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Seeing a Sea of Ships - Exploring the Ship Design Space in the Digital Domain

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ABSTRACT

We tackle in this work aspects of the ship design space in the digital domain, with an overview of the current status and opportunities to shift from fixed arrangements towards open technologies, proposing a mix of open and proprietary databases. The discussion is focused on the visual domain and digital thread in ship design. Literature examples from the Brazilian case and the visualization of the ocean space are presented (Numerical Offshore Tank - TPN), followed by the Japanese services to design and optimize hull for specific missions (NMRI), and lastly the current open ship design library developed in Norway (Vessel.js, NTNU). We present the argument that seeing a sea of ships, that is, visualizing the behavior of many options is already a reality, accessible from a portable device, without the need a large cluster as in the past, exemplified by web-based cases. Our conclusion is that computer graphics approaches to Ship Design should be considered open and exchangeable. Naval architects should focus on what they do best: creating, analyzing, refining, storing and populating the database of the know-how from the institution (e.g. university, research institute or company).

KEY WORDS

Virtual Prototype; Web-based simulation; Hull simulation; Digitalization.

SEEING THE DESIGN OF A SHIP

The Visual Domain in Maritime – Towards a Coherent Digital Thread

Bertram (2023) uses an analogy with DNA and its four simple elements to express the ship design process when highlighted by computer. His CAVE acronym stands for Creation, Analyses, Visualization and Enlightenment, and the use of these terms are used to remind us that creation remains in the realm of the human (centric or driven), but that the computer (created by us) accelerates and improves the final result of the design, that is, the ship. We explore in the rest of this work this idea, that the *tool* computer, when properly used, is essential to CAVE, and exploring the ship design space is, in essence, exploring the opportunities that the computer gives us to CAVE when the abstract idea and physical existence of a ship are parsed to the digital domain.

A great practical example of this whole loop is presented by Ulstein Group in a 3m11s video about the vessel SX121 Island Performer, a subsea (RLWI/IMR) vessel delivered in 2015 (https://www.youtube.com/watch?v=I9YGFm2AzTo). This short piece of visual information can cover in its small duration the power of the CAVE analogy. The hundreds of thousands of hours that humans used to design, analyze, and construct that vessel are summarized in this brilliant piece of advertise. Figure 1 presents a collage of this vide, highlighting the human activities in the design, engineering,

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construction and sea trial of the ship. Such video enlightens us on the nature of the ship upstream value chain (Brett and Ulstein, 2012).

Figure 1: Ship design as a human-centric and human driven activity – collage from Ulstein Island Performer video

The one of a kind nature of the maritime domain, thus, bring two additional assumptions when watching the video: i) innumerous designs and analyses were explored and discarded for Island Performer exists as it is; and ii) the ship existed first in the digital world, decomposed in thousands of files, bits and bytes of text, drawings, functions and tables.

The older generation of ship designers is still proud to remember how the maritime industry was pioneer in adopting CAD (or computer aided ship design, CASD) in the 70s and 80s (Gaspar, 2019). CASD thus appeared as the future step to document, copy, reuse and detail the design, a digital alternative for the blueprint firstly, and a drastic way to change the engineering and yard offices lately. The equivalent process of doing each of the parts, assemblies, blocks and other drawings were firstly mimicked in the new CAD systems, one digital file for each required drawing, and multiple copies of parts due to individual storage of each drawing in a unique.

The old school may argue (with reason) that the high dependency on CASD for all the calculations may remove the student from the tactile knowledge of a ship, since the abstraction required for a 3D drawing of a hull is different than decomposing it on the 2D surfaces that are cut to physically assembly the hull from frames and plates. But undoubtedly the screens, computers, keyboards and mouse are responsible for:

- 2D/3D design processes quicker; designers can create new concepts in short time.
- Reliable documentation of the whole ship design process, from early design to construction and maintenance.
- Exploration of a large number of options during early stages, smartly copying, pasting and adapting past design into new ones
- Exchange and exporting drawings and descriptions between formats, as well as filtering level of detailing.
- Connect design (creation) with performance (analysis), and visually understanding cause and consequence of changes in internal (e.g. geometry) and external (e.g. environment) parameters, enlightening the decision-making process.

Not all promises from the last decades, however, are fully concretized. Take the hype idea of *integrated model,* and *3D as basis* for all models. Ideally, the 3D concept developed during the tender package could be the start point to feed the next phases, like 2D general arrangements, and detailed engineering .Very little, however, of the original 3D file is really used in the next phases of engineering analysis and detailing, with each of the design groups, such as hydrodynamic, structures and cargo systems to name few, redoing and redrawing the hull and GA over and over again in each of their specific software – a task *fancily* called *manual flow* in the flowcharts.

Additionally, traceability is not a strong point when multiple software is used, and usually a major change in the design implies a large time of re-work and precious engineering time in correcting each of the non-connected engineering models.

The same lack of integration is observed in the subsequent phases, with multiple proprietary databases, sometimes inside the same company. Observing the development of the systems from the past, five reasons can be commented, namely: proprietary formats, lack of integration, licensing and profitability of the tool, high cost to training and a deviation from the principle of parsimony (Gaspar, 2018).

The commercial aspect of modern CASD software also keeps an unnecessary level of paperwork and licensing *contortionism* with outdated technology from the 90s, a political approach that yet requires a dedicated server which checks a license for each of the computers that are using the software. While this seemed a good solution to avoid piracy and gain control from the side of the creators on the past, this looks extremely counter-productive in face of the modern online tools, apps and pay per use technologies that we have available in non CASD computer software. On the top of it, count the hours that IT technicians use to install the software in each machine, a long process configuring client and server due to antiquate anti-piracy policies. We dare to speculate that the ship design developers would benefit of providing as open as possible solutions to install and use their software in order to gain terrain in the market share (Fonseca *et al.*, 2023).

We present in the rest of this paper three developments towards a coherent digital thread, shifting from fixed and closed platforms towards open technologies and the choice of open and/or proprietary databases. The next section presents an example from University of São Paulo (USP, Brazil) developed more than two decades ago, which still holds valid and feels *modern.* This is followed by the developments at the National Maritime Research Institute (NMRI – Japan), in hydrodynamic simulation, combining processing demanding CFD of a hull with efficient machine learning (ML) techniques to quickly obtain the hydrodynamic response of a set of hulls, developed by the Japanese in the last decade. Lastly, it gives an update on the open ship design library developed at the Norwegian University of Science and Technology (NTNU-Norway), with a web-based proof of concept able to generate and simulate 10 000 designs in time-domain analyses in real time, using validated surrogate models.

SPACE AND BEHAVIOR - VIRTUAL TOWING TANK

The numerical offshore model basin, TPN-USP (Nishimoto et al., 2003, Gaspar *et al.,* 2009), is a 20+ year old ongoing initiative between a collaboration of Brazilian universities, research institute, and the oil company PETROBRAS. Its utilization was initially focused on analyses and verification of the design of complex offshore systems that normally requires even more complex tests in physical model basins. Today, it also included a physical basin calibrator and simulators for crew training and operational assessment.

TPN was created as a time domain simulator that encompasses several methods and algorithms in a single tool. The main characteristic of the simulator was the possibility of carrying out a coupled analysis of the lines with the bodies. The lines are modeled with Finite Element Method that demanded great computational power two decades ago. Its procedure followed the trend of the time, with pre and pos processing or the analyses in separate instants (Figure 2).

Parallelization of the code was the key innovation at the time (Luz *et al.,* 2009). The distribution of process was linear among processors. First the cases processes were processed and in sequence the bodies and lines processes. The communication among the processes occurred as: 1) Before initializing the simulation, main process import the data file and distributes it among other processes. 2) In each time step of simulation, the body process receives the force that each line process computes, sums the other loads and computes the acceleration, velocity and position of body, sending this data to the case process that it belongs. The case process replenishes its body's processes whit this data and the line forces that attach the bodies (linking lines) for the calculus of next time step. Simultaneously, it gives directly to the lines processes the position of corresponding body, since the calculation of force acting in the line depends only upon its upper ending coordinates. A common bottleneck was the the number of processes being superior than available CPUs, which required some sort of multiprocessing parallel Interface to distribute automatically the extra load homogeneously among CPUs.

TPN had its architecture based mostly in open software (e.g. Linux, OpenFOAM), and used proprietary commercial program when necessary (e.g. WAMIT). The same idea was applied to its database of solutions. Some of them were based on open data, from non-proprietary calibration and simulation, which could be shared; others, were based on analyses developed for its main partner (PETROBRAS), and were proprietary, not to be shared outside the laboratory, but nevertheless contributing to increase the expertise of the team.

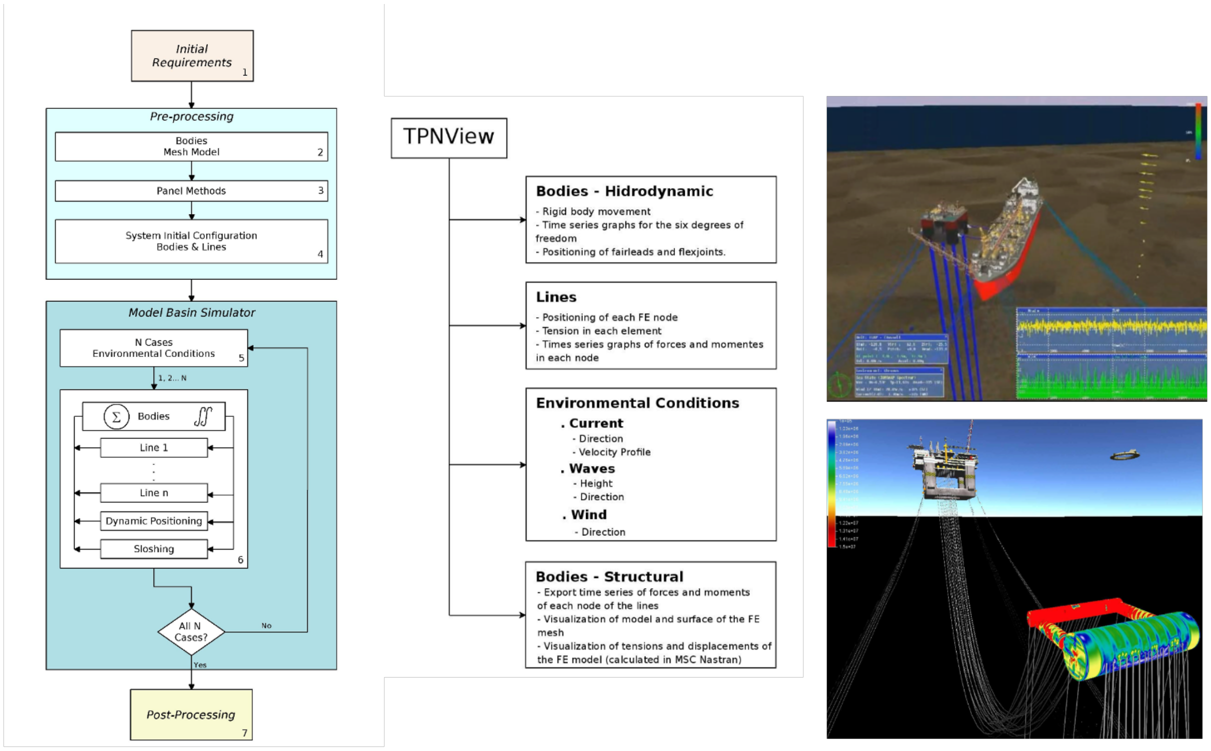

Figure 2: A time domain simulator encompasses several method and algorithms in a single tools in TPN

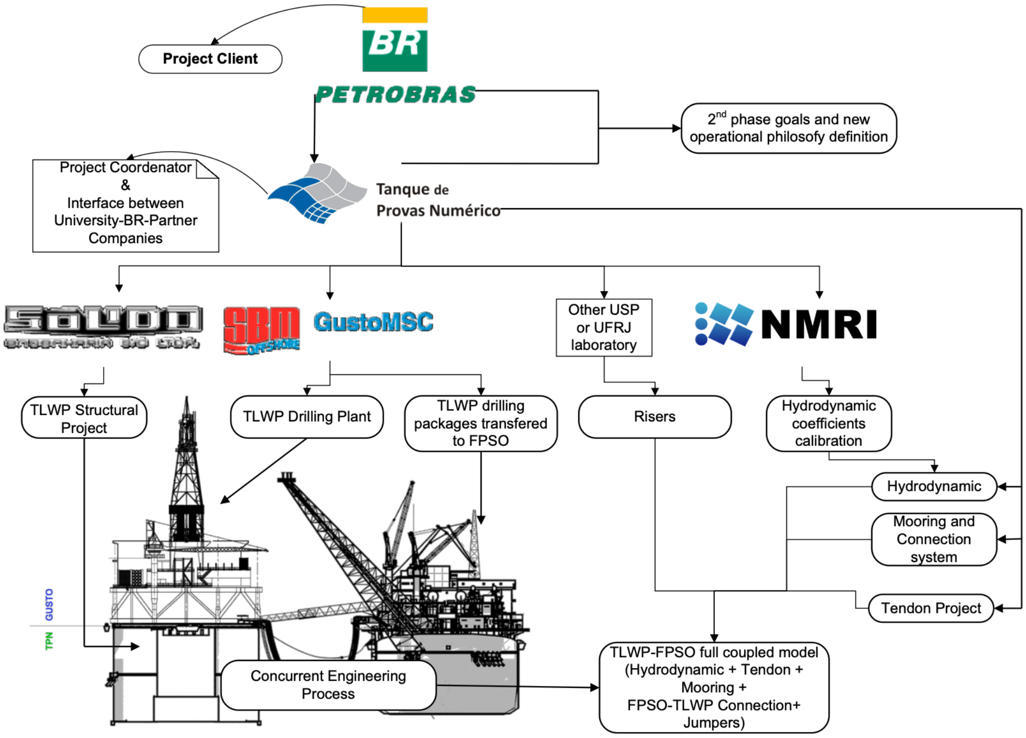

Figure 3: System Dimensioning Integration of TPN Simulator (Rampazzo et al., 2010)

The initiative was very successful, both national, boosting the offshore innovation in Brazil, and international, placing TPN as a key provider of simulation and visualization solutions for evaluation the design of vessels and multi-bodies operations. Other research institutes, such as Marin (NL), Marintek (NO) and NMRI (JP) developed at the same time complementary initiatives, and in few years the new ideas from early 2000s, like realistic graphics and hybrid methods combining physics based with surrogate models were implemented in most maritime research institutes. Figure 3 exemplify this synergy, in a collaboration from 2010 between TPN, Petrobras, engineering companies and the NMRI, for the development of a conceptual design of a FPSO + TLWP coupled system.

HULL AND SEA - SIMULATION AND OPTIMIZATION

In certain Ship Design *niches,* especially the ones connected to the high-sea transport of heavy cargo, the field of simulation-based design has become a prominent approach for shaping hull forms since the early 2000s, with the promise that CFD could *scrap* few percentages in efficiency, which could materialize in huge fuel savings over long trip. Such specialized analyses become thus a service offered by few, firstly in research institutes, and later by (some) software companies (Bertram, 2014).

Even with many advancements, ensuring design optimality under diverse operational scenarios yet remains a challenge. Researchers have explored stochastic shape optimization and visualizing design space to enhance robustness. Stochastic optimization studies have focused on minimizing total resistance and improving operability across different ship speeds. Visualizing the design space aids decision-making by elucidating effective parameter limits (Ichinose, 2022). Recent research has delved into using machine learning (ML) methods to analyze propulsive performance. Artificial neural network (ANN) models have been developed to estimate total resistance, trim conditions, and added resistance. Despite their efficacy, these automated design methods often lack transparency, posing challenges for designers. Efforts to develop explainable artificial intelligence or organizing hull-form databases for deeper understanding are underway.

Integrating visualization methods into machine learning-based hull design methodologies can be useful for effective decision-making and consensus-building among stakeholders involved in ship design. Visualizing and analyzing hull form performance requires a structured approach to organize and parameterize their database. Unlike propellers, which can be defined through factors like pitch and skew, hull forms present a challenge due to their complex 3D shapes. While various parameterization methods have been explored, no single standard has been universally adopted.

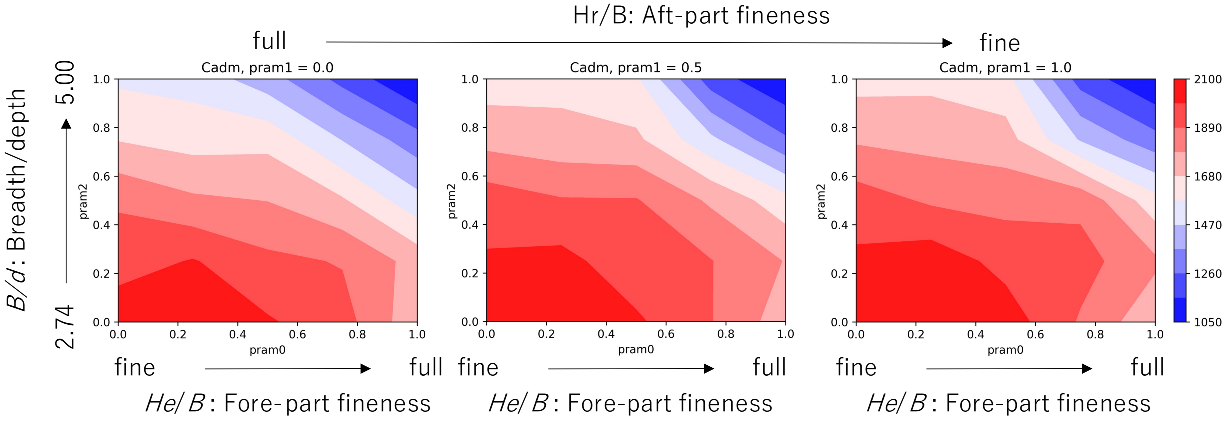

Figure 4: Distribution of admiralty coefficient (C_{ADM}) isolating the fineness factor in the aft part (Hr/B) (Ichinose, 2022).

In recent years, computer graphics techniques have been integrated into hull form deformation processes (Ichinose, 2022) Concurrently, shape morphing, originally developed for satellite image transformation, has found utility in ship design, preserving detailed shape information and facilitating better understanding of results. However, the practical application of shape morphing is hindered by its limited degrees of deformation, typically restricted to mixing two or three hull forms due to visualization challenges. Addressing this limitation, Ichinose has extended the morphing method into a multidimensional context and proposed a Hull-form coordinate system that defines each ship type. Figure 4 is an example of visualizing the design space of ship forms using the Hull-form coordinate system. Here, the admiralty coefficient (C_{ADM}) in the figure is a performance coefficient representing transport efficiency, which is widely prevalent in the naval architecture field. Observing this performance distribution, it is evident that there are areas where performance remains stable despite slight changes in shape parameters and areas where performance is unstable in response to shape deformation.

In designing within the Digital Domain, particular attention must be paid to simulation errors and variance. That is, the optimal point obtained in numerous optimization simulations may not necessarily be the shape to be adopted in an actual construction project. We require a iteration of CAVE, from creation to enlightenment. Therefore, instead of a single optimal shape in the domain, it is necessary to adopt a group of candidate shapes, including the second and third viable options, in the design. Visualizing thus a design space that indicates a stable performance domain is a crucial technological element in engineering projects.

Furthermore, in engineering projects, efforts to improve physical interpretability through visualization are also essential for consensus formation and decision-making among designers and stakeholders in the Digital Domain. Figure 5 illustrates another example of visualizing a large set of simulations at once, presenting how the distribution of waves changes with the deformation of the hull form. We observe that, when the forepart becomes a full body, the generated wave height increases sharply (Figure 5, red perimeter). Thus, by optimizing the design space with physical interpretability, it is possible to achieve designs with high robustness.

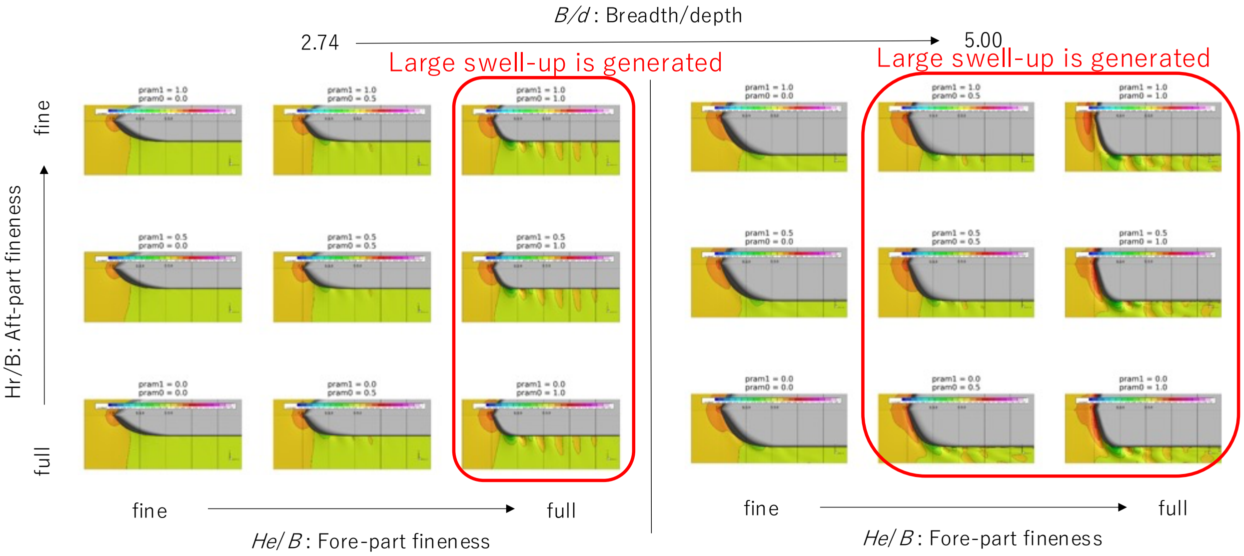

Figure 5: Listed figures of wave patterns in fore parts isolated by breadth-to-depth ratio (B/d) (Ichinose, 2022).

A bottleneck in adopting design methodologies that explore and visualize the entire design space is the time-consuming nature of simulations. Especially since the Navier-Stokes equations, which are the governing equations of fluid dynamics, are nonlinear and require numerical discretization to be solved, numerical analysis demands extensive time for grid generation. As an alternative to such numerical calculations, design charts have traditionally been used. However, there is a recent trend towards replacing design charts with machine learning methods. For this, a database with a large number of validated hydrodynamic simulations is needed. This database does not need necessarily to be open. The methods, however, need (and are), given that merging ML and surrogate models is a task beyond the ship design domain. In response to this, research is being conducted in ship design to visualize pressure distributions on hull surfaces and flow fields using machine learning surrogate models, traditionally performed with CFD simulations (Ichinose & Gaspar, 2023). Utilizing such surrogate models for CFD, it is possible to visualize thousands of cases in a matter of seconds as shown in Figure 6. This represents an evolution in the application of machine learning in ship design that goes beyond merely replacing traditional design charts and highlights the anticipated growth in design development through using the existing validated databases.

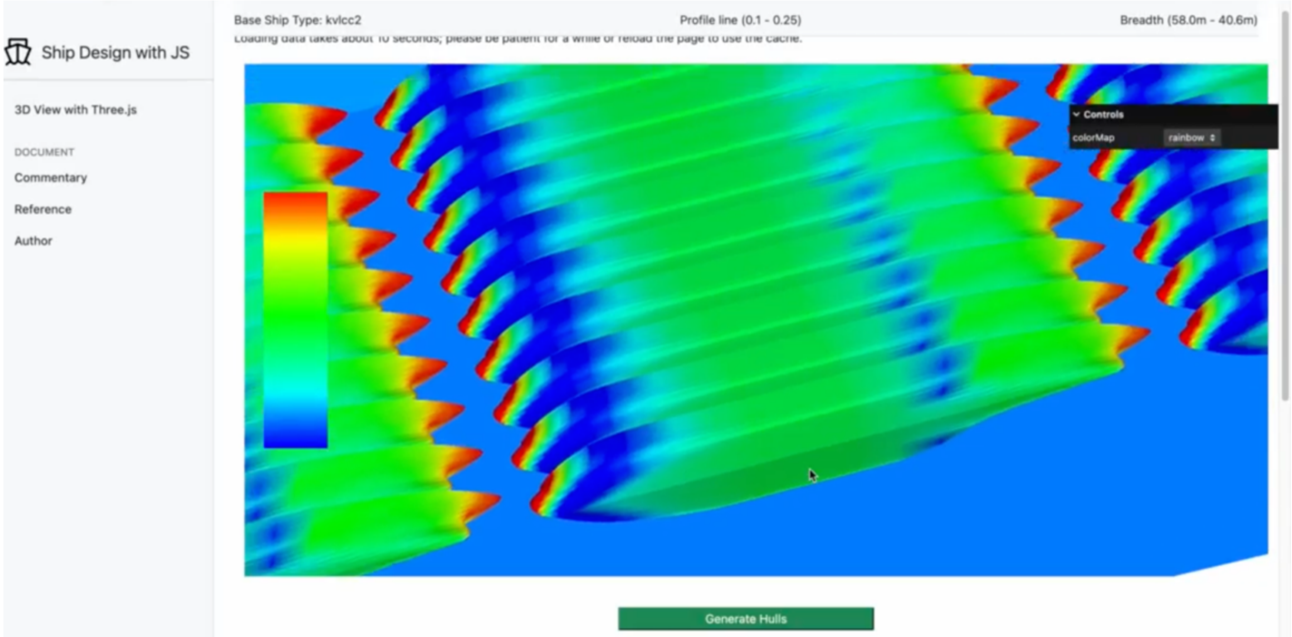

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Figure 6: Example of Visualizing Pressure Distribution Across Thousands of Cases in Seconds Using a Machine Learning Surrogate Model for CFD, extended from Ichinose and Gaspar (2023)

A (DIGITAL) SEA OF SHIPS - THE ARGUMENT FOR WEB-BASED TECHNOLOGIES

Open digital methods allow us today to simulate and visualize in real-time 100s, 1 000s or even 10 000s of hull designs using a laptop. Actually, as the technology is web-based, probably with a modern mobile or tablet, using as example the open Vessel.js (https://vesseljs.org/) library. As introduced in earlier IMDCs (Gaspar 2018; 2022), this open ship design development is aimed at the design and simulation of maritime entities, combining ship design thinking within a JavaScript-based object-oriented approach. As the library is web-based, all examples and codes discussed there are available to be accessed, modified, and re-used by a community. The data and methods there are therefore transparent and can be tested and scrutinized.

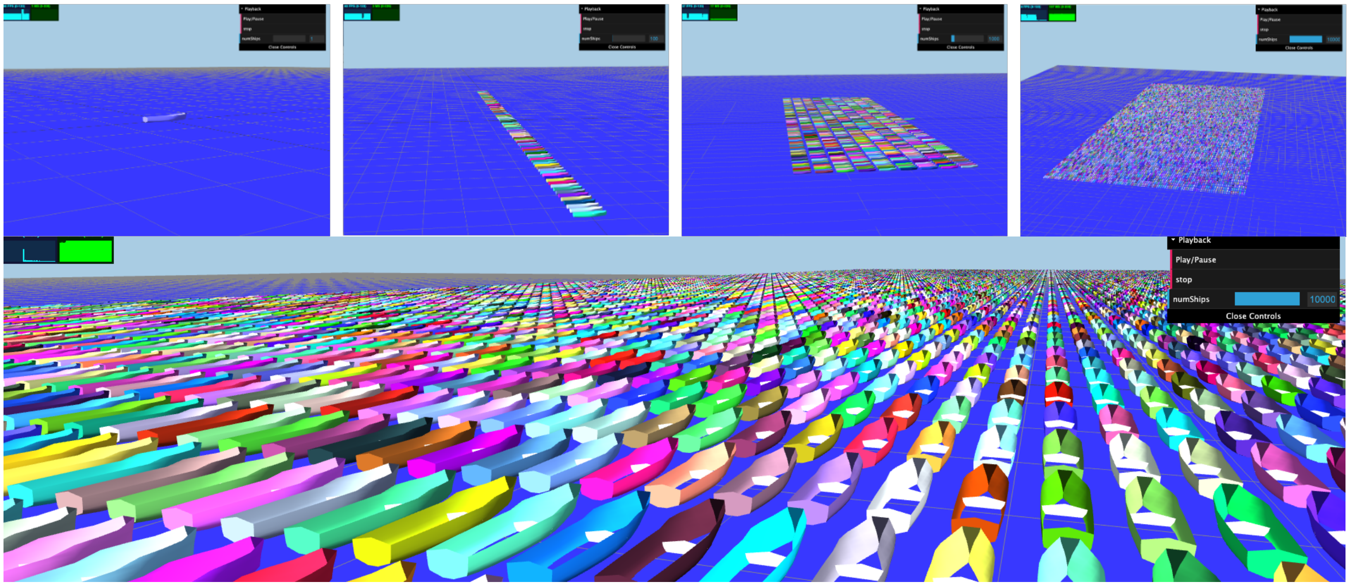
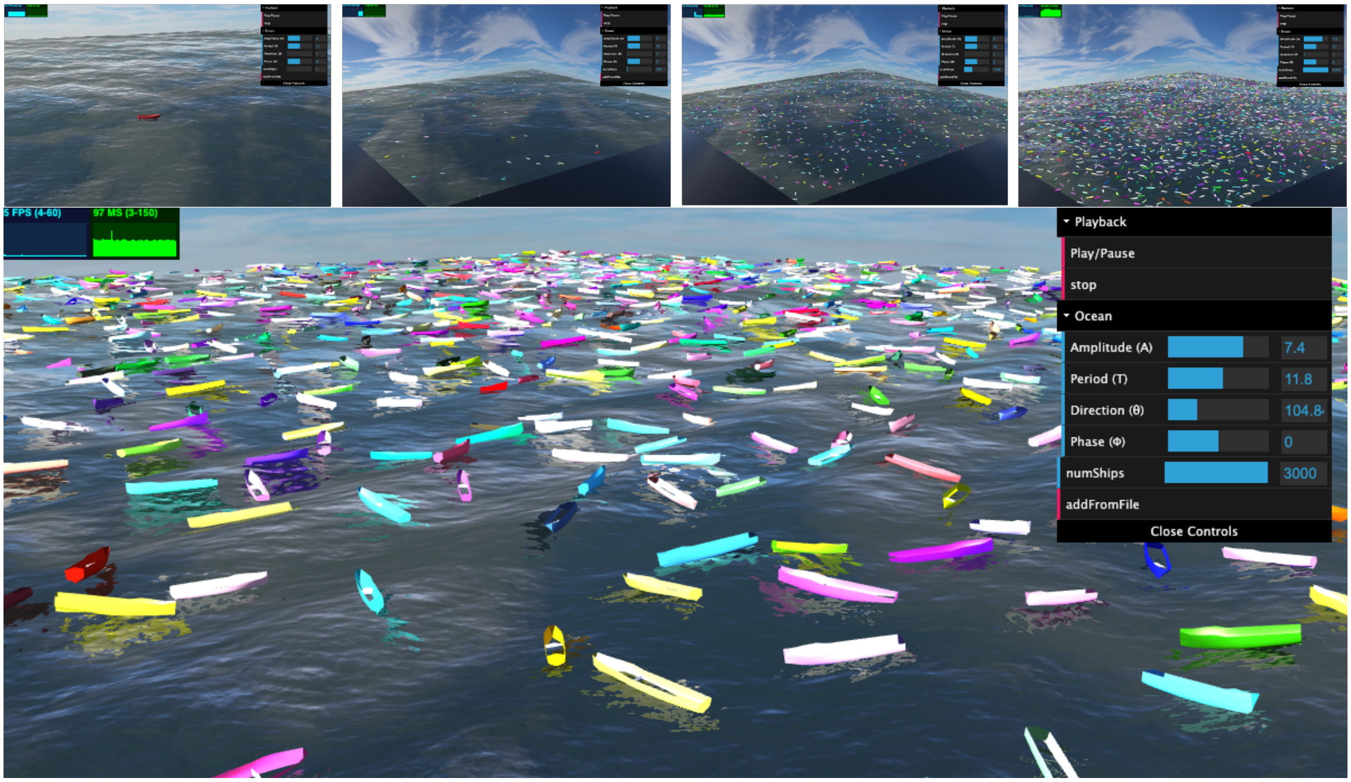


Figure 7: Visualization of 1, 100, 1000 and 10 000 hull in a fixed 4km x 4km virtual square.

Figure 7 presents the *Sea of Ships* currently implemented in the examples sections of the library (Ferrari and Gaspar, 2024). It presents a proof of concept able to load a database of many hulls, varying in real time from 1 to 10 000. As this was tested using a normal personal computer, we believe that a gamer PC, aimed at fast 3D rendering could jump this number to even one order of magnitude higher.

To exemplify open simulation, the described static representation is then connected to the seakeeping simulator described in Chaves and Gaspar (2016). It uses validated closed-form expressions from Jensen *et al. (2004)* to estimate wave-induced motion for mono-hull vessels. These expressions require only vessel main dimensions and basic hull form coefficients, being especially relevant for conceptual design, where little information about the hull form is available. The approach allows the designer to vary amplitude (A), period (T), direction (θ), phase (ϕ), and quickly assess their influence on the wave-induced motion. The case from 2016 was the first to present in an open web-based version the response of a vessel. Now, we implement it to the *Sea of Ships*, simulating seakeeping for 1, 100, 1 000 and 3 000 hulls in the same environment, in real time (Figure 8).

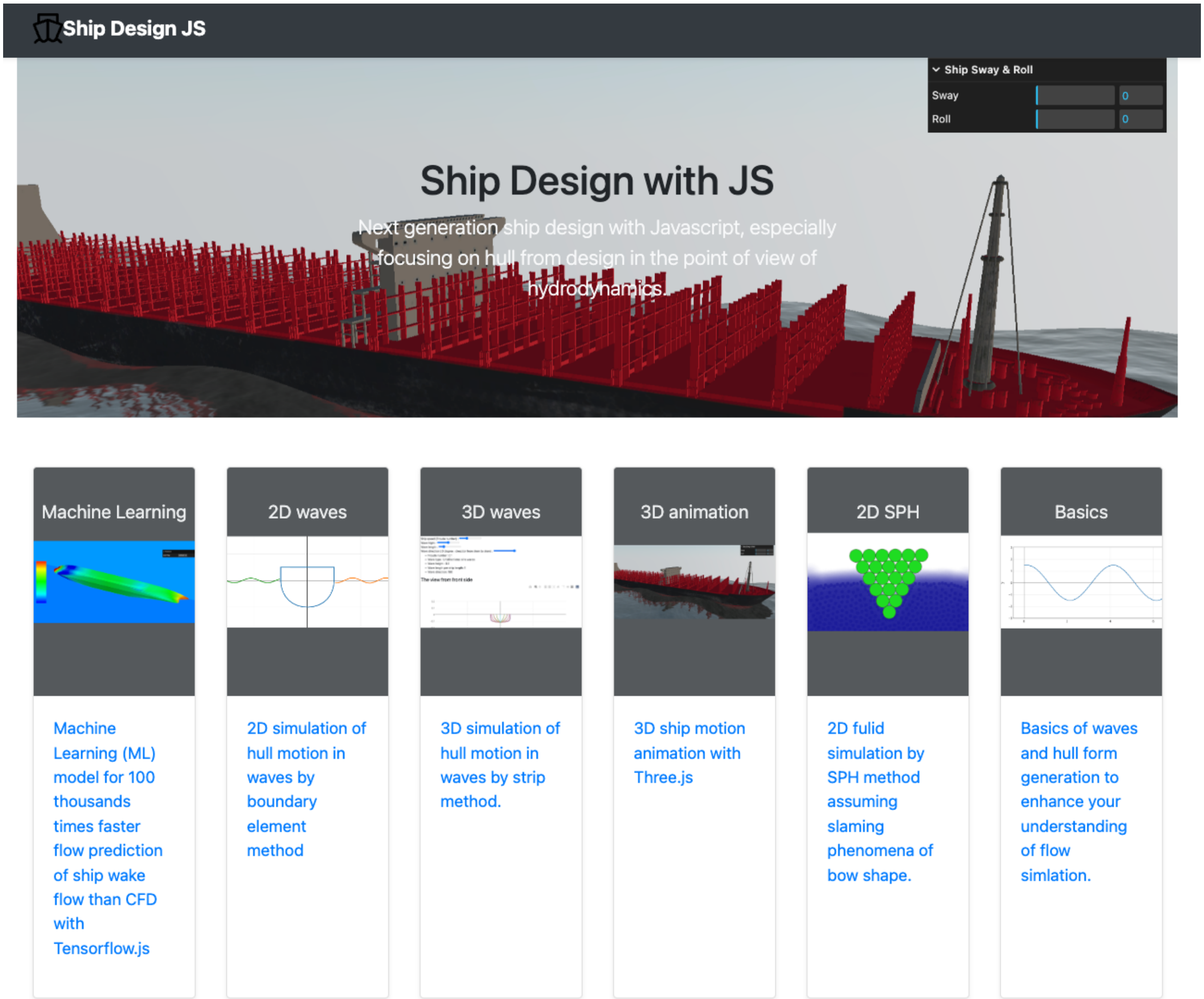


Amplitude (A) 7.4
Period (T) 11.8
Direction (θ) 104.8
Phase (Φ) 0
numShips 3000

Figure 8: Simulating the seakeeping behavior of 1, 100, 1000 and 3 000 hulls using closed-form functions, in a virtual 4km x 4km ocean with virtual waves.

Compared to traditional engineering programming environments, web technologies provide more options and freedom for the creation of sophisticated user interfaces. The developer of a web application may use sliders, text fields and buttons to gather inputs from the user – exemplified in Figure 8 by the sliders to modify the simulation parameters. Results can be presented as formatted text, tables, plots or interactive visualizations, either 2D or 3D. Multiple textual and graphic elements can be combined in dashboards to present a cohesive experience to the user, allowing them to vary inputs and observe the effects of the variation on the results in real-time.

It is important to note that the possibility of assessing in real time such sea of ships is not a common feature in the majority of commercial software. The usability of this exercise is being tested also outside the boundaries of NTNU. Similar to the case discussed at TPN, collaboration between research institutes to check the validation and usability of open web-based technologies is increasing (Q.E.D. this article). The attempt made by NTNU seem in Figure 8 inspired a Japanese version, result from the recent MoU signed between NTNU and NMRI. Diverse implementations of the method were combined with existing initiatives at NMRI (Figure 9).



Ship Design with JS

Next generation ship design with Javascript, especially focusing on hull from design in the point of view of hydrodynamics.

Machine Learning

Machine Learning (ML) model for 100 thousands times faster flow prediction of ship wake flow than CFD with Tensorflow.js

2D waves

2D simulation of hull motion in waves by boundary element method

3D waves

3D simulation of hull motion in waves by strip method.

3D animation

3D ship motion animation with Three.js

2D SPH

2D fulid simulation by SPH method assuming slaming phenomena of bow shape.

Basics

Basics of waves and hull form generation to enhance your understanding of flow simlation.

Figure 9: NMRI Research on Web-based Hydrodynamics, based on a joint initiative with NTNU from 2023.

FINAL NOTES: THE OPEN AND COLLABORATIVE APPROACH

We close this paper with a call for colleagues and students to consider trying develop their own version of a *A Sea of Ships.* The code and examples to replicate the examples in Figure 8 are open and available. We believe that by implementing open and collaborative methods in the everyday design tasks, both at academic and industrial environments, will foster innovation. Simple practices for versioning, tagging and library concepts are recommended (Gaspar, 2018). A Github page for a project – either public or private (paid) is also an experience highly recommended. As this is used to manage large software projects, it has functions like allocating tasks, discussions a traceability in pair (or even better) than most of PDM/PLM solutions. Giving up proprietary data-files in exchange of a standard among all tools seems to be a feasible (and lucrative) path.

The open initiatives here discussed are a working in process, and much of the libraries and methods intends to be improved in the years to come. The main point defended in this paper is that technology is not a bottleneck any longer, and a development that in 2003 would require a cluster of computers and proprietary software, can be done nowadays using a laptop and downloading from an open repository. The real value lies in the humans working with ship design, and their ability to access and filter the open and proprietary databases. In other words, how efficient ship design data is able to be transferred from books and experience to useful reusable models. As for the development of real ship design engineering in an open library, we recognize the value of current engineering tools and PLM suites; no doubt, they are responsive for the visible gain in productivity that the maritime industry faced in the last decade. Industry 5.0, with an open digital thread that all actors may follow is thus the next step (Sepalla *et al.,* 2023).

As a final call, we believe that a large part of the digital tools for Ship Design should be considered open and exchangeable. Naval architects should focus on what they do best: creating, analyzing, refining, storing and populating the database of the know-how from the institution (e.g. university, research institute or company). Learning from modern software companies shows that the gain nowadays, both technological and commercial, seems to be in efficiently handling digitally the intrinsic ship design knowledge (databases), providing services from the know-how rather than a more powerful computer, a mesh more refined or a cluster with *n+1* CPUs. Seeing is a reality one click away.

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