NCOS ONLINE AND THE FUTURE OF PORT OPERATIONS: INSIGHTS FROM THE DIGITAL INTEGRATION AT THE PORT OF HAMBURG, GERMANY

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1. **ABSTRACT:** NCOS ONLINE, developed by DHI, is a modular, physics-based port management system designed to enhance maritime operations' safety and efficiency. This system aims to optimize vessel traffic, expand the capacity of existing port assets, minimize delays, and equip port and maritime safety authorities with a high-precision virtual environment for informed decision-making. Implemented in over 15 major ports globally, DHI collaborates closely with each port to tailor the system and its advanced numerical models, ensuring precise simulation of port operations. This paper presents NCOS ONLINE and a case study on its implementation at Germany's largest seaport, the Port of Hamburg, focusing on addressing both current and future challenges.

2. INTRODUCTION

Ports worldwide are constantly facing emerging challenges. On one hand, climate change is driving an increase in intensity and frequency of extreme weather events. On the other hand, the increasing size of vessels calling on ports – characterized by higher displacement, larger windage areas, and deeper drafts – is exerting greater stress on port infrastructure. Consequently, ports experience more frequent incidents of mooring failure, emphasizing an urgent need for infrastructure upgrades. In response, modern digital technologies offer an innovative alternative to traditional hard engineering solutions. These smart tools enable ports to better understand and manage risks associated with these new conditions. Consequently, ports can safely expand the capacity of their operations and assets, which were not initially designed to withstand these emerging loading conditions or face constraints in necessary upgrades.

NCOS ONLINE [1], developed by DHI, is a physics-based port management and decision-support system that enables ports to systematically screen for risks throughout each stage of a port call. Figure 1 illustrates the various modules available in the NCOS ONLINE system. The system predicts environmental conditions (wind, waves, and currents) in the port up to seven days in advance via the

MetOcean portal, providing clear warnings for severe weather that exceed predefined thresholds. Utilizing these predictions, other modules are employed to assess and manage risks. This includes safe vessel passage and maneuvering through dynamic simulations of the vessel's Under Keel Clearance (UKC). Additionally, the mooring analysis module, leveraging Artificial Intelligence (AI) and DHI's extensive FleetManager database of vessels, aids in determining the optimal mooring arrangement. It simulates mooring scenarios in the cloud using digitized 3D vessel hulls to accurately calculate forces on the mooring system and automatically generate mooring reports for the port and pilots. On the land side, the YardSafe module addresses safety risks for stacked containers against wind gusts.

Figure 1: Modules of DHI's NCOS ONLINE port operating system.

Once set up, NCOS ONLINE can assist ports with long-term planning. This system, a digital twin of the port, offers an accurate virtual representation of the port's assets. It enables engineering, asset management, and planning teams to effectively evaluate port development proposals. This includes studying the impacts of climate change on infrastructure, such as rising water levels and flooding, and devising appropriate mitigation strategies. Furthermore, it facilitates informed decision-making regarding the efficacy of investments in port development, for instance, in the strengthening or upgrading of quay walls or quayside mooring equipment. NCOS ONLINE also identifies bottlenecks in navigational channels, to optimize dredging campaigns for maintenance or upgrading to accommodate larger vessels.

After this introduction, this paper presents DHI's software for Dynamic Mooring Analysis, MIKE21 MA. The subsequent section provides examples demonstrating the application of DHI's numerical modeling software in digitally supporting modern port operations through the NCOS ONLINE system. This is followed by a detailed case study on the implementation of NCOS ONLINE at the Port of Hamburg.

3. DYNAMIC MOORING ANALYSIS (DMA)

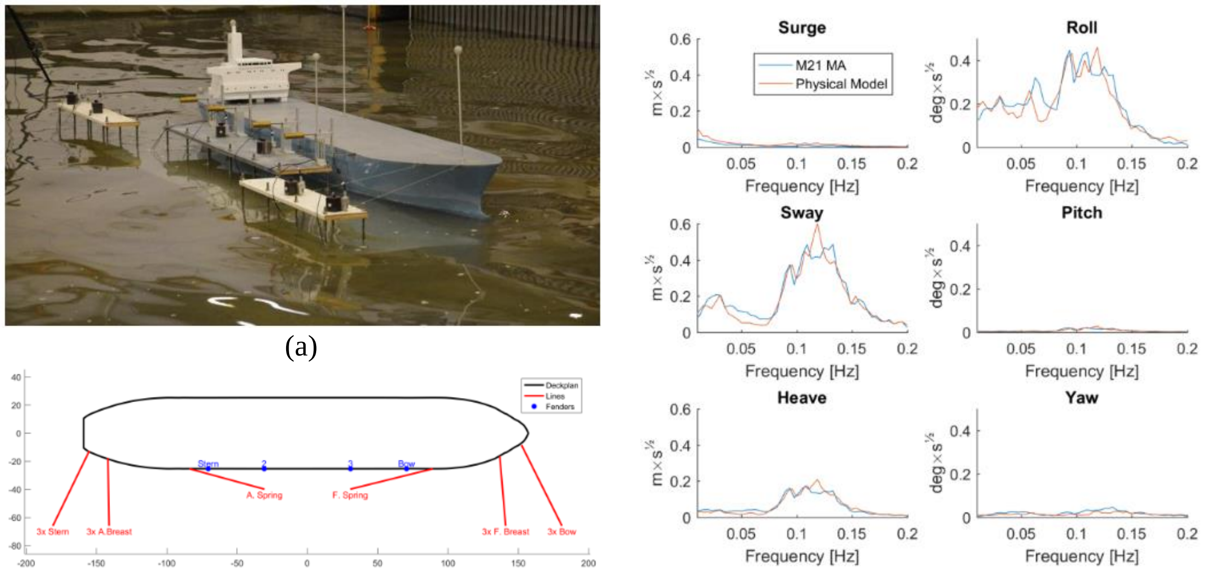
Mooring analysis is an essential component in ensuring maritime safety and in determining the load capacity of quay walls. This analysis is critical to prevent ships from breaking loose, to mitigate the risk of overloading the mooring system under extreme conditions, and to maintain acceptable vessel motions when moored under operational conditions. Static Mooring Analysis (SMA) is typically employed during the preliminary design stages of mooring systems and quay walls. SMA does not account for the variability of environmental conditions nor for their interactions with the moored vessel and the mooring system. Conversely, Dynamic Mooring Analysis (DMA) provides a more comprehensive and reliable tool. It incorporates realistic wind, wave, and current loads, and models the fluid-structure interaction between the vessel and its surrounding aquatic environment in a detailed manner.

The MIKE21 Mooring Analysis (MIKE21 MA) tool [2], part of the MIKE Software Suite from DHI, is a sophisticated tool designed for Dynamic Mooring Analysis (DMA) under realistic, site-specific environmental conditions. The DMA modeling process in MIKE21 MA begins with the application of DHI's Frequency Response Calculator (FRC). This engine calculates the vessel's three-dimensional hull interaction with surrounding water in the frequency domain, including stiffness, damping, and inertial coefficients. The output from the FRC is subsequently utilized in the MIKE21 MA engine for dynamic, time-domain analysis of the mooring system and the vessel. MIKE21 MA offers an intuitive and professional DMA modeling framework, featuring:

- Integration of realistic, site-specific environmental hydrodynamic loads, enabled by seamless coupling with MIKE hydrodynamic and wave models.
- Definition of realistic wind loads, encompassing wind gusts and realistic wind spectra.
- Accurate 3D representation of vessel hulls and quay walls, supported by an extensive library of vessel hulls, with provision for expansion.
- A comprehensive library of load-deflection curves for various mooring lines and fenders. These can be customized further with user-defined material profiles.
- Advanced quay-side mooring equipment such as AutoMoor and DynaMoor from Trelleborg.

MIKE21 MA demonstrates a high capability for accurately predicting the motions of moored vessels and the forces within mooring systems across a diverse range of complex scenarios. The model's reliability was substantiated through a series of physical model tests conducted in DHI's 3D Shallow Water Basin [3]. A notable example of these validation tests involved an open-water berth scenario for an LNG tanker, as depicted in Figure 2. In this validation case, an LNG tanker, with a Length Overall (LoA) of 318.2 meters, a beam of 50.6 meters, a draft of 12 meters, and a displacement of 133,824 tons, was moored at a water depth of 15 meters. The mooring setup included 14 synthetic rope lines with 11-meter tails and 4 SCN2000 E1.5 fenders. Figure 2a, and 2b exhibit the scaled physical model and the mooring arrangement, respectively. The tanker was subjected to wave conditions characterized by a significant height of 1 meter and a peak period of 8 seconds, with waves approaching in a beam-on direction. For the wave forcing input in MIKE21 MA, a MIKE21 Boussinesq Wave (BW) model was employed to numerically replicate these wave conditions.

A comparison of the tanker's motion spectra, derived from the physical model tests and the MIKE21 MA simulations, is presented in Figure 2c. The comparison illustrates that MIKE21 MA has effectively and accurately reproduced the results of the physical model, particularly in terms of the distribution of energy across various wave frequencies. The obtained results of vessel motions and mooring forces from the numerical model are within 11% of the corresponding physical measurements. Notably, the model successfully captures the low-frequency responses, especially in sway and roll motions. This response, evident in both the physical and numerical models, is attributed to the combined effects of long wave generation and its interaction with the natural resonance frequency of the mooring system.



(a) (b) (c)

Figure 2: Open-water mooring of an LNG-tanker: (a) physical model setup, (b) Mooring system definitions and (c) Comparison of motion spectra from the physical test and the MIKE21 MA numerical model.

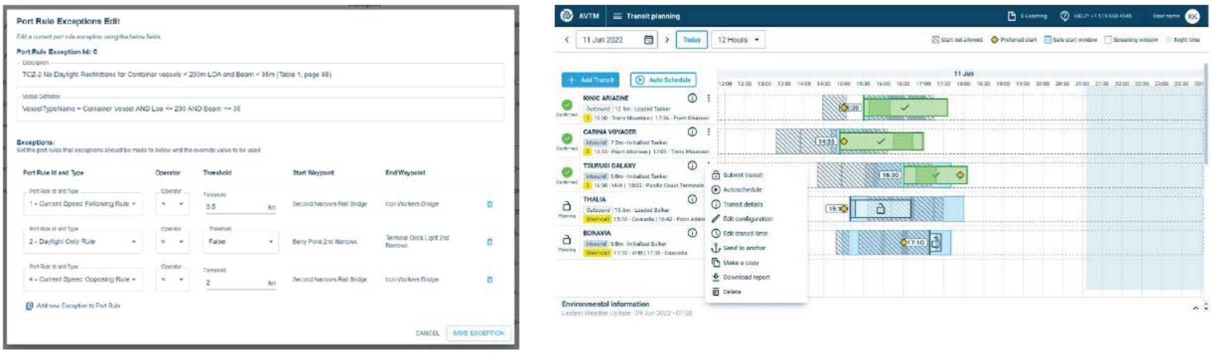
4. DIGITAL SUPPORT FOR MODERN PORTS

DHI offers the MIKE Software Suite (including MIKE21 MA) as a standalone product for numerical modelling. Moreover, DHI utilizes MIKE as the backend for numerical modelling required for its operational platforms like NCOS ONLINE. Example use cases of NCOS ONLINE for various optimization objectives of port operations are outlined in this section.

4.1 Port Traffic Scheduling

In 2022, the Port of Vancouver, Canada's largest port, adopted NCOS ONLINE as part of its Active Vessel Traffic Management Program. This initiative, developed by DHI, marks a significant evolution in port management, combining a physics-based vessel transit centralized scheduling system with a fully digitized set of Port Rules. This innovative approach allows for safer and more efficient vessel scheduling by integrating the dynamics of Under-Keel Clearance (UKC), areal clearance, and maneuvering safety, along with automated enforcement of auxiliary Port Rule safety standards and thresholds.

The implementation of this system not only improves transit scheduling efficiency but also streamlines overall port operations, overcoming previous challenges in this domain. The operational advantages are complemented by the system's contribution to the port's capacity to handle an increasing frequency of larger vessels, thus supporting trade expansion and business growth. Additionally, this solution brings environmental benefits. By optimizing capacity goals with reduced reliance on dredging, it lowers both operational costs and environmental impacts, aligning with the port's sustainable development objectives. Figure 3 shows the NCOS ONLINE user interface for the Port of Vancouver for editing the Port Rules and the result transit planning.



(a) (b)

Figure 3: User interface of NCOS ONLINE for the Port of Vancouver: (a) Editing the Port Rules, and (b) The result transit schedule.

4.2 Support Larger Vessels and Optimize Management of Port Dredging

NCOS ONLINE was installed in the Port of Brisbane, Australia's East Coast, in early 2017 following a major capacity study supporting 8500 TEU container vessels into the port. A significant full scale UKC monitoring campaign was carried out for more than 10 vessels and NCOS ONLINE predictions turned out to be highly accurate. As a result, NCOS ONLINE took over the operational support for deep drafted vessels in the port from August 2017.

DHI team worked closely with PBPL, Marine Safety Queensland and Brisbane Marine Pilots to address these risks as part of the implementation of NCOS ONLINE. Using this approach, DHI utilized several rounds of user experience workshops with PBPL staff and primary stakeholders to build trust in the system and integrate critical feedback to further improve the system.

Using NCOS ONLINE, the Port of Brisbane was able to increase the maximum allowable vessel draft by 0.5m and hence saving about 9 million cubic meters in dredging volumes. The port was able to increase its service to bulk carriers with draft > 14m by 33%. The Port of Brisbane is now, thanks to these efforts, Australia's fastest growing container port. It is anticipated that the port will save about $52.6 million in dredging costs over a period of 20 years. Figure 4 illustrates an example of the NCOS ONLINE web-based user interface for the port of Brisbane.

(a) (b)

Figure 4: NCOS ONLINE for the Port of Brisbane: (a) A map view of the water depth, and (b) Dashboard for required dredging volumes in port channels and basins to serve design vesels.

4.3 Safe Navigation and Efficient Typhon Warning

ICTSI, a prominent independent terminal operator with a presence in 19 countries, operates the advanced Manila International Container Terminal (MICT) in the Philippines. In 2019, MICT initiated a digital strategy with DHI, utilizing the NCOS ONLINE system to enhance maritime operational efficiency. A channel capacity study revealed additional capacity achievable with minimal dredging. The system now operates in forecast mode, providing daily guidance for the safe navigation of large container ships through the channel.

NCOS ONLINE's forecast mode proactively informs the Berth Planning, Harbour Master, and Pilot teams of navigation risks arising from adverse weather, sedimentation changes, or challenging conditions in the turning basin. It enables the port team to evaluate and choose safe pilotage and scheduling alternatives, allowing for the optimization of shipment drafts, and maximizing tonnage.

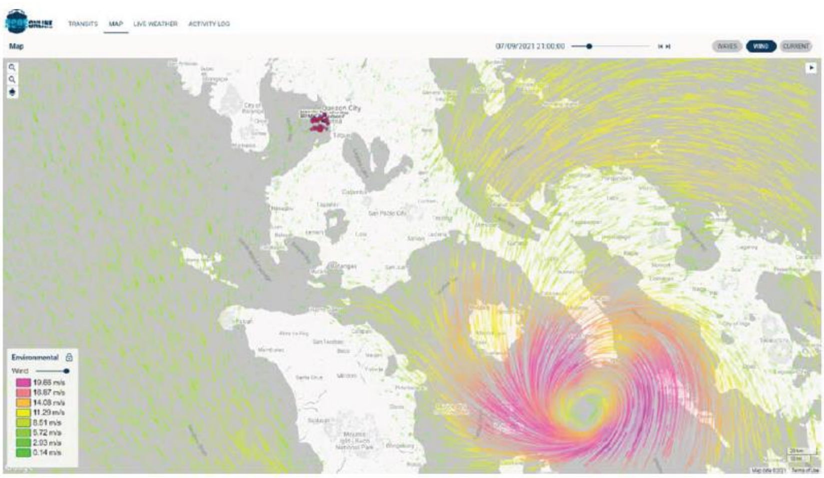


Figure 5: Wind speed map for a typhoon weather system as visualized in NCOS ONLINE for Manila International Container Terminal (MICT), the Philippines

Moreover, NCOS ONLINE equips MICT with automated wind and typhoon reports every six hours, integrating operational wind thresholds for berth planning into its alert systems. Beyond alerting to severe weather, it aids in the strategic planning for channel and berth reopening, crucial for balancing safety and operational resumption. For instance, during Typhoon KARDING, leveraging NCOS ONLINE reports enabled MICT to safely extend operations by 22 hours, illustrating the system's value in aligning safety with operational demands. Figure 5 illustrates wind speed map for a typhoon weather system as visualized in NCOS ONLINE for the MICT.

5. IMPLEMENTATION OF NCOS ONLINE AT THE PORT OF HAMBURG

The Port of Hamburg, Germany's largest seaport, stands at the forefront of international maritime commerce. Esteemed for its cutting-edge logistics and modern facilities, the port is integral to European and global shipping networks, demonstrating exceptional proficiency in managing a wide array of cargo with high efficiency. This section delves into the technical challenges encountered by the port. Following this, we explore the deployment of the mooring analysis module of NCOS ONLINE at the Port of Hamburg, referred to as the Mooring Program for the Port of Hamburg (VfHH). This discussion includes an evaluation of the program's advantages for the port's operations and explores potential avenues for future enhancements.

5.1 Port of Hamburg: Current and Future Challenges

Development of Shipping Vessels

The evolution of container vessel sizes and capacities over the years has been a notable aspect of maritime industry advancement. Initially, container ships were modest in size, designed to efficiently transport goods across oceans. However, as global trade expanded, so did the need for larger vessels. Container ships with a capacity of over 8,000 TEU were considered gigantic in year 2000. Since then, the scale of these ships has consistently expanded. Currently, Ultra Large Container Vessels (ULCVs) with lengths of 399m and over 20,000 TEUs call daily at the port of Hamburg [4]. This class of vessels has been operational since 2017.

Terminal operators are proactively preparing for the accommodation of the "Megamax-26" class, encompassing vessels with lengths up to 435m and widths reaching 66m. The advancements in maritime technology extend beyond the increasing dimensions of container ships. There has been a notable enhancement in ship-side mooring equipment, particularly in the efficiency of winches and mooring lines. Empirical data from the Port of Hamburg indicate a progressive increase in the mooring system capacities of larger vessels, correlating with their size and more recent construction dates. Notably, the brake holding capacity (BHC) of winches on 400m vessels, which averaged around 100t in 2015, has evolved to nearly 120t per rope [4].

State of Port Infrastructure

In the Port of Hamburg, specific quay wall cross-section designs have become standard over time. Initially constructed in the early 20th century, quay walls were composed of gravity walls supported by wooden piles. Subsequently, the design evolved to steel sheet-pile walls with a reinforced concrete superstructure. This modern design efficiently handles varying pressure from diverse terrain types and sustains heavy traffic loads. Notably, four significant quay wall structures have been adapted for ULCVs in the Port of Hamburg, undergoing strategic rehabilitation in various port sections. These structures are typically anchored with tiebacks and feature a superstructure with an enhanced deep foundation system [4].

Climate Change

The Port of Hamburg faces intensifying challenges due to the ongoing and future impacts of climate change. Expected changes include variations in the frequency, intensity, geographic spread, duration, and timing of extreme weather and climate events, largely attributed to global warming. These climate-related shifts are particularly critical for port and harbor operations.

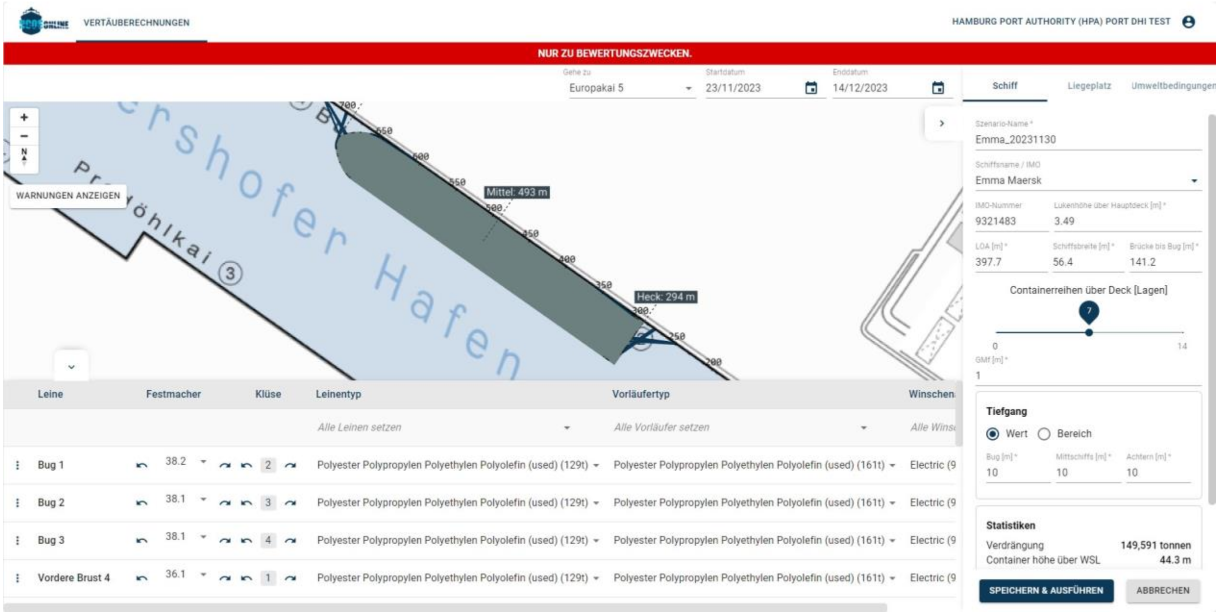
For instance, rising sea levels, driven by melting glaciers, could alter design water levels within the port. Increased sea surface temperatures and enhanced evaporation rates are likely to lead to more severe storms, elevated wind speeds, higher tides, and increased precipitation. These extreme weather conditions – encompassing excessive rainfall, wind, waves, heat, humidity, and cold – pose significant risks to human safety, economic stability, and healthy environment. Additionally, such conditions have the potential to inflict damage on maritime infrastructure, including breakwaters, quay walls, and drainage systems, and to disrupt daily port operations [5].

5.2 The Mooring Program for the Port of Hamburg (VfHH)

Beginning in 2017, the Hamburg Port Authority (HPA) transitioned to using fully dynamic mooring simulations as the sole foundation for its assessments and requirements, using DHI's MIKE 21 Mooring Analysis toolbox [2]. To validate the efficacy of this novel approach, a comprehensive comparison between the new dynamic method and the traditional calculation method was imperative. This also included correlating the outcomes of prior mooring studies with comparative calculations based on EAU 2012 standards [6], as presented in Bartholomä and Heitmann [4].

In 2018, the HPA teamed up with DHI to implement the mooring analysis module of NCOS ONLINE for the Port of Hamburg as a cloud-based DMA system specific for the port terminals, named the *Mooring Program for the Port of Hamburg (VfHH; Das Vertäuprogramm für den Hamburger Hafen)*. This program aligns with recommendations of EAU 2020 [7] and PIANC [8], which emphasize the necessity of mooring analyses for all berths servicing current ULCVs (LoA > 360m) and future Megamax vessels. This system is designed for detailed simulations and risk assessments of mooring scenarios in the port.

The development of the VfHH included efficient creation and linking between local databases from various HPA departments and external service providers (e.g., terminal operators and shipping lines), as well as the cloud-based DMA modelling system. Additionally, the front-end web-based interface of NCOS ONLINE was adapted for the VfHH in close collaboration with the HPA to ensure user-friendly, intuitive, and innovative experience for system users (see Heitmann et al. [9] for more details). Figure 6 shows a snapshot of the VfHH's user interface for the selection of the moored vessel and definition of its characteristics. Furthermore, the user interface allows for the selection of terminal and mooring arrangement and the definition of wind loads. The system applies artificial intelligence to recommend an optimal mooring arrangement, which can also be edited by users.



(a)

Figure 6: Dashboard of the mooring tool (VfHH): Choice of vessel and its characteristics

When the user of the VfHH system is finished with defining a mooring scenario using the user interface, the DMA can be executed in the cloud by clicking the "execute scenario" button and the system prepares a report on the DMA results in PDF format, for use by the Harbor Master, Captain, and pilots. The report contains a detailed illustration of the mooring arrangement for the fore and aft of the moored vessel, as exemplary given in Figure 7. Moreover, the report presents polar plots for the operating limit (maximum) wind speeds from all directions for predefined criteria for forces in mooring lines, winches, bollards, and fenders (Figure 8).

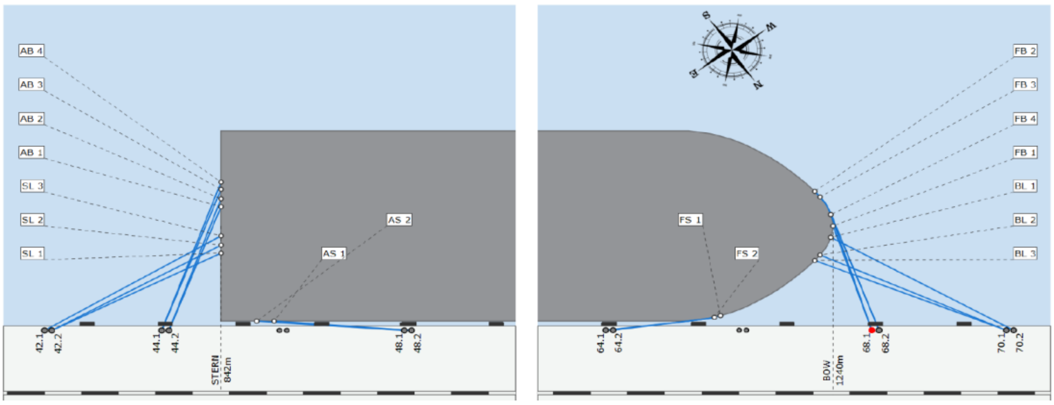
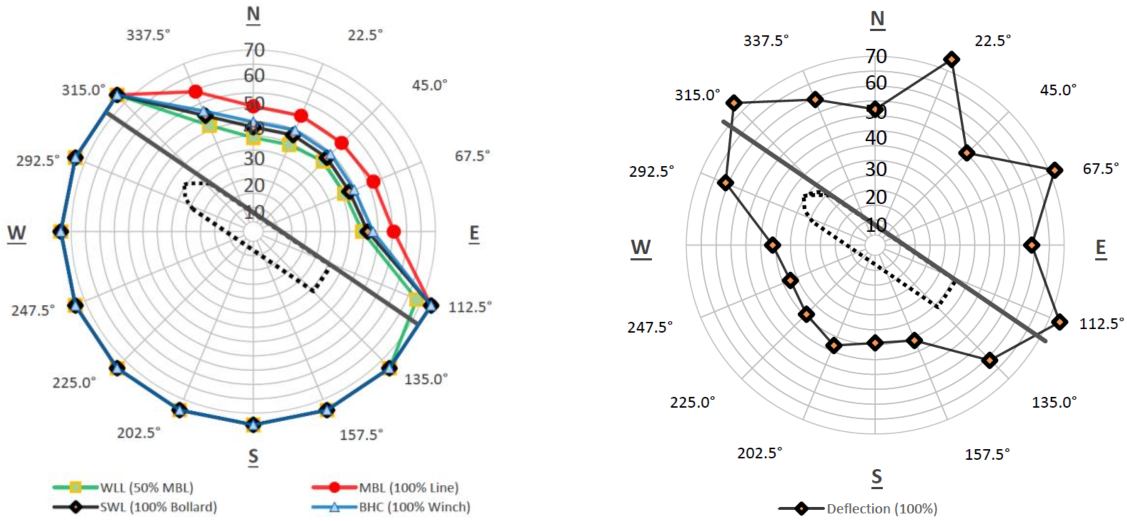


Figure 7: Exemplary mooring arrangement of Emma Maersk on the Burchardkai 4-5 terminal as produced in a report from the VfHH. The bollard with maximum forces is highlighted in red.



(a) (b)

Figure 8: Exemplary DMA output for operating limits in the VfHH report for the mooring of Emma Maersk on the Burchardkai 4-5 terminal showing polar plots of maximum permissible wind speeds for: (a) Working Load Limit (WLL = 50% MBL), Minimum Breaking Load (MBL) of mooring lines, Safe Working Load (SWL) of bollards, and Brake Holding Capacity (BHC) of winches, and (b) maximum fender deflection.

5.3 Exemplary Benefits and Planned Improvements

Since 2016, advancements in bollard testing, Dynamic Mooring Analysis (DMA) with MIKE21 MA, implementation of NCOS ONLINE, and database expansions have enabled the Harbour Master's Division to refine storm mooring protocols for Ultra Large Container Vessels (ULCVs). These developments allow for the specification of more effective mooring arrangements to enhance safety during storm conditions. Under these new protocols, ULCVs facing offshore winds of Bft8 or higher must employ a minimum of eight mooring lines at both forward and aft stations, keep anchors ready for immediate deployment, and have all side thrusters on standby.

A notable enhancement is the shift from automatic to manual winch holding mode in such conditions. While automatic mode allows the winch to absorb about 33% of its brake holding force, manual mode significantly increases this capacity to approximately 80% of the line's Minimum Breaking Load (MBL), due to tightened brake holding jaws and the robust winch substructure.

To prevent overloading of quayside mooring infrastructure, the mooring system for ULCVs was updated in 2021, reflecting the growing size of these vessels. Previously, a 3-3-2 line arrangement using two double bollards sufficed for mooring two ULCVs. The revised strategy now employs a 2-4-2 arrangement across three double bollards, ensuring optimal load distribution and transfer with no more than two lines per bollard head, thereby significantly enhancing the overall safety and efficiency of moorings in adverse weather conditions.

The Port of Hamburg is actively pursuing advancements in safety and convenience, focusing on (among others) two key areas: wind simulations and condition assessment. For wind simulations, the Hamburg Port Authority (HPA) is creating a detailed wind atlas to enhance local simulations, aiding in infrastructure planning and navigational safety. In condition assessment, two projects are underway: one for monitoring quay structures using sensors for real-time safety evaluations, and another for developing guidelines to assess the structural integrity of quay walls. These efforts are critical for ensuring the port's ongoing safety and operational efficiency.

6. CONCLUSIONS AND OUTLOOK

NCOS ONLINE serves as a 24/7 digital support system, enhancing decision-making in port operations through a web-based interface that combines user-friendliness with the robust, accurate numerical models developed by DHI. This paper provided various instances of NCOS ONLINE applications across major global ports, illustrating its versatility in achieving diverse port optimization goals. Additionally, the paper discussed the numerical modeling software MIKE21 MA, including a specific validation test. A detailed case study on the Port of Hamburg's implementation of NCOS ONLINE highlighted how Dynamic Mooring Analysis (DMA) with MIKE21 MA and the VfHH initiative are instrumental in bolstering terminal safety and equipping the port to handle larger vessels both currently and in the coming years.

The Hamburg Port Authority (HPA) aims to integrate Dynamic Mooring Analysis (DMA) into the AGF permits (permits for exceptionally large vessels) issued for ships over 360 meters in length. This integration will enable the HPA to provide vessel-specific DMAs based on actual equipment available, enhancing the safety and information clarity of the AGF permits. These tailored DMAs will inform the ship's master, harbour pilot, and the Vessel Traffic Service (VTS) center about safe mooring limits under various wind forces and offer guidance for mooring during storms.

Another key application is the risk assessment for Ultra Large Container Vessels (ULCVs) in high wind situations. This involves conducting short-term, individualized DMA calculations, considering each vessel's specific mooring arrangement, and loading condition, in coordination with terminal operators and specialists in evaluating the so-called BABLI files.

During operations, the HPA's VTS Centre will utilize these mooring analyses for anticipated strong wind scenarios to coordinate towing support measures effectively. Additionally, a future 'expert mode' in the mooring application will allow for the creation of freely parameterizable analyses from scratch, enabling the planning of new quay sections, bollards, and fenders. These continuous developments and measures are set to raise safety standards in the Port of Hamburg for a variety of vessels, showcasing the HPA's technological leadership and commitment to operational excellence and safety in port planning.

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