made to the marks and lights in the subsequent phases of the project in order to ensure compatibility and coherence with the neighbouring marking system and local preferences/requirements and formal validation by relevant authorities.

2.1.1 Proposed modified layout

Two runs (simulations 11 and 12) have been performed with a widened channel of 320 m. The channel has been widened by 40 m on each side, thus maintaining the centreline and recommended track.

2.2 Design vessels

The new container terminal shall welcome the largest container vessels, therefore the navigation simulations consider the Mærsk Triple E (400 m LOA) which corresponds to the largest container vessels currently in service. An even larger vessel model (the Golden CMS) which is 440 m long 60m wide was available in the FORCE library and is also considered in the simulations.

The details of the vessel models are listed in Table 4-1.

2.3 Met-ocean conditions

2.3.1 Wind

Wind is assumed to be the governing effect on the vessel manoeuvrability, considering the very high windage area for loaded containers and relatively benign current conditions at the location.

The wind comes predominantly from Westerly and Southerly directions, see wind rose corresponding to future conditions are the port, Figure 2-2.

It is expected that the most critical directions will be beam-on i.e. from 25° and 205° but other directions will also be tested during the simulations, see the simulation run-matrix in Table 4-2.

The wind speed considered is 15 m/s, hourly average. This speed was selected based on a request from the Port pilots and is also in line with recommendations from PIANC WG 121 Ref [1]. One simulation is planned with a lower wind speed of 10 m/s, see Table 4-2.

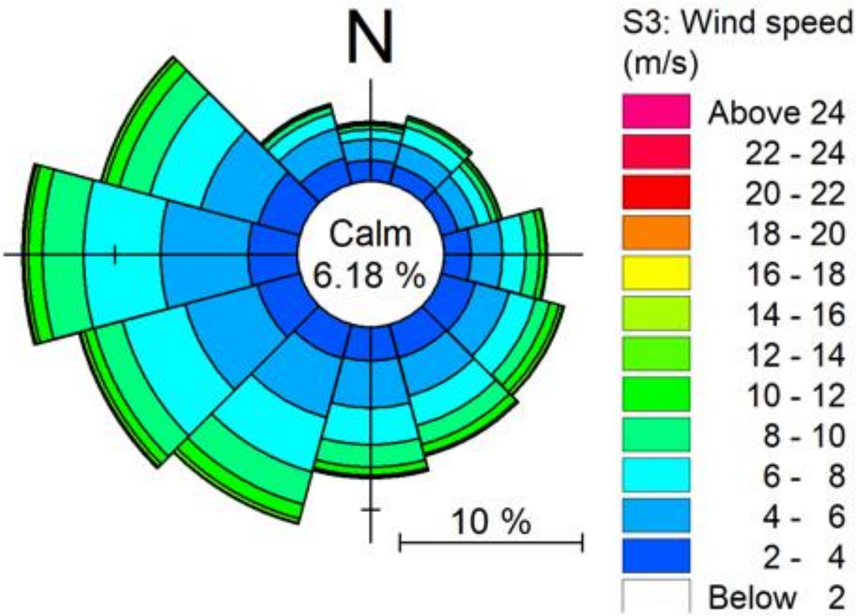

Figure 2-2 Wind rose - Ref [4]

2.3.2 Waves

In the channel, the Southern direction is predominant, Figure 2-3. However, the most adverse direction – in line with the wind direction selected – is considered for channel simulations, i.e. beam on from 25° and 205°.

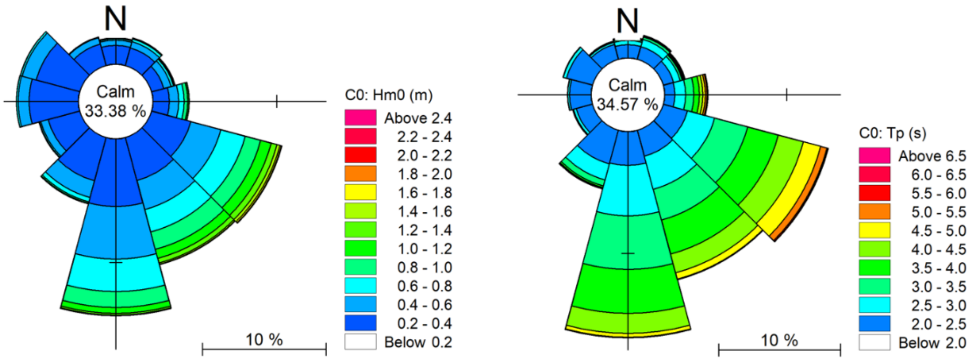

Figure 2-3 Wave rose - Future conditions in the channel, Ref [4]

Waves are considered either with an 1.7 m Hs /5s Tp when coming from South and South-East direction (based on SW model Ref [4] with a wind speed of 15 m/s), or 0.5-0.8 m Hs / 4s Tp when coming from other directions.

It shall be noted that the wave is not considered as a governing effect on the vessel's manoeuvrability.

2.3.3 Current

The current in the area is quite low (see Figure 2-4) and therefore not considered having a significant effect on the vessel's manoeuvrability. Therefore, current is neglected in the navigation simulations.

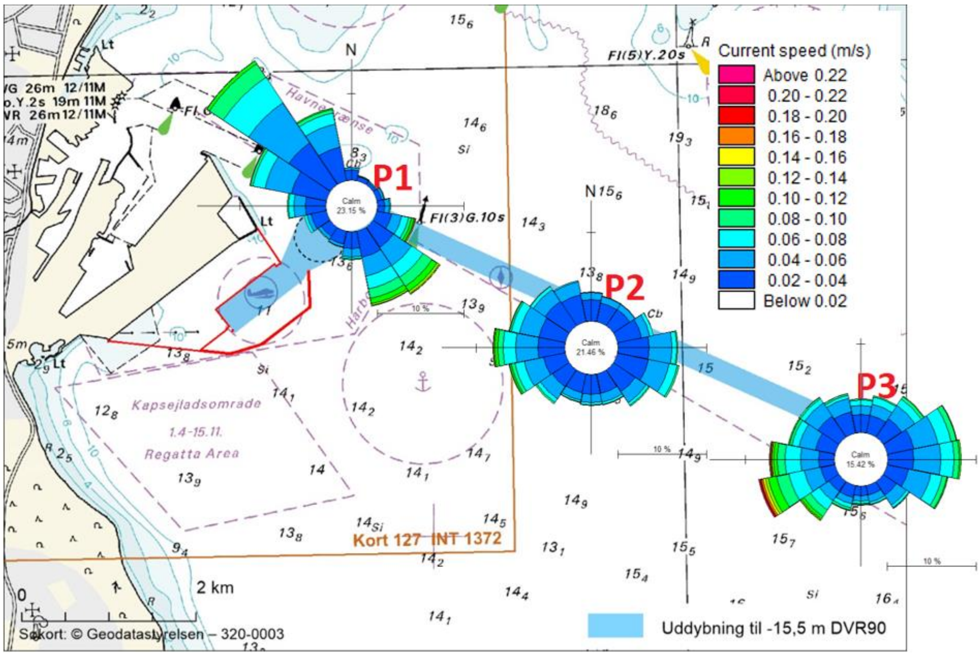

Figure 2-4 Current rose, future conditions, Ref [3]

3 Assessment of dredged channel geometry

The future channel width is currently planned as 240 m. The PIANC WG-121 2014 report “Harbour Approach Channels, Design Guidelines” Ref [1] provides a methodology for calculating the basic manoeuvring lane width according to the largest design vessel, the met-ocean conditions and foreseen navigation speed in the channel. Following this methodology with preliminary assumptions, the recommended width is calculated to be in the excess of 320 m. The channel is therefore considered too narrow. This is investigated during the simulations.

The future depth of the channel is currently considered as -15.5 m, similar to the future port and turning area dredged depth, which provides a residual under-keel clearance of 0.5 in case of 15m draft. This seems low considering the potential movements of the ship under high cross winds and due to squat effect as well as other hydrodynamic ship movements during manoeuvres. This aspect is investigated if possible, during the simulations, but will be further evaluated through the dedicated navigation simulation study for the access channel Ref [2].

4 Navigation simulations

4.1 Hardware and software

4.1.1 Area engineer

To run the simulations a numerical layout model is set up by use of the software "Area Engineer". The model includes:

- 2D geometric definition of i.e. bathymetry, fenders and other physical objects.
- 3D definition of surrounding jetties, buildings, tanks, etc.
- Visualization tools for monitoring of environmental effects.
- Aids to Navigation such as marks and light descriptions.

4.1.2 Operation control centre

The real time simulations are performed by the Operation Control Centre (OCC). It is a state-of-the-art numerical navigation model, which simulates the effect and interaction between met-ocean conditions, and ship models and link to other external sources affecting the model ship such as push and pull tug operations. The effects are specific to each individual ship model and include:

- Wind forcing
- Current forcing
- Wave forcing
- Tug selection and handling
- Visibility conditions

4.1.3 Hardware

The simulator equipment operated is composed of three stationary PC in network, three 21" monitors displaying instructor screen (OCC), the ship instruments, and ship chart plotter (ECDIS). Furthermore, three 55" screens displaying the 3D visual environment, providing a 180°-panoramic view of the area.

Figure 4-1 Simulator screen and commands set-up

It shall be noted that the 3D visuals created for the navigation workshop Ref [2] were not used as part of this study.

The ship main controls (main rudder, main engines, thrusters, visual orientation) are provided via a hardware console as shown in Figure 4-2 below.

Figure 4-2 Ship main control hardware console.

4.1.4 2-D environment

The 2D environment consist of planar representation of the physical elements of the layout, in the format typical of official electronic navigation charts. It presents also the layout of navigation aids (Buoys, lights, recommended navigation tracks, and dredged area) as well as the seabed natural or dredged elevation relative to Chart Datum.

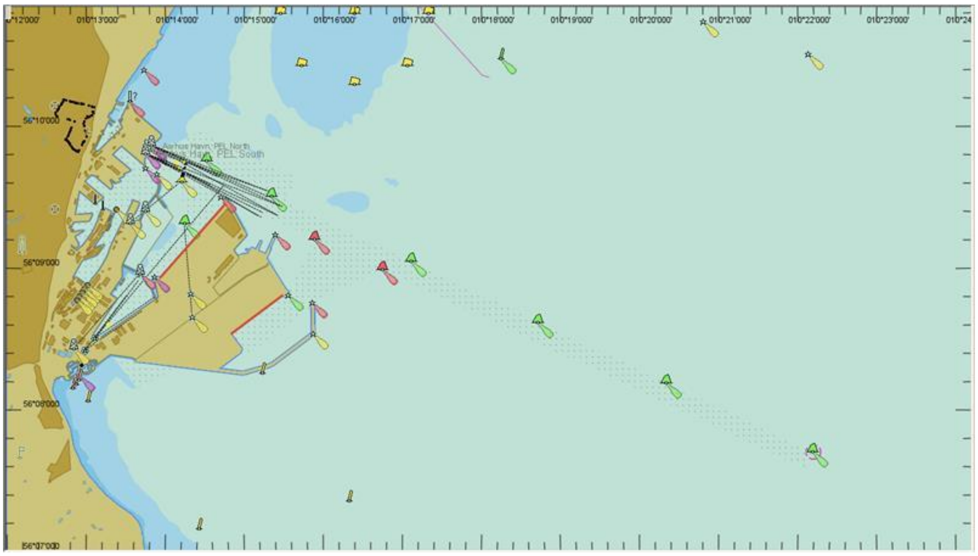

Figure 4-3 2D environment

4.1.5 Ship models

Ship models with dimensions as close as possible to the design vessels were selected for the simulations.

Ship models nos. 3663 and 3749 were used for the simulations.

Table 4-1 Ship models particulars

Ship no.	**Type**	**Description**	**Loading con-di-tion**	**LOA [m]**	**LBP [m]**	**B [m]**	**D [m]**	**Model visualisation**
3663	Con-tainer	Mærsk Triple E 18,000 TEU	Loaded	399	376.21	59	16	
3749	Con-tainer	Golden CMS 22,000 TEU	Loaded	440	418	60	16	

It shall be noted that the drafts of the Triple-E and Golden CMS are maximum design drafts, corresponding to a maximum number of containers, and thus a maximum windage area. Therefore, there is some conservatism in the effect of wind (which is higher in the simulations than what can reasonably be expected) and on the general manoeuvrability of both vessels. However, for the purposes of this study, the models are deemed adequate for the verification of the channel.

4.2 Main assumptions

The following main assumptions were considered for the navigation simulations:

- In general, vessels will arrive loaded, and will depart loaded.

- The basin and channel are not deep enough to allow for the navigation of the loaded Triple-E and Golden CMS vessel models (fully loaded). Therefore, to simulate the navigation of the loaded vessels in the most realistic way, some adjustments are made to the water depth in the basin and channel to maintain a minimum UKC, see 4.3.3.

- When used, the power of the tugs is only utilized typically up to 75% for all normal operations. If the degree of utilization is above 75% the operation is considered above safe limits unless it is done intentionally under controlled conditions to speed up the manoeuvres.

- The target speed when entering the turning area is set to 5 knots, as advised by Aarhus Havn pilots during the navigation simulation workshop for the port layout, see Ref [2].

4.3 Methodology

4.3.1 Tugboat configuration

Simulation 9 is a departure run started at the berth, and considers the following tug configuration:

- 2x55t towing tug at fore and aft
- 2x90t push/pull tugs at quarter points

Simulation 10 (see Table 4-2) includes the use of a 55ton steering tug.

4.3.2 Standard manoeuvres

All the manoeuvres except simulation no. 09 start approx. 1NM from the channel entrance in the Aarhus bay with a speed of 8 knots and misaligned with the channel to assess the feasibility of aligning the ship with the channel before entry. The simulations stop once the vessel enters the turning area.

Simulation n. 09 is a departure, with the following standard manoeuvre:

- The vessel is lift off from the berth with tugboats. The vessel is then brought out of the port basin, at the centre of the turning area. Assisted by tugboats, the vessel is turned towards the channel exit and starts to accelerate.

4.3.3 Adjustment of water level

The ship models for the Triple E and Golden CMS are provided with a design maximum draft of 16.0 m. The dredged depth of the channel is 15.5, therefore the water level needs to be artificially increased in order to allow the simulations with these models.

It was noticed during test runs that when navigating inside the channel under high winds, the UKC is reduced due to roll/squat, therefore, the water level has been increased by 2 to 2.5 m total.

A specific test with low wind speed and low sailing speed was carried out in simulation no. 13 in order to assess the possibility to bring in the vessel with small residual UKC in clear and calm weather.

4.3.4 Run-matrix

The run-matrix of the simulations performed as part of this navigation study is shown in Table 4-2.

A total of 15 simulations were performed with 14 approaches and 1 departure. It should be noted that three simulations (named 'Workshop_AarhusPort'_15, 16 and 17) analysed in this report were carried out during the workshop with the port pilots see Ref [2].

Table 4-2 Navigation simulation run-matrix.

Run	Ship			Tug Assistance		Other Traffic	Manoeuvre			Operator	Wind		Waves - in the channel			Current		WL	Comment condition	Remark	Safety Level 2)	Remark
No.	No.	Type	Loading condition	(Yes/No)	No. tugs / BP	(Yes/No)	Type	Ori-ent.	Berth	Initials	Speed (m/s) hourly	From	Height (m)	Period (s)	From	Speed (kts)	Going			Conditions	1-5	Debrief Remark
AarhusPort_01	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	GUAL	15	25	0.5	4	25	-	-	MSL+3			3	Channel too narrow. Difficult to sail at speed lower than 6knots
Workshop_ AarhusPort_15	3749	22,000 TEU	Loaded	Yes	2x 55t + 2 x 90t	yes	Ap-proach	Port	New - Basis	Aarhus Havn - Thomas Sil-lesen/Poul Pedersen	15	25	0.8	4	35	0.5	205	MSL+2.5	MSL +2.5 to allow sufficient UKC	Full channel Avoid turning in channel	4	Either too narrow or not deep enough. Turning of vessel with only two tugs pushing. Turning performed almost within the circle without going into the channel. Full power on all tugs was not sufficient to control the vessel
Workshop_ AarhusPort_16	3749	22,000 TEU	Loaded	Yes	2x 55t + 2 x 90t	yes	Ap-proach	Port	New - Basis	Aarhus Havn - Thomas Sil-lesen/Poul Pedersen	15	205	1.7	5	205	0.5	25	MSL+2.5	MSL +2.5 to allow sufficient UKC	Full channel Avoid turning in channel	4	Either too narrow or not deep enough. Turning of vessel with only two tugs pushing. Turning performed in the turn-ing area on the channel side - very close to the edge of the dredged area. Full power on all tugs was not sufficient to control the vessel
Workshop_ AarhusPort_17	3749	22,000 TEU	Loaded	Yes	2x 55t + 2 x 90t	yes	Ap-proach	Port	New - Basis	Aarhus Havn - Thomas Sil-lesen/Poul Pedersen	10	205	1.7	5	205	0.5	25	MSL+2.5	MSL +2.5 to allow sufficient UKC	Full channel only	4	Better control over the vessel in the channel. The speed still needs to be high in the channel, therefore the speed is too high when entering the turning ba-sin.
AarhusPort_02	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	GUAL	15	90	0.8	4	90	0.5	205	MSL+2			2	relatively easy to keep heading inside the channel. Ability to slow down to 5.5knots, stop and start turn even without tug assistance. But channel still "feels" too Narrow.
AarhusPort_03	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	GUAL	15	135	1.7	5	135	0.5	205	MSL+2			2	relatively easy to keep heading inside the channel. Ability to slow down to 5.5knots, stop and start turn even without tug assistance. But channel still "feels" too Narrow.
AarhusPort_04	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	GUAL	15	180	1.7	5	180	0.5	25	MSL+2			4	Able to maintain heading well at speeds above 7 knots. Very dif-ficult to impossible to go below 6 knots sailing speed and main-tain control in the last approach to the basin. Channel feels too narrow and does not offer enough space for adjusting heading.
AarhusPort_05	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	GUAL	15	315	1.7	5	205	0.5	25	MSL+2			2	relatively easy to keep heading inside the channel. Ability to slow down to 4.7knots. Channel still "feels" too Narrow.
AarhusPort_06	3663	18,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	MADO	15	25	0.5	4	25	0.5	205	MSL+2			2	Able to maintain heading well at speeds above 7 knots. Ability to slow down to around 4.6 knots when entering the turning area. Channel feels too narrow and does not offer enough space for adjusting heading.

Run	Ship			Tug Assistance		Other Traffic	Manoeuvre			Operator	Wind		Waves - in the channel			Current				Remark	Safety Level 2)	Remark
No.	No.	Type	Loading condition	(Yes/No)	No. tugs / BP	(Yes/No)	Type	Ori-ent.	Berth	Initials	Speed (m/s) hourly	From	Height (m)	Period (s)	From	Speed (kts)	Going	WL	Comment condition	Conditions	1-5	Debrief Remark
AarhusPort_07	3663	18,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	MADO	15	205	1.7	5	205	0.5	25	MSL+2			3	Able to maintain heading well at speeds above 7 knots. Difficult to slow down below 4.5 knots when entering the turning area. Channel feels too narrow.
AarhusPort_08	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	MADO	10	25	0.5	4	25	0.5	205	MSL+2	Lower speed		3	Able to lower the speed to around 4 knots in the last NM, however very close to the edge of the channel.
AarhusPort_09	3749	22,000 TEU	Loaded	No	N/A	No	De-par-ture	N/A	New - Basis	MADO	15	205	1.7	5	205	0.5	25	MSL+2		Wind speed reduced to 10 m/s to be able to lift the ves-sel from the berth	3	Difficult to keep the heading, channel too narrow.
AarhusPort_10	3749	22,000 TEU	Loaded	Yes	1x Svitzer Mars	No	Ap-proach	N/A	New - Basis	MADO	15	25	0.5	4	25	0.5	205	MSL+2	With steer-ing escort tug		5	Not possible to reduce the speed of the vessel under 6 knots and to maintain the con-trol of the heading.
AarhusPort_11	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis - Wid-ened	MADO	15	205	1.7	5	205	0.5	25	MSL+2	Widened channel		3	Not able to lower the speed be-low 6.2 knots in the last NM, very close to the edge of the channel. The rest of the channel navigation was controlled.
AarhusPort_12	3749	22,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis - Wid-ened	MADO	15	25	0.5	4	25	0.5	205	MSL+3	Widened channel		3	Not able to lower the speed be-low 5.5 knots in the last NM, very close to the edge of the channel. The rest of the channel navigation was controlled.
AarhusPort_13	3663	18,000 TEU	Loaded	No	N/A	No	Ap-proach	N/A	New - Basis	GUAL	5-10	205	0.5	3.9	205	0.5	25	MSL+1		Test for re-duced UKC with lower wind speeds	2	When sailing at speeds below 5 knots, with wind at 5 m/s the rol angle is small (0.2°) and heave remains around -0.2m. Leading to a residual UKC of 0.3m. Increased wind to 8-10m/s re-sult in residual UKC of 0.1m to 0.0m which is too close to the channel bottom.

4.3.5 Safety level mark

Each simulation is evaluated by safety level marks as follows:

1 High, run proceeded without problems.

2 Good, run occurred without excessive use of available internal forces to carry out planned manoeuvre.

3 Acceptable, internal forces may have once been used to near or full capacity to carry out the planned manoeuvre.

4 Not acceptable, the use of 100 % internal forces was necessary at several occasions to carry out planned manoeuvre.

5 Fail, ship grounded, collided, loss of control.

4.4 Results of simulations

The original channel width of 240 m does not leave any margin for adjustment of heading or error of navigation with the two large container vessels, as can be seen on Figure 4-4. The full width of the channel was used, and the vessel often reached the limit of the dredged area. The maximum width of the swept area reached 275 m, as shown in Figure 4-5.

In most simulations with the Golden CMS, it has proven difficult or impossible to slow down to approx. 5 knots in the last nautical mile of the channel under high cross winds. With the more manoeuvrable Mærsk Triple-E, it appears possible yet still challenging.

In most simulations, an artificial tide of 2m is modelled to allow navigation of the vessel models with large drafts. This simulates a static UKC of 1.5m (depth + tide – draft = 15.5 + 2 – 16 = 1.5 m). The minimum dynamic UKC, observed during all the simulations was 0.22 m. In order to have a similar UKC with a 15 m draft vessel, the corresponding depth of the channel would be 16.5 m.

When the weather conditions are adequate (wind < 5m/s beam-on and low waves), it reduces the roll angle of the ship allows to sail at lower speeds (< 5 knots) resulting in the ability to keep a residual UKC of about 0.3m, in this case a ship with a rated draft of 15m may be sailed int the channel at -15.5m CD. See figure Figure 4-22 showing partial time series of UKC (port and starboard) while sailing at 4.5 to 4.8 knots.

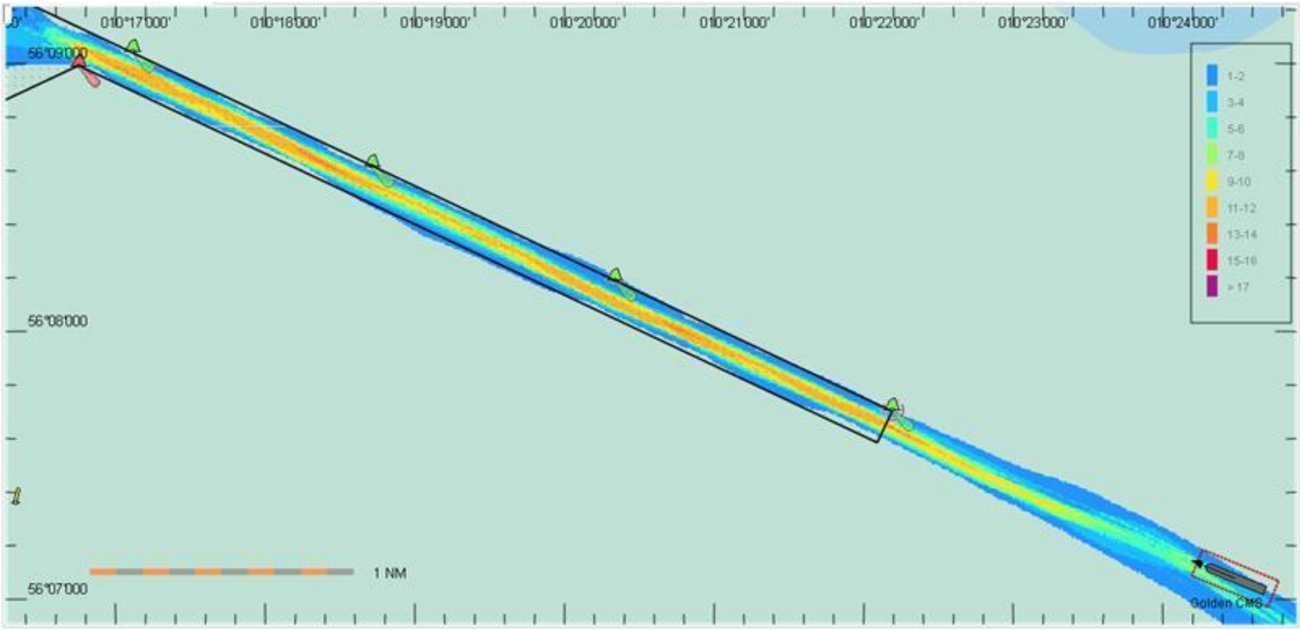

Figure 4-4 Density track plot of all workshop simulations.

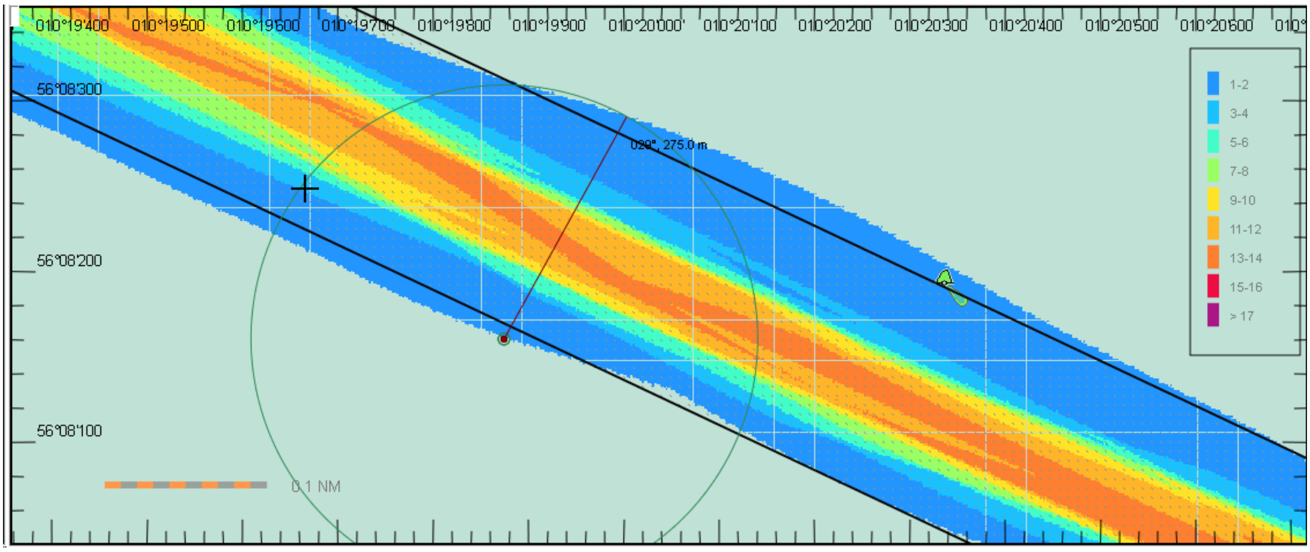

Figure 4-5 Density track plot of all workshop simulation - close up at max width of swept area.

- Simulations 01 to 04 are performed with the Golden CMS and the wind comes from either 25 or 205 °, e.g. beam on. It can be seen from Figure 4-6 to Figure 4-9 that keeping a straight heading in the channel is challenging. The vessel reaches the limits of the dredged area. Furthermore, the speed required to maintain the control of the vessel is quite high. In the workshop simulations, the vessel speed was too high for safe manoeuvres inside the turning area.

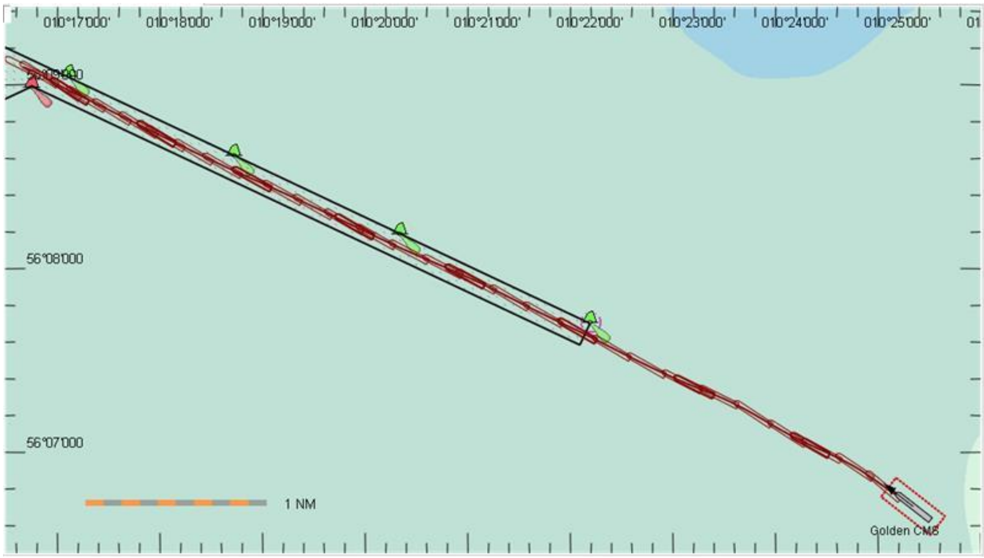

Figure 4-6 Simulation 01 - Golden CMS Approach - 15 m/s wind from 25°.

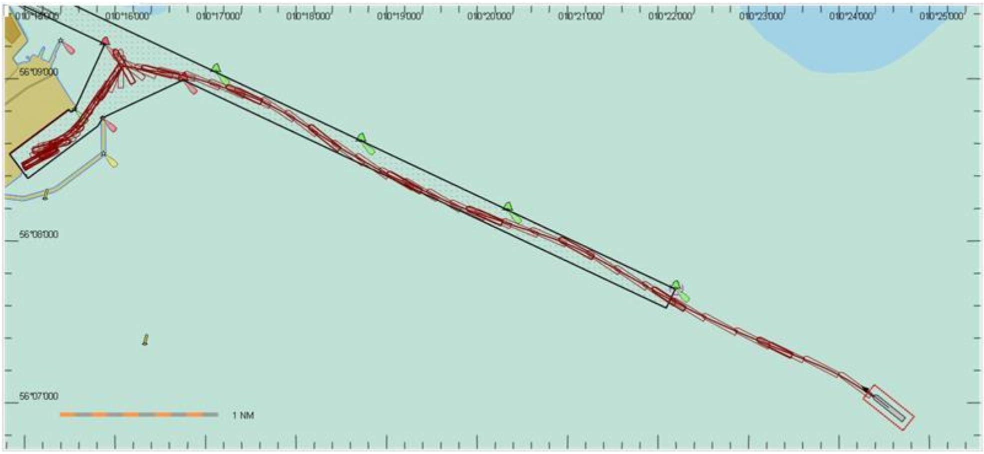

Figure 4-7 Workshop simulation 15 - Golden CMS Approach - 15 m/s wind from 25°.

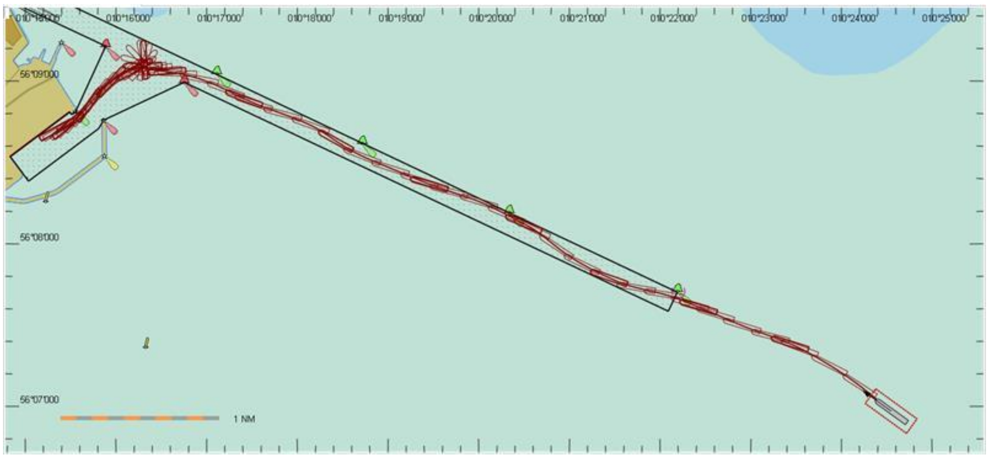

Figure 4-8 Workshop simulation 16 - Golden CMS Approach - 15 m/s wind from 205°.

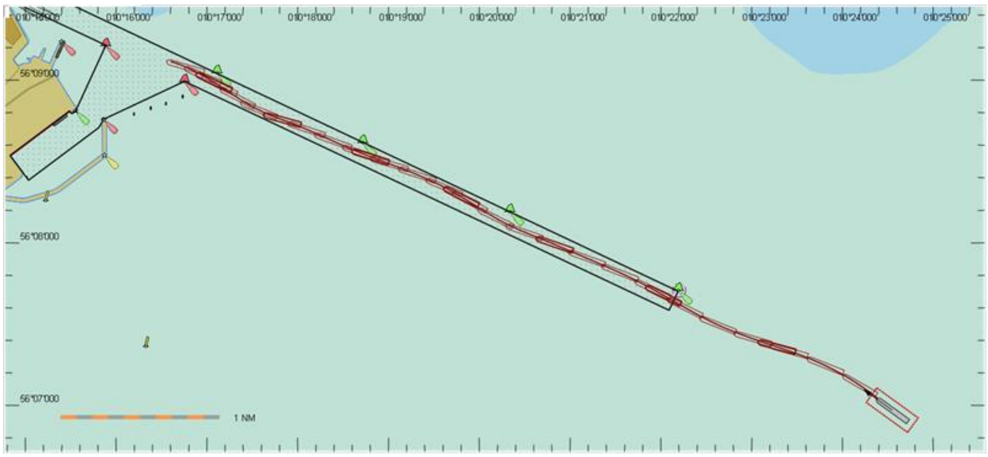

Figure 4-9 Workshop simulation 17 - Golden CMS Approach - 10 m/s wind from 205°.

- Simulations 02 to 05 simulate winds coming from other directions than beam on wind. The Golden CMS is more easily controlled in the channel although the general feeling is that the channel is still too narrow. It can be seen on Figure 4-11 and Figure 4-12 that the vessel gets very close to the edge of the channel, and that there is little to no margin for adjusting the heading.

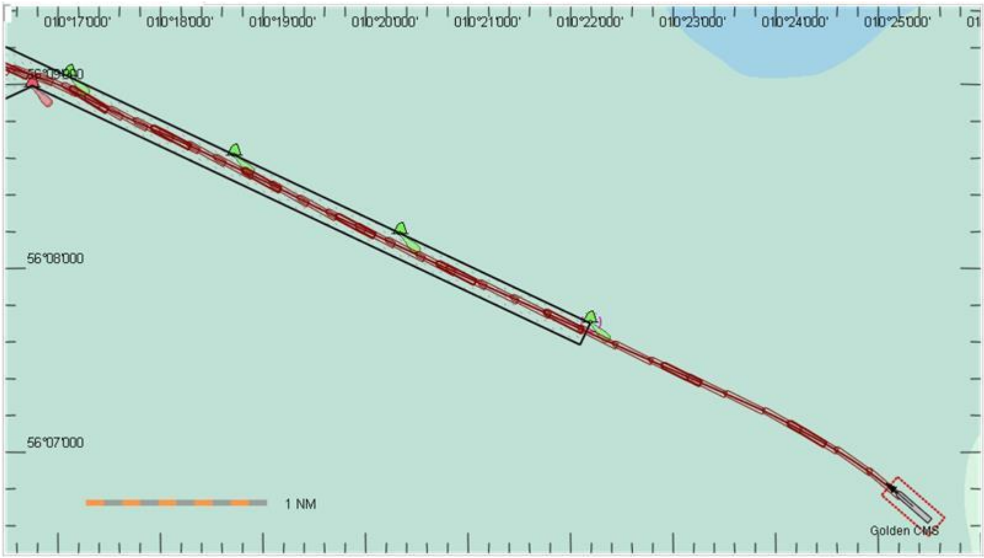

Figure 4-10 Simulation 02 - Golden CMS Approach - 15 m/s wind from 90°.

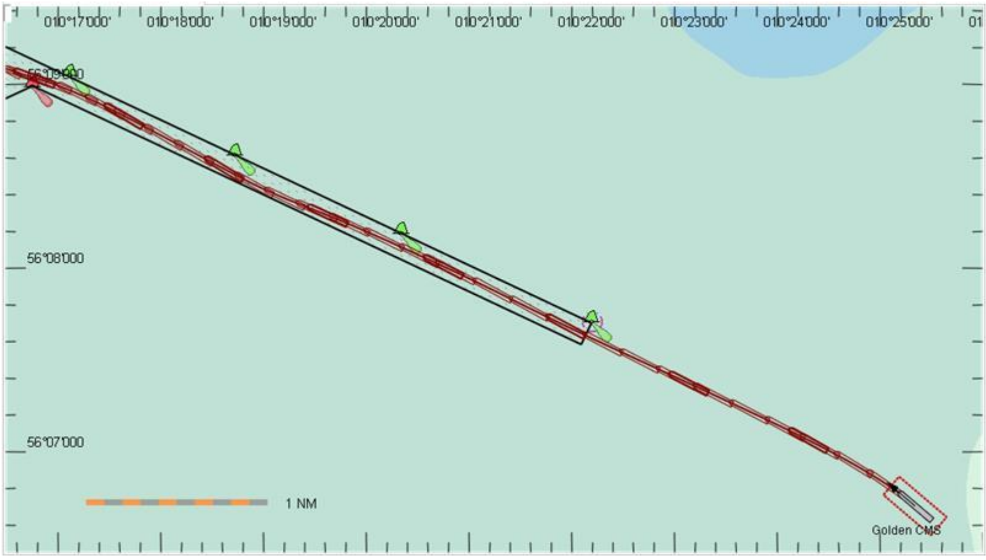

Figure 4-11 Simulation 03 - Golden CMS Approach - 15 m/s wind from 135°.

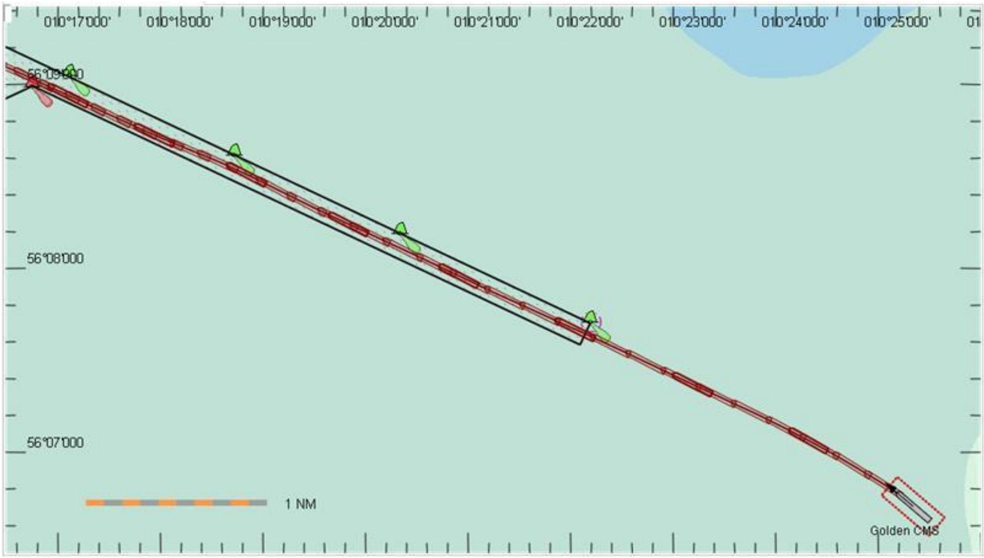

Figure 4-12 Simulation 04 - Golden CMS Approach - 15 m/s wind from 180°.

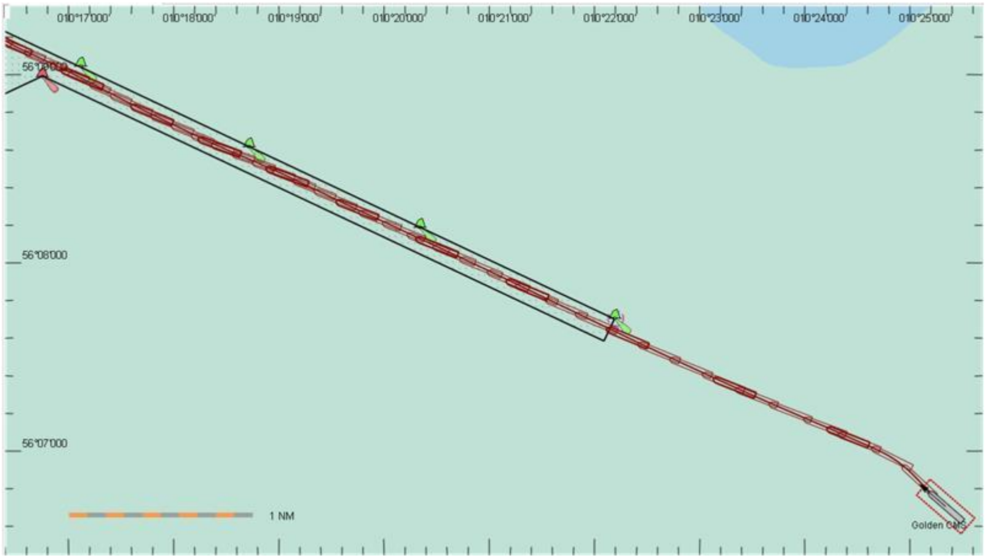

Figure 4-13 Simulation 05 - Golden CMS Approach - 15 m/s wind from 315°.

- Simulation 06 and 07 are performed with the Triple-E. The vessel is much more manoeuvrable however, it is still difficult to keep the heading of the vessel aligned, and the vessel is too close to the edge of the channel. The vessel speed could be lowered to around 5 knots at the turning basin entrance.

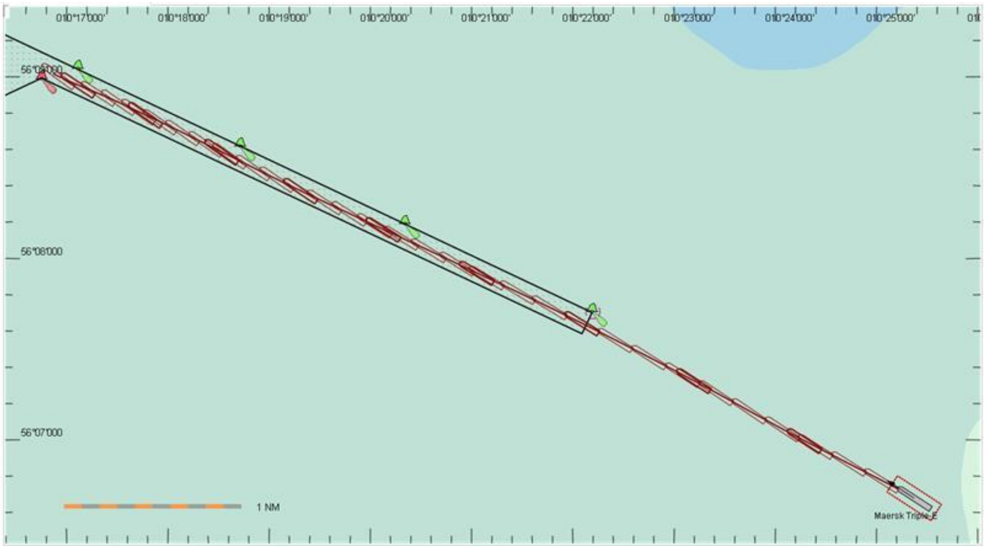

Figure 4-14 Simulation 06 – Triple-E Approach - 15 m/s wind from 25°.

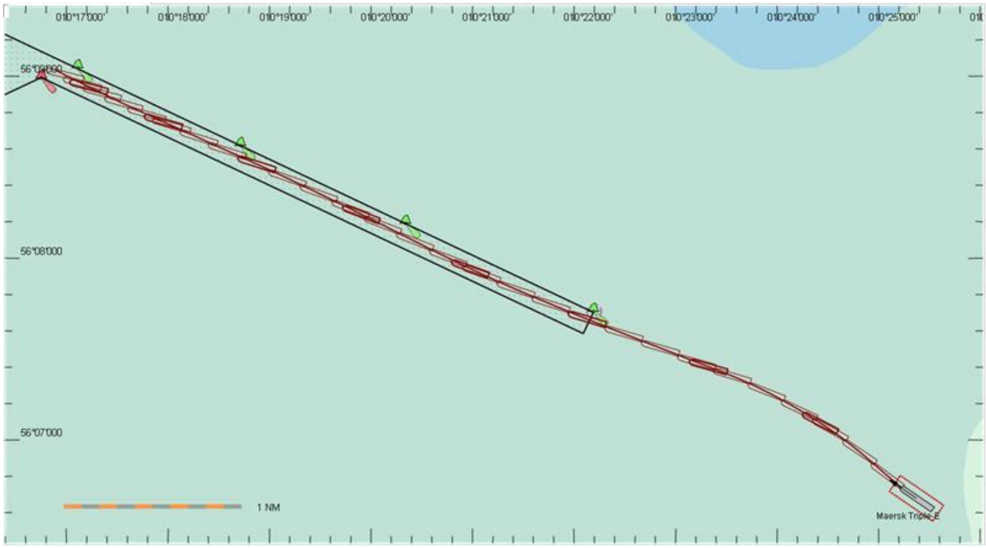

Figure 4-15 Simulation 07 – Triple-E Approach - 15 m/s wind from 205°.

- Simulation 08 shown in Figure 4-16 was performed with a wind speed of 10 m/s from 25°. The goal with this run was to test if the vessel speed could be lowered in the last nautical mile, under a not as extreme but more frequent wind speed. Although the vessel is close to reaching the edge of the channel in the last nautical mile, the vessel speed could be lowered to 4 knots instead of 6 knots in simulation 01 (see Figure 4-6). The vessel reached 6 knots after 1 NM, 4.8 knots at the start of the last NM, and 4 knots when entering the turning area.

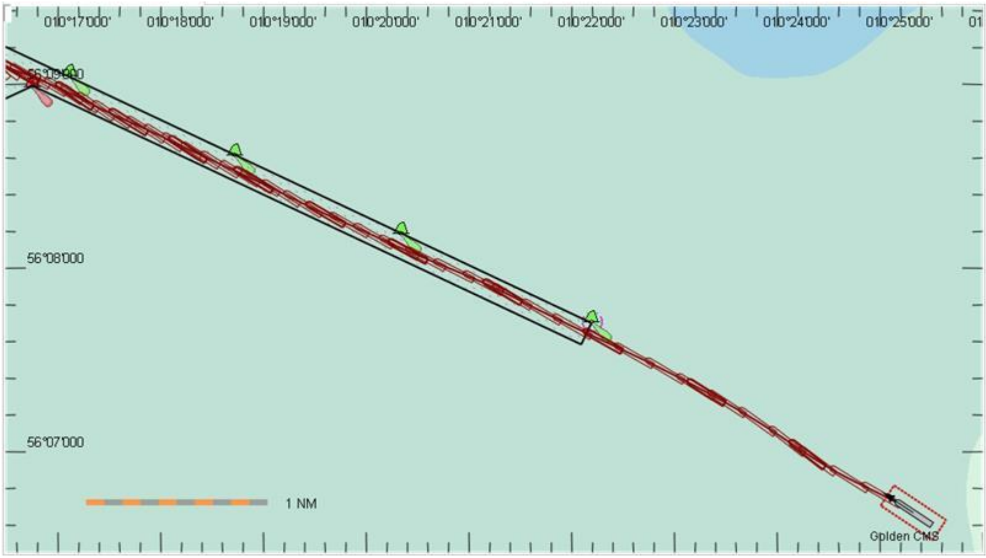

Figure 4-16 Simulation 08 – Golden CMS Approach - 10 m/s wind from 25°.

- Simulation 9 is a departure with the Golden CMS under cross wind of 15m/s. As can be seen on Figure 4-17, when departing, although the vessel is picking up speed, the vessel still drifts a lot due to the orientation when entering the channel which is not as aligned with the channel as it can be when approaching.

Figure 4-17 Simulation 09 – Golden CMS Departure - 15 m/s wind from 205°.

- Simulation 10 included a towing tug, in order to improve the manoeuvrability in the last NM, while decreasing the speed. However, despite the tug assistance, the speed of the vessel could not be lowered below 6 knots without losing the control of the heading.

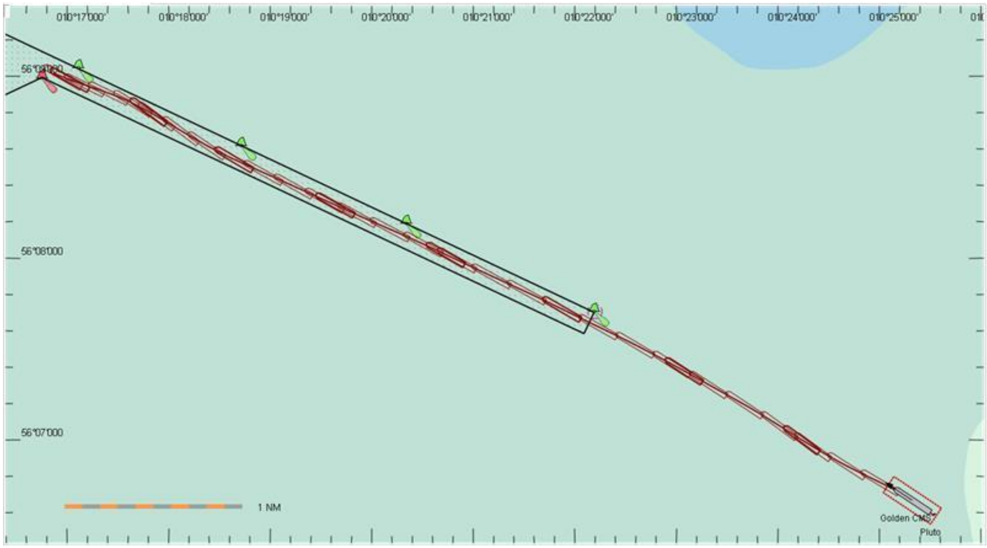

Figure 4-18 Simulation 10 – Golden CMS Approach - 15 m/s wind from 25° with towing tug.

- Simulations 11 and 12 were performed with a channel width of 320 m. The Golden CMS is within the boundaries of the channel with a small margin.

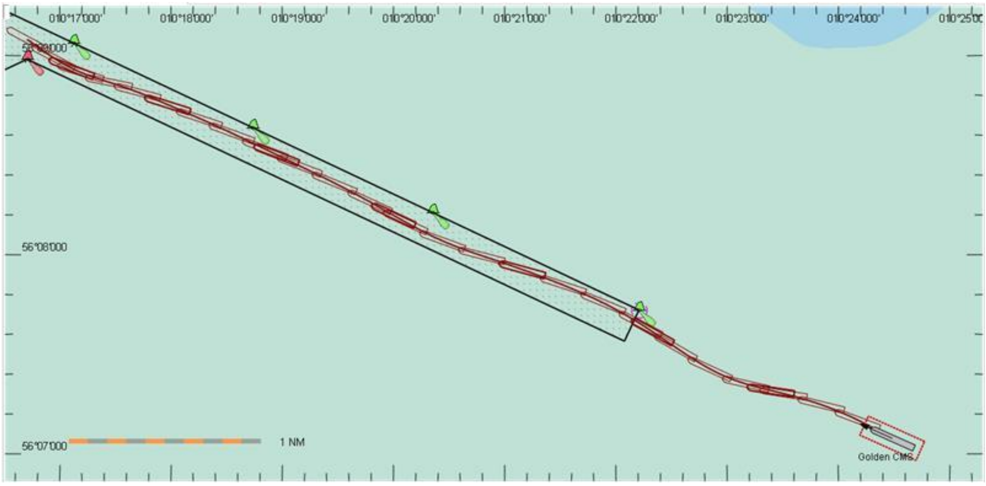

Figure 4-19 Simulation 11 – Golden CMS Approach - 15 m/s wind from 205° - widened channel to 320m.

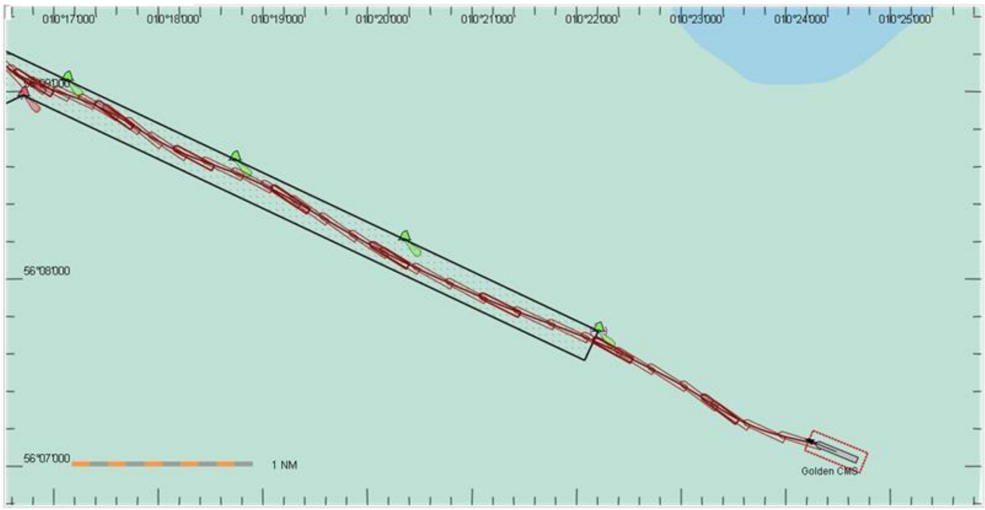

Figure 4-20 Simulation 12 – Golden CMS Approach - 15 m/s wind from 25° - widened channel to 320m.

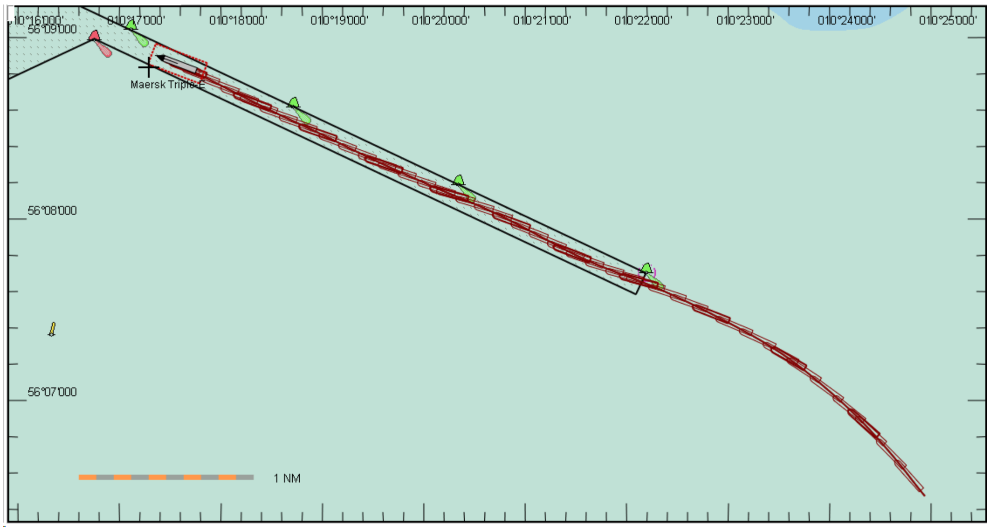

Figure 4-21 Simulation 13 – Golden CMS Approach – 5-10 m/s wind from 205°.

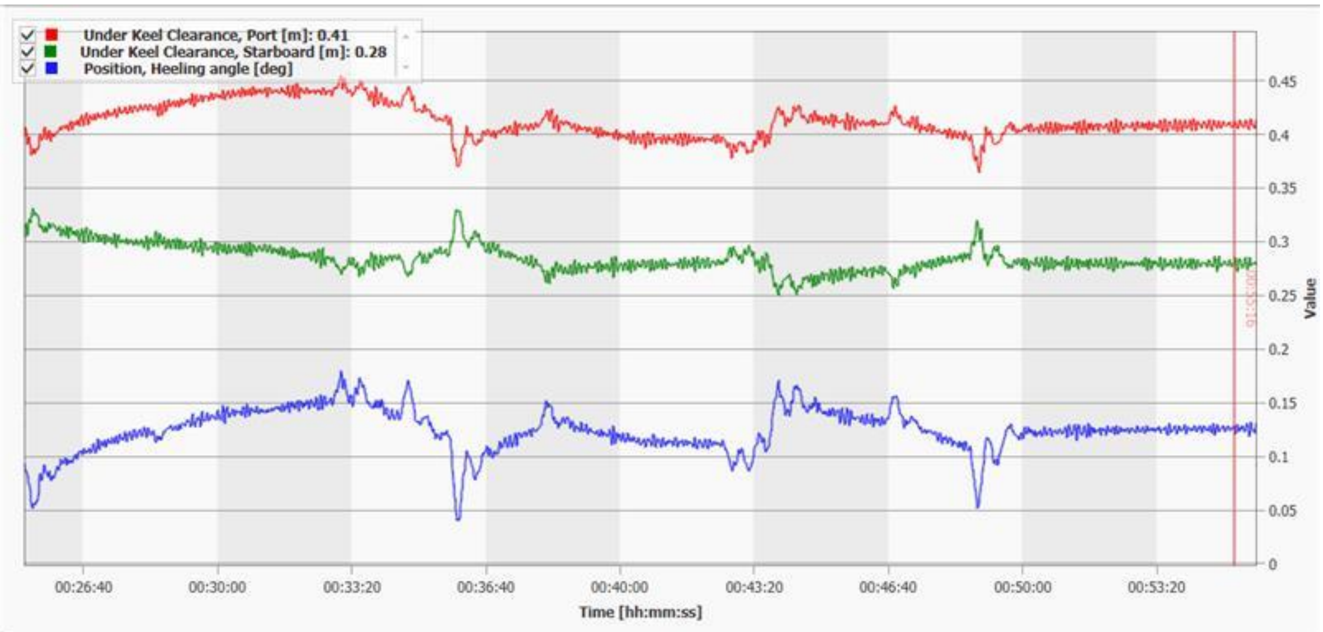

Figure 4-22 *Simulation 13 -– Triple-E Approach - 5 m/s wind from 205°, partial time series of UKC (port and starboard) and heeling angle while sailing at 4.5 to 4.8 knots in the channel.*

5 Conclusions

5.1.1 Channel Width

Based on the simulations carried out as part of this study under severe wind conditions (up to 15 m/s), it is assessed that the 240m wide channel is too narrow, not leaving enough room for any course correction for navigating the largest vessels Triple E and Golden CMS. The use of a 55t escort tug under these severe conditions is not sufficient to improve significantly the manoeuvrability of the Golden CMS when the vessel speed is lowered near the turning area entrance. The potential beneficial use of an escort tug for steering could be further investigated through additional simulations including more environmental conditions tested and/or higher tug capacity.

Based on the simulations carried out, it is recommended that the channel is widened to minimum 320m.

5.1.2 Channel Depth

The simulations show that with a combination of moderately high sailing speed (6-8 knots) required to maintain efficient steering and high wind speed (up to 15 m/s beam-on) with largest container vessels result in a reduced draft due to a combination of the squat effect with a heave movement of up to 0.8m, and heeling angles of up to +/- 1.2° resulting in a loss of UKC of approximately 1m. The maximum total reduction in UKC observed was 1.3 m.
A final residual UKC of 0.5m after all effect accounted for is recommended.

This leads to a recommendation, for operating with 15 m/s wind to either dredge the channel 2 m below the rated draft of the triple-E calling at the port or limiting the draft/loading condition of the vessel to 13.5m.
Alternatively, reduced operating conditions may be assumed to allow the sailing speed to a minimum (reduce squat effect) and reduce the roll, by allowing only operation in the channel at lower wind speed operational limits. See section 5.1.3 below.

5.1.3 Operational limits

<u>Channel depth and limit operational wind speed</u>

In calm conditions (wind < 5m/s or head-on) and at relatively low sailing speed (<5 knots) in the channel, a small residual UKC of 0.3-0.4m relative to rated (static) draft may be assumed leading to the allowable rated draft of 15m in the 15.5m deep channel. This was tested (simulation no. 13) but it should however be planned carefully and ensure that wind/wave condition do not worsen during the channel transit which may exceed 1 hour.

In severe conditions (beam-on wind 15 m/s) as tested, due to the required high sailing speed (typically >6 knots) and high roll angle and heave movement, a large residual UKC compared to rated (static) draft of 2m is recommended.

Speed at turning basin entrance

In calm conditions (wind < 5m/s or head-on) and low sailing speed (<5 knots) can be reached at the entrance of the turning basin area.

In sever conditions (beam-on wind 15 m/s) as tested, the sailing speed cannot be reduced to below 6 knots. It shall be further investigated whether this speed is adequate and allows safe manoeuvres inside the turning area, or if the operational conditions shall be restricted to lower wind speeds.

6 References

Ref [1] PIANC WG-121, 2014 report "Harbour Approach Channels, Design Guidelines"

Ref [2] COWI, March 2021, A104076-PD-073 "Navigation simulations, Port expansion"

Ref [3] COWI, January 2021, A104076-PD-013 "Numerisk modellering af strømforhold"

Ref [4] COWI, January 2021, A104076-PD-014 "Numerisk modellering af bølgeforhold"