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D2.2 – Description of the LincoSim HPC Simulation platform

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

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People responsible / Authors:	Francesco Salvadore / Raffaele Ponzini, Claudio Arlandini, Arianna Bionda, Giuditta Margherita Maria Ansaloni.
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Responsible (WP Leader)	Francesco Salvadore (CINECA)	-
Approved by Peer reviewer	Arianna Bionda e Gianpaolo Perlongo (POLIMI) Javier Hernández Duque (GHENOVA)	23-12-2021

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Author(s) contact information

Name	Organisation	E-mail
Francesco Salvadore	CINECA	f.salvadore@cineca.it
Raffaele Ponzini	CINECA	r.ponzini@cineca.it
Claudio Arlandini	CINECA	c.arlandini@cineca.it
Arianna Bionda	POLIMI	arianna.bionda@polimi.it
Giuditta Margherita Maria Ansaloni	POLIMI	giudittamargherita.ansaloni@polimi.it

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1 Executive Summary

The e-SHyIPS project aims to define the new guidelines for an effective introduction of hydrogen in maritime passenger transport sector and to boost its adoption within the global and EU strategies for a clean and sustainable environment, towards the accomplishment of a zero-emission navigation scenario. The goal of e-SHyIPS is to move from the idea to the application, filling the existing gap in normative and technical knowledge concerning all the related aspects on hydrogen in the maritime transport sector. By means of an ecosystem approach, e-SHyIPS proposes theoretical pre-normative research activities on standards, simulation and laboratory experiments, design of an appropriate certification process, spot future standardization activities to enhance the EU normative and regulatory landscape.

The present deliverable D2.2, “Description of the LincoSim HPC Simulation Platform”, is the first part of larger set of activities enclosed within the more general Task 2.2. dedicated to the customization of the virtual towing tank application for the needs of overall project. The main aim of D2.2 deliverable is therefore to introduce main concepts of one of the pillar technological tool selected to support e-SHyIPS activities: the virtual towing tank.

The e-SHyIPS project has been designed so that is fully based on computational tools and do not mention any physical experimental facility to produce data necessary to quantify and rank different hull performances. For this reason, the availability of a fully validated virtualized counterpart of the elective physical tool for hull analysis is of capitol interest for the project. In this document we will first describe the actual status of the virtual towing tank including the description of a set of validations performed and published on international papers. We then will list a set of new requirements tailored to support the e-SHyIPS project specific activities. The reason behind the necessity of considering new functionalities is strictly related to the signature of the e-SHyIPS project: the presence of H2 based propulsion systems. In particular, at the actual stage the virtual towing tank allows to perform calm water analysis while new functionalities would support also sea keeping analysis thus including the presence of regular waves. The level of integration of new features in the existing platform will require specific analyses, since not every functionality is suited for general representation within a web-based graphical user interface. Furthermore, to support also preliminary compartments and tanks positioning for quick evaluation of different configuration we agreed to integrate into the virtual towing tank tool standard tools for hydrostatic and stability evaluation. Hydrostatic is used to study the attitude of the hull in calm waters at zero velocity (bunkering; fueling), while

stability allows to study the hull in calm waters at zero velocity during bunkering and fueling operations.

The final outcome of this deliverable will be therefore a complete and clear presentation of the virtual towing tank as is today and as it will be at the end of Task2.2 with a vision of the possible strategic usage within e-SHyIPS.

2 Introduction

For thousands of years, man has been designing and building boats to tackle journeys and work on water, but only in the last 250 years, man has been using the so-called naval towing tank to analyze and validate their performance in advance. William Froude, who was the first to design and build a towing tank in 1870, open to humanity the possibility to use long, straight basins to evaluate and analyze the performance of a vessel by means of the analysis of its scaled model. However, it must also be considered that a naval towing tank is a rather expensive experimental facility to manage, being no less than a few hundred meters long, right up to the longest tank in the world, that of the Krylov Institute in St Petersburg, which is 1324 meters long. On the other hand, although completely free as a criterion, the values of the model scales typically vary between 1/8 and 1/12, so the models themselves can be several meters long thus impacting costs in terms of budget and time to result. As can be easily understood, managing a wide variety of possible configuration variations for a given hull in terms of shape, trim, displacement, Center of Gravity (CoG) position and more, can quickly become burdensome both in economic terms and in terms of waiting time.

For these reasons, in the modern era, alternative tools have been developed such as heuristic formulas based on hydrodynamic analogies, analytical formulas based on the resolution of problems similar to those of interest but referring to analytically solvable configurations. While these approaches have an enormous advantage based on the short time with which they are able to provide information similar to that which can be obtained in a naval towing tank, they also lack generality. In other words, they are not valid when the undergoing working hypotheses are not verified; also, they lack completeness of information, since not all the information that can be obtained from a naval towing tank experimental session can be replicated using these tools. Moreover, statistical and heuristic formulas are not valid for new materials and/or technologies since they implicitly need a reference basis considering mature technologies, materials, propulsion systems, construction standards, arrangements and regulations.

On the other hand, an entirely general methodology, equivalent to the naval towing tank in terms of configurations that can be addressed and the richness of data, is potentially the one based on the use of CFD high-fidelity methodologies. Thanks to the exceptional technological development of computational systems and numerical methodologies over the last 50 years, it has been possible to start talking about effective virtual towing tanks for some years now. Virtual towing tank means the computational transposition, or virtualization, of a real experimental measurement system such as the towing tank as conceived by Froude in 1870. It is easy to see how strategic such a tool is when economic and/or time resources are a strong constraint on the project, or when the main interest is to probe a wide range of possible variations in parameters with a series of hypothesis-testing investigations.

2.1 Scope and Objectives

Within e-SHyIPS, with the intention of investigating and identifying a series of practical prerequisites to support the emerging marine regulations for hydrogen-powered boats, it is strategic to be able to probe a wide range of design options for the identified hull types with reference to their future conversion to a hydrogen-based propulsion system. For this reason, LincoSim, i.e., the virtual ship tank developed in 2018 for the Horizon 2020 project LINCOLN[1], is a strategic tool to support the activity of e-SHyIPS with particular reference to the preliminary assessment of project hypotheses for the design/reconversion of pre-defined types of existing vessels with their operational profiles to hydrogen-based propulsion systems. In other words, LincoSim will be one of the pillar tool for early stage evaluation of general arrangement of the selected scenarios. The LincoSim architecture allows a typical designer user to be able to perform complex simulations and this could also be a significant plus for the usage of the tool in the loop spiral of the naval design.

2.2 Connection with Other Deliverables

The present deliverable, Description of the LincoSim HPC Simulation platform (M12), represents the first part of the overall activities enclosed within the more general Task 2.2. Task 2.2 is dedicated to the customization of the virtual towing tank application and is targeted to be completed at month 24 (M24). In D2.2 deliverable the actual status of the LincoSim platform and the definition of the new functionalities tailored to support the e-SHyIPS project will be presented.

For this reason, D2.2 is strongly related to D2.3 (Evolution of the Hydrodynamic analysis implementation on LincoSim platform, M24), since together they will fulfil the activies of Task 2.2. Also, D2.2 with D2.3 will gather inputs form D2.1(Functional and Technical Requirements for scenario report) where the general arrangements for the selected scenario are defined, and they will be used by D2.4 (Preliminary vessel design for each scenario) for preliminary vessel design. D2.2 is also linked to D3.1 (Preliminary Safety System´s Definition) and to D3.6 (Safety systems Arrangements Preliminary Design) since hydrodynamic results can be of interest in view of safety systems requirements, arrangements, and design.

2.3 Structure of the Document

Within this document, with the aim of presenting the virtual towing tank and showing how it can be used to support the e-SHyIPS project, we will discuss in detail:

1. A description of the state of the art of technological components constituting LincoSim today.
2. The validations made to date for the methodologies proposed in LincoSim.
3. The strategic uses of LincoSim in e-SHyIPS in its current state of development.
4. New requirements that have emerged in e-SHyIPS that can be integrated into LincoSim.
5. Conclusions and future developments.

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[1] https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-transport/waterborne/lincoln

3 State of the art: LincoSim today

3.1 Technological Platform Description

One of the main goals of the LincoSim virtual towing tank is, as introduced, to make available to a typical *designer user* the state-of-the-art resources of CFD (Computational Fluid Dynamics) numerical simulations, exploiting High-Performance Computing (HPC) architectures to produce results in times compatible with industrial design. To reach these goals, the platform has been designed with a series of layers able to manage the communication between the intuitive interface with the user and the complexity of the automatic CFD simulation including the use of High-Performance Computing platforms. A schematic of the overall architecture is shown in Figure 1.

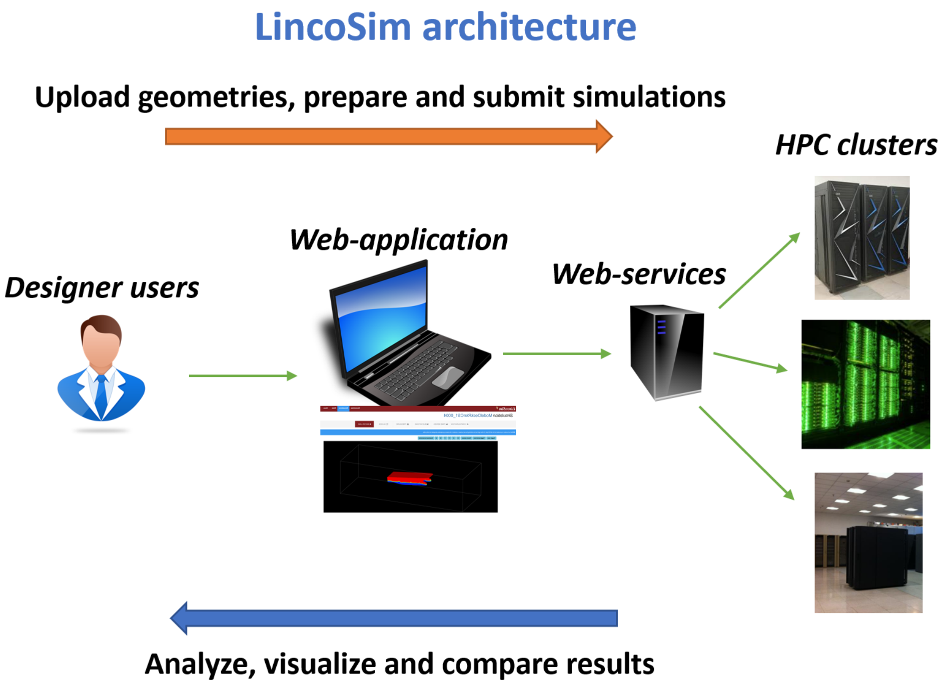
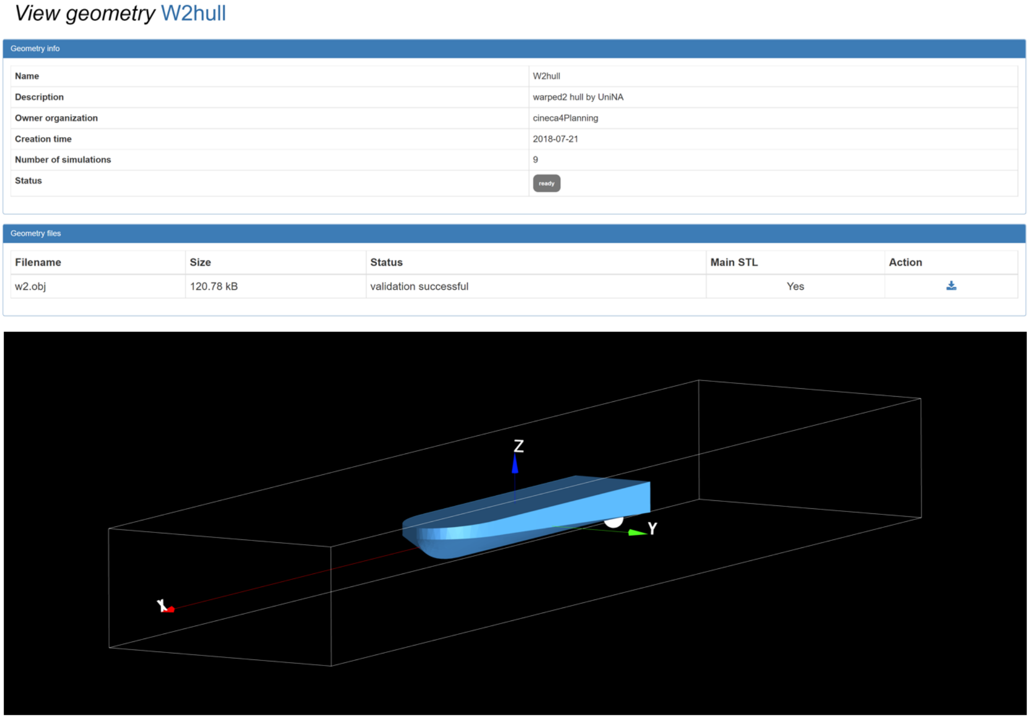


Figure 1 - Schematic of LincoSim architecture from the user workflow point of view.

The interaction with the user is completely managed via a web interface, thus avoiding problems related to software installation and/or compatibility between versions, operating systems, or other components. The web interface is the access point of the web application that through its services (Application Programming Interfaces, APIs) manages the storage in a database and an advanced logic of operations. First of all, the web application manages the authentication/authorization system based on RBAC (Role-based access control) in such a way as to guarantee ownership of the objects not to individuals but to groups of users (e.g., belonging to the same organization/company). Through the interface, users can manage the geometries of the hulls accessible through a dedicated dashboard. After uploading the geometry – in a triangulated format such as stereolithography (stl) or Wavefront object (obj) – in view of the CFD simulation, a validation is performed, basically including a test of water-tightness. From the same web interface, it is then possible to access an interactive three-dimensional visualization of the saved geometry. The geometry is physically saved on the web server. The validation procedure requires a certain (moderate) amount of time, which is why it is not performed synchronously with HTTP web requests but through a mechanism of brokers and internal queues on the web server, all in a transparent way for the user. Figure 2 shows some screenshots related to the interface that controls the geometry.



View geometry W2hull

Geometry info

Name	W2hull
Description	warped2 hull by UniNA
Owner organization	cineca4Planning
Creation time	2018-07-21
Number of simulations	9
Status	ready

Geometry files

Filename	Size	Status	Main STL	Action
w2.obj	120.78 kB	validation successful	Yes	

Figure 2 - Geometry management in LincoSim: general info, validation result, and three-dimensional visualization.

Once at least one valid geometry is loaded, a simulation can be created. The input of a simulation has been standardized as:

- the user group to which the simulation refers
- the geometry of the hull
- the HPC cluster to be used for the calculations
- the simulation setup, i.e. the type of simulation to carry out tailored for each specific organization
- the set of input data that characterize the physics of the flow, that is:
    - mass
    - coordinates of the centre of gravity
    - moments of inertia
    - speed of the hull
    - initial water level
    - water temperature
    - initial hull trim angle

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Once the input is defined, the user can launch the simulation which can be of "single" type or "range" type, the latter corresponding to launching many simulations at once with a flow parameter that varies in a set of values defined at launch time. Launching a simulation triggers the invocation of a web-service that performs a series of actions both on the database side of the application and on the interaction side with the HPC computing machines. At the HPC cluster level, the launch of the simulation corresponds to the launch of queued jobs. In particular, an initial preparation run job is launched in which data is taken from the web server (geometry and input) and copied to the simulation folder in the HPC cluster file-system. The simulation setup must be available (and possibly optimized) on the selected HPC machine, but it is the simulation definition interface that already guides the user by preventing the use of clusters for which a certain simulation setup is not available. The first job launched in the queue in turn launches the computing job in which the simulation setup is actually executed on the available input data. The simulation setup is in fact the heart of the calculation, capable of executing in a completely automatic way operations that usually require an important human contribution within the simulation configuration. A diagram summarizing the groups of operations executed during a typical simulation is introduced in Figure 3 on the left.

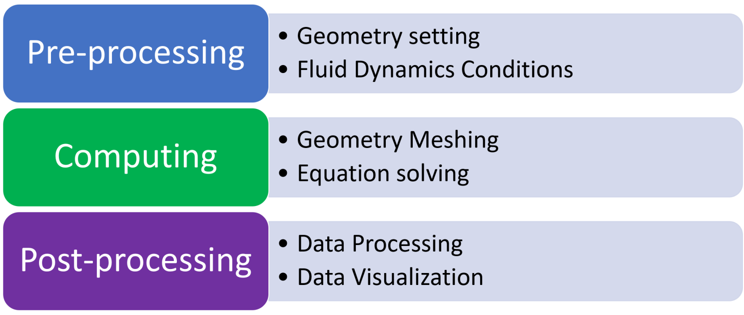

Figure 3 - Schematic of typical steps of a CFD simulation including pre/post-processing tasks.

In Figure 4, an example of a mesh is provided showing details on the boundary layer representation in the numerical domain. The production of an adequate mesh in an automatic way for every condition of the simulation (geometry of the hull and conditions of the flow) represents one of the greatest challenges among all the components of the simulation.

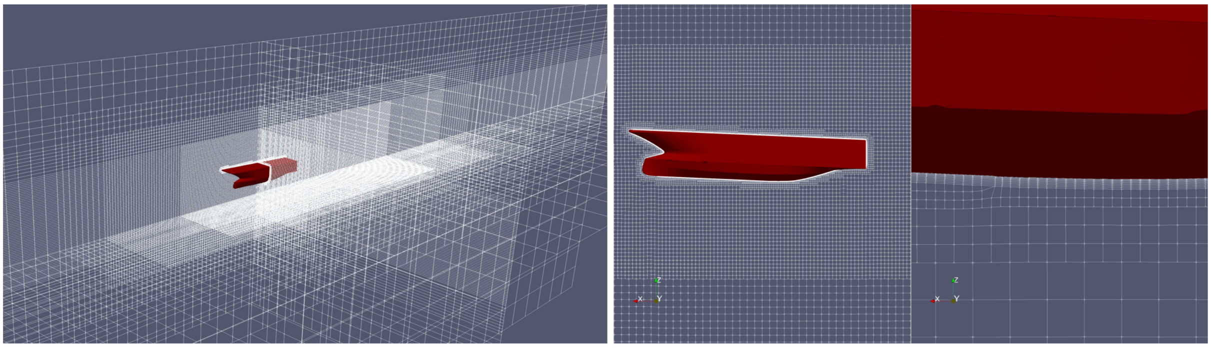

Figure 4 - Example representation of mesh for a catamaran geometry: three-dimensional box layout (left), hull region (middle) and boundary layer detail (right).

The last phase of the simulation setup consists in the post-processing and in the extraction of the meaningful results for the presentation to the user. Indeed, minimal post-processing is already carried out during the simulation in order to show some meaningful charts to the user during the run. This way, the user can directly assess the convergence and stop the simulation, in advance with respect to the automatic convergence check and simulation stop. The post-processing at the end of the simulation extracts a set of standardized information of common interest for the naval designer. The output information list is:

- time series: pressure and viscous forces, moments, sinkage, trim, vertical and angular velocity, drag, displacement;
- 2D wave elevation contour;
- 3D wave elevation isosurface;
- 1D customizable streamwise wave elevation plot;
- hull pressure plot;
- mesh slices;
- 1D pressure streamwise slices;
- 3D Wet surface on hull;
- profile of wet surface hull.

On the other hand, Figure 5 shows some screenshots related to the corresponding visualizations in the web application.

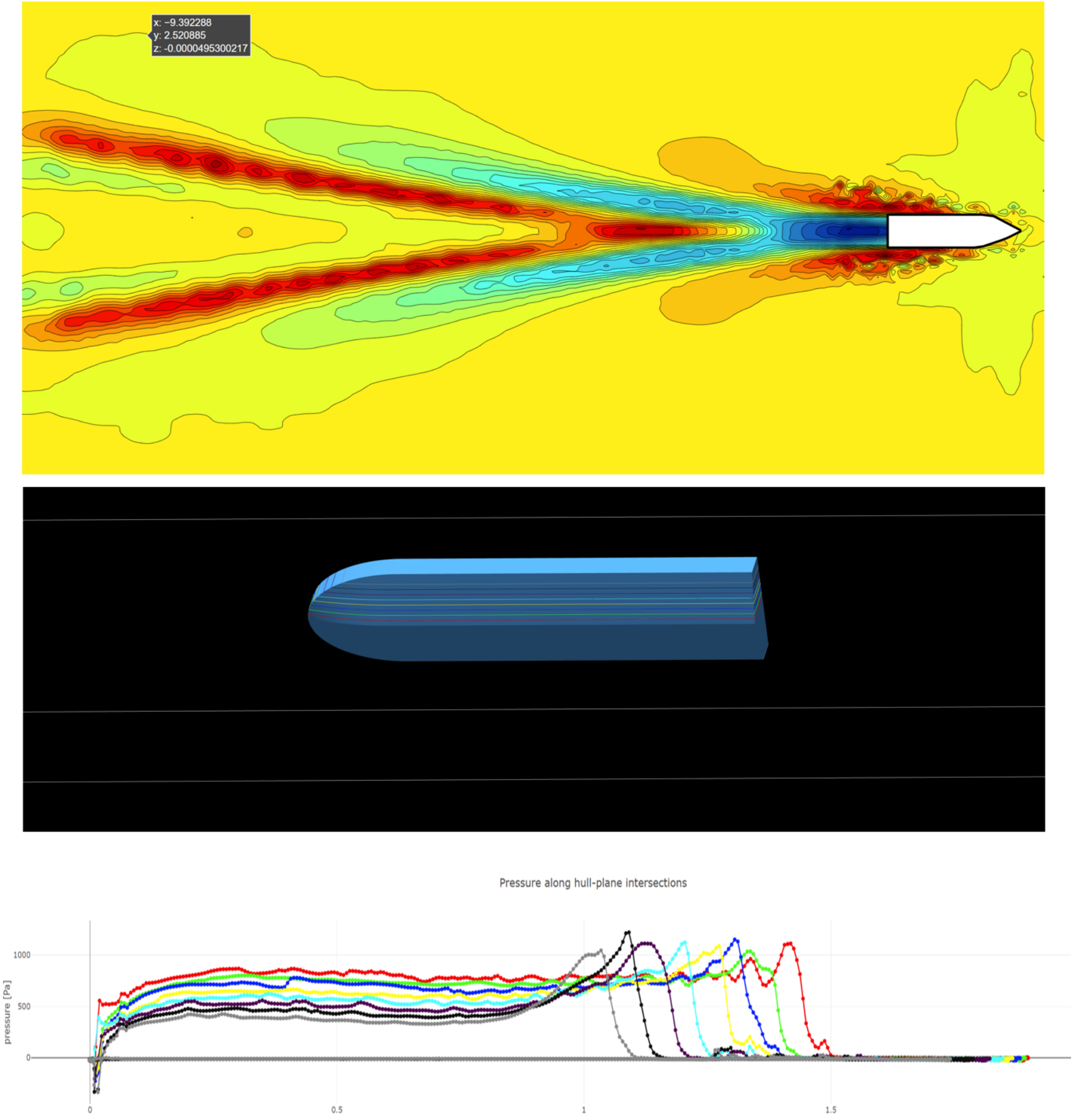

Figure 5 - Typical output visualization available in LincoSim: wave elevation contour (top), pressure along hull slices (bottom).

The visualizations are one-dimensional, two-dimensional or even three-dimensional and in all cases are navigable by the user in an interactive way so that significant behaviours can be analysed in detail. It is also possible to download the output data to be visualized in local software, should the user have specific skills in this regard. And it is finally also possible to download a complete PDF report of the simulation -- input and main results -- that can be important for a business use and, for instance, in case other documentation is available to be attached to the obtained results.

From the platform implementation point of view, it is clear that the management of the different layers of the platform requires suitable tools used for the development of a rather complex software stack. The design choice has been to always use open-source tools to produce an object potentially also spreadable in other contexts even with a limited budget. In extreme synthesis, these are the major components used by the platform:

- Front-end: Angular framework with several additional libraries including in particular for the visualizations *three.js*, *plotly.js* and *D3.js*.
- Back-end: *NGINX* as HTTP server, *web2py* for web-APIs, *Celery* and *RabbitMQ* for local queues on the web server.
- Metadata: *PostgreSQL* database is used, driven by the *pyDal* Data Abstraction Layer; the database is also supported by *ElasticSearch* as a specialized search-engine.
- HPC machines: by architectural choice, no services run on the computing machines while the simulation setups operate by directly invoking the APIs of the web server when necessary; vice versa, the web server is able to access the machines via automatic *ssh* access; *PBS* and *SLURM* are supported as queue managers on the clusters.

For further details on the technical description of the LincoSim platform please refer to the published articles [1] and [2].

Although the architecture of the system is potentially generic, LincoSim has so far been oriented to calm water simulations at 0 DoF (Degree of Freedom), 1 DoF (heave motion), or 2 DoF (heave and pitch motions). The described data abstraction, standardized both as input and output, reflects in fact quantities and visualizations that are significant in the context of simulations of this type. Adding potentialities to the system is possible but it requires a revisiting of some components in a not trivial way. In particular, considering, as an example, simulations with waves, it would be necessary to extend the set of input data (e.g., height of the wave, period) and even the set of outputs to show the customer. Extensions of this type require significant efforts, but they can clearly strengthen the potential of the platform in the direction of being useful for naval design.

3.2 *Available Methodology Validations*

The CFD engine used in LincoSim for the hydrodynamic simulation of multiphase flow is generic in the sense that it can be defined within a simulation setup in a relatively free way as long as it is able to use the inputs and produce the outputs, according to the standard scheme defined and implemented in the platform interfaces. The virtual towing tank is however oriented to high-fidelity simulations capable at the same time of being computationally addressable in a realistic view of industrial application. In this respect, the CFD engine is currently realized through the OpenFOAM toolkit[2]. In particular, the *interFoam* multiphase solver is used alongside several additional tools provided in the platform such as, for example, tools for meshing via *snappyHexMesh* application and tools for result extraction. Among others, the peculiar advantage of OpenFOAM, is its open-source nature, which makes it possible to run a large number of independent runs without incurring dramatic software licensing costs.

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[2] https://openfoam.org/

The *interFoam* multiphase solver is typically used by including turbulence models, thus performing so-called RANS (Reynolds Averaged Navier-Stokes Simulation) simulations. Such an approach allows to reach high-quality results without resorting to types of simulations that cannot be addressed in a realistic context, such as LES (Large Eddy Simulation) or DNS (Direct Numerical Simulation). However, the RANS methodology, as on the other hand the CFD methodology, requires particular attention to achieve results comparable with the experimental ones. In particular, among the major sources of error the following three groups can be considered:

- computing mesh not adequate for the simulation of the spatial scales present in the problem;
- turbulence model not able to represent the real physics of turbulence especially in particular conditions, such as low Reynolds numbers and important presence of separations; in this regard the use of wall functions represents in some cases an oversimplification of the boundary layer situation;
- numerical methods not sufficiently accurate (e.g., excessively dissipative).

In the LincoSim terminology, each simulation setup must therefore be able to manage the different aspects of automatic configuration in order to minimize simulation errors in the widest range of input conditions. From the simulation point of view, this is undoubtedly a big challenge. The fine-tuning of a virtual towing tank cannot therefore prescind from an important phase of verification and validation that allows to estimate the variability of the results regarding the various modalities of calculation (verification) and the comparisons with meaningful experimental observables (validation). From a purely theoretical point of view, verification and validation (V&V) are required for the analysis of each new physical case (geometry or flow conditions). On the other hand, this requirement appears dramatically onerous and excessive in the engineering domain so that a certain V&V can be considered valid even for a case different from the one addressed as long as it is reasonably similar. From a LincoSim point of view, the user may eventually be able to perform a verification using ad-hoc simulation setups -- identical if not for the level of grid thickening for example -- while for validation the problems are more challenging, if we consider the temporal and economic cost of the realization of an experimental Towing Tank campaign (Experimental Fluid Dynamics, EFD). In e-SHyIPS, LincoSim is the primary source of evaluation of the hydrodynamic performance of the hulls and for this reason it becomes essential to understand its value and limitations, in view of the fluid dynamic validations currently available for the platform.

In this paragraph we summarize the results of two previously validated and published campaigns between virtual towing tank and experimental towing tank data.

In the first campaign a series of single hulls (four geometric variations) was considered: the hulls were analyzed for Froude numbers between 0.25 and 1.75, therefore in planing condition. The hulls are schematized in Figure 6.

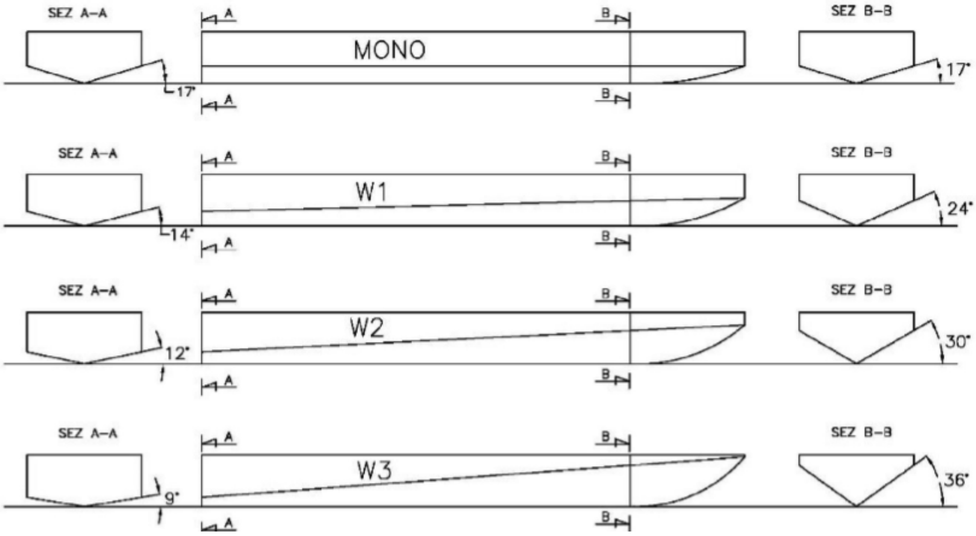

Figure 6 - Geometrical configurations of the planing hull series considered for LincoSim validation.

In the second validation campaign, a trio of catamarans (same geometries but at different separations) with Froude numbers ranging from 0.22 to 0.8 were analyzed. The schemes are shown in Figure 7.

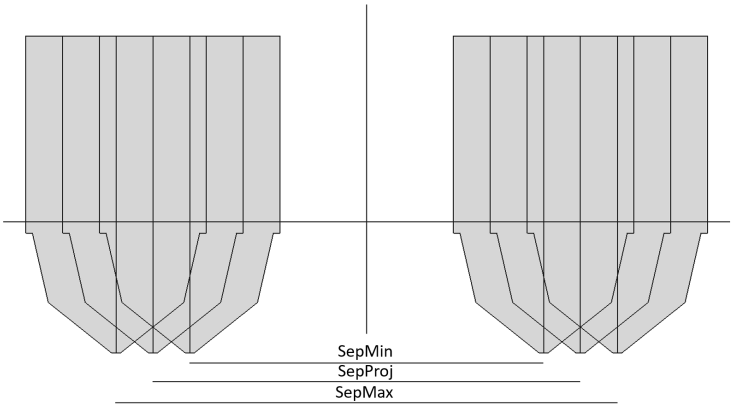

Figure 7 - Geometrical configurations of catamaran considered for LincoSim validation with different demihull separations: minimum separation (SepMin), project separation (SepProj), maximum separation (SepMax).

The validation results reported here compare the main observables that can be extracted with LincoSim, namely the calm water performance represented by drag, pitch, sinkage.

CFD vs EFD comparisons are shown in Figure 8 for the Mono configuration of the single hull geometry.

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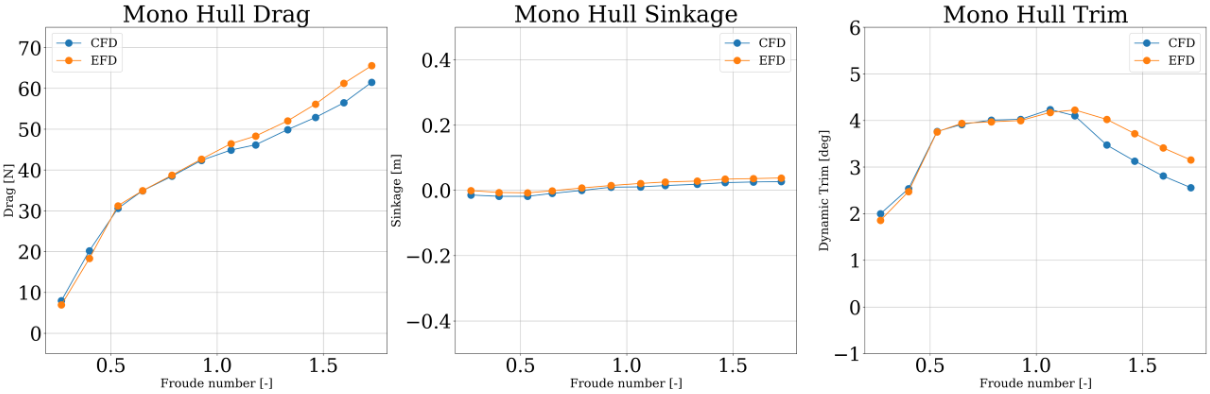

Figure 8 - CFD versus EFD data comparison for Mono Hull. From left to right: Drag, sinkage and dynamic trim are plotted against Froude number.

Adherence between numerical and experimental results is always very good for drag and sinkage, while for trim there is a systematic error -- measurable but always limited to half a degree -- for Froude numbers corresponding to planing conditions. From the point of view of the engineering application, in addition to the one-to-one comparison of the results, the comparison between the trends when the geometric configurations conditions vary is particularly significant, allowing the evaluation of a certain geometric case during the design phase. Figure 9, as an example, shows the comparisons of trim trends for the 4 single-hull geometric configurations vs. the Froude number:

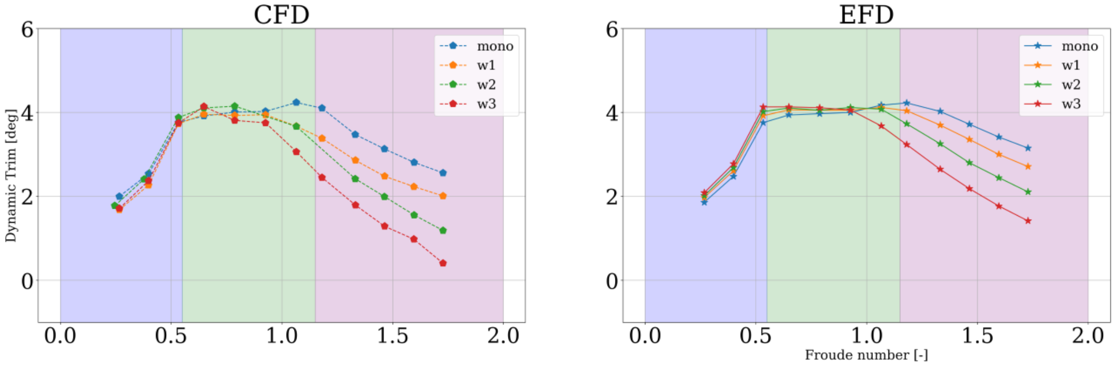

Figure 9 - Dynamic trim CFD versus EFD data comparison for all the hull shapes.

Even if numerically some discrepancies are observed in terms of absolute values, the reproduction of the trends when varying the geometry is quite similar between experimental evaluation and virtual towing tank counterpart. This proves the significance of a tool like LincoSim in the context of industrial design.

As for the V&V of the catamaran case, we represent in Figure 10 the comparison trends of experimental drag, trim and sinkage with the numerical results at different levels of grid refinements.

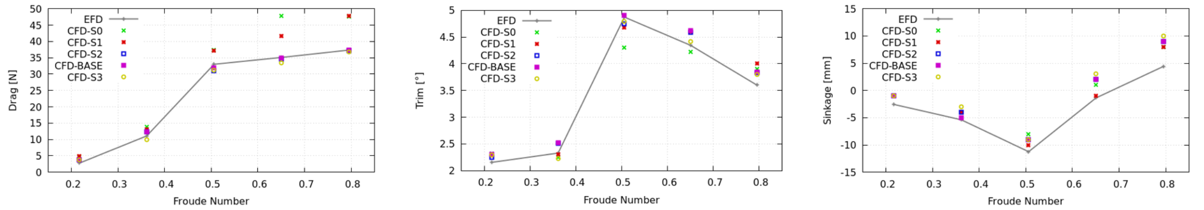

Figure 10 - Mesh sensitivity analysis for catamaran case considering drag (left), trim (middle) and sinkage (right). Points refer to results at different grid refinements from S0 (coarsest) to S3 (finest). BASE is the selected optimal refinement. EFD data are reported as points connected by straight lines.

The trends demonstrate first of all the quality of verification of the numerical methods and the choice of the mesh made (CFD-BASE) with respect to the sequence of increasingly refined meshes considered (S0, S1, S2, BASE, S3). In fact, the variations between the results using S0, S1 and S2 are significant while they become minimal by refining further to BASE and S3. Second, the convergence trends are adequately close to the experimental data, thus demonstrating the quality of the validation.

Even for the catamaran case, it is of particular interest to evaluate the trends resulting from the different geometric configurations -- in this case the separation between the hulls. As an example, Figure 6 shows the drag trends at different separations, comparing experimental and numerical results.

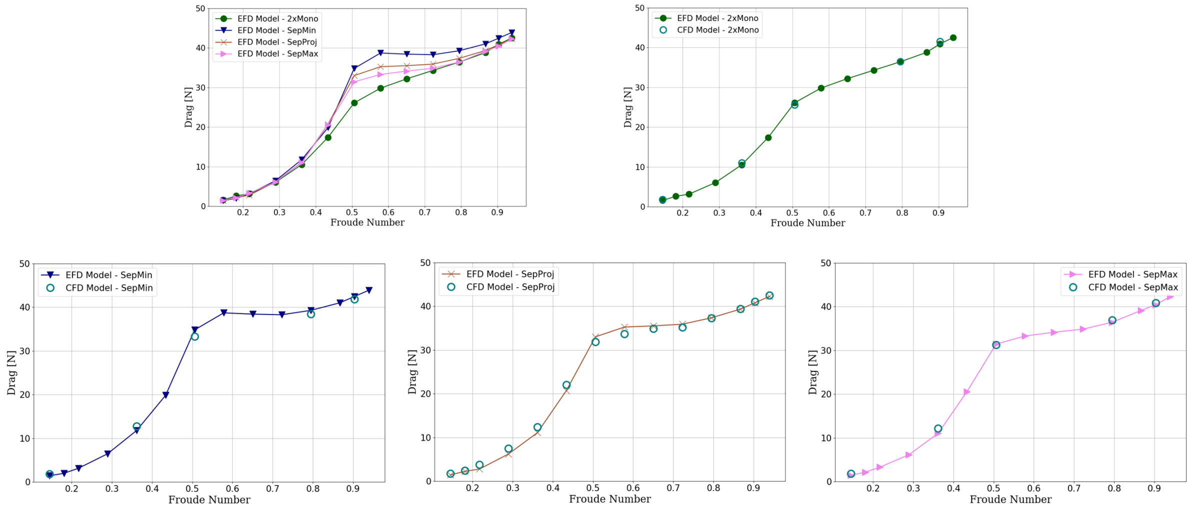

Figure 11 – Drag against Froude plots for catamaran case. EFD results for different geometries SepMin, SepProj, SepMax and doubled Mono data (top-left). EFD (lines and circle points) versus CFD (triangle points) results are provided for Mono (top right), SepMin (bottom left), SepProj (bottom center) and SepMax (bottom right).

Besides, to understand the physical mechanisms of the catamaran results in more detail, it is of interest to also extract fluid dynamic field comparisons. For example, wave-cuts along the plane of symmetry of the hulls can provide insight into the nature of interference between the hulls. Figure 7 shows some EFD vs CFD comparisons for two Froude values and considering the intermediate separation case. The high level of similarity between the results of CFD and EFD shows one of the crucial advantages of the RANS methodology which is capable of reproducing not only the global observables but also the fluid dynamic fields. The user is therefore able to gain a much deeper understanding of the reasons for the final performance, thus giving indications for possible design modifications.

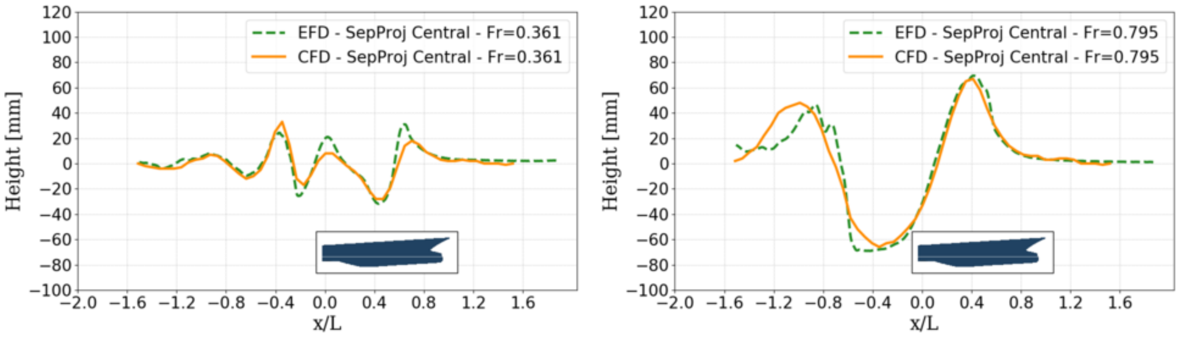

Figure 12 - Central wave-cuts comparisons between EFD and CFD of SepProj case. Froude numbers are 0.361 (left) and 0.795 (right).

It is worth noting that the use of a numerical simulation tool gives access to a complete series of detailed quantities that are difficult if not impossible to evaluate in an experimental context, such as the correlation of the pressure resistance versus the viscous counterpart, or the spatial distribution of the pressure contribution on the hull.

All the results shown in this section have been obtained through parallel computations, natively supported by OpenFOAM through the Message Passing Interface (MPI) standard library. The advantage of parallel computing for industrial purposes is enormous as it allows the user to obtain results in incredibly fast times. As an example, a calm water simulation at 2 DoF under intermediate Froude conditions requires a number of computing cells between 1 and 2 million and this requires a computing budget in the order of 500 core-hours. Using a modern computing system with 100 cores (typically two nodes of 50 cores each) and assuming ideal scalability, it is clear that the actual computation time is reduced to a few hours, consistent with the timeline of a typical ship design.

On the whole, it can be concluded that the LincoSim virtual towing tank is a tool capable of simulating with a good margin of accuracy monohull or catamaran hulls for calm water analyses including free sink and trim hull dynamics (two Degrees of Freedom, 2DoF). The results are adequate for both displacement and planing hulls. The reliability of the results is good overall, both as absolute errors and especially as the ability to distinguish trends, but clearly may require specific verification and validation when brand new conditions are explored or when particularly accurate or reliable results are required. For further details on the validation cases of the virtual towing tank please refer to articles published in international journals (see [3] and [4]).

4 Strategic usage in e-SHyIPS

In general, LincoSim presents a set of strategic strengths:

- No expertise CFD knowledge required from users (ship design).
- Contribution to concurrent engineering, several options could be studied.
- Contribution to Design Office cost reduction. Pay per use instead of SW investment.
- Contribution of CFD´s tools in preliminary stages of the design, validating different options or detecting potential constraints that would be otherwise detected in last stages of the design.

Within e-SHyIPS, how can we make strategic use of the validated virtualized measurement tool described above? The first and more general answer is: to support early-stage design of hull general arrangement. This is a central point in ship design in general and within e-SHyIPS in particular.

To gather the maximum advantage by using LincoSim in e-SHyIPS there are essentially two strands that can be defined as follows:

- Performance analysis in calm waters: practical examples of use;
- Performance analysis in the presence of waves: requirements analysis.

Below we will describe in detail, through some practical examples, the first strand being in fact corresponding to the current state of development of the virtual tank and therefore also ready to be used on the hulls defined by the scenarios described in deliverable D2.1. We will show how an automatic and standardized modelling tool is able to provide quantitative information useful for classifying, comparing, and finally differentiating apparently very similar hulls.

In the following paragraph, we will analyze the requirements for the insertion of new modelling tools in the virtual tank with an emphasis on the novelties required to support the safety analysis studies as they emerged from WP3 and in view of the risk assessment analysis performed in the second part of WP2. As a matter of fact, considering the new hydrogen-based propulsion system for the new vessels, safety aspects and the explosive risk inherent with this fuel emerge and need to be addressed also considering the accelerations related to the presence of wave motion during navigation, refuelling, and bunkering. These data could be useful to validate acceleration level for specific equipment and its location onboard, as in the case of fuel cell or tanks. In this context, the analysis of the safety of the system also has a significant impact on the choice of components and materials, especially the tanks, which are the subject of WP4.

We would like to start mentioning that for an effective tool also usability, completeness, and ease of use are relevant parameters. In this vision, the integration of standard tools of analysis in the same virtual towing platform can be a significant improvement. In this view, project partners highlighted the advantage of embedding in LincoSim in particular:

- **hydrostatic evaluation**: this capability would enable designers to study the attitude of the hull in calm waters at zero velocity (bunkering; fueling);
- **preliminary stability evaluation**: this capability would enable designers to study the stability of the hull in calm waters at zero velocity (bunkering; fueling).

The integration of these two new tools will complete the LincoSim User Interface avoiding unnecessary exchange of data with other external software tools. In other words, these new features will support the study of:

- compartments and tanks positioning for quick evaluation of different configuration;
- hull shape and volumes to get a quick understanding about possible hull shape changes needs related to the new weigh configuration.

4.1 Performance analysis in calm waters: practical examples of use

Calm water performance analysis is the basis for the type of information that can be obtained from a vessel, whether real or virtual. In short, this type of analysis consists of the evaluation of a series of indicators useful for understanding the actual performance of a hull as it varies in speed, CoG, weight, or shape of parts of the hull itself. What do we mean in this context by indicators that are useful for defining performance and therefore classifying a hull?

Let's consider as the first case of application the one typically investigated in the naval tank, i.e., the performance analysis of a hull when the speed varies. The main indicator for analyzing the performance of a hull is undoubtedly the resistance or power curve of the hull. This curve makes it possible, for example, to correctly size the effective dimensions that a propulsion system must have to guarantee an adequate operating profile for the boat (e.g., sizing of powering, fuel cell system, tanks, batteries). This first kind of output, for instance, could be used by the other virtual design tool used in the project (COSMOSS) for power need evaluation.

The second indicator of interest is the definition of the trim that the hull assumes at the various speeds, since the hull is a rigid body that is free to rotate and translate around its axes. There are also numerous other indicators, not only derived from these first two, such as the wetted surface of the hull and the length and shape of the waterline profile on the hull.

In addition to the hull related quantities, there are other quantities related to the waves generated by the hull itself, which we may be interested in, for example, in terms of maximum wave height, to understand how the wake of the hull impacts the surrounding environment (channel navigation) and manoeuvring in marina/port for bunkering. Other indicators that are much more technical and specifically related to the computational nature of the virtual tank are the pressure distribution on the hull (not available in the traditional naval tank). In other words, a virtual towing tank is a tool that enables researchers to perform analyses that a real equivalent to the one performed in a real towing tank, but open also the opportunity to analyze a set of new and more rich data that can enable to get a better understanding on the physical phenomenon we are emulating using a computational tool.

Here below for sake of clearness, we highlight the list of quantities that are usually analyzed in real towing tanks and their virtual counterpart.

Table 1 - Towing tank and virtual towing tank available quantities.

Index Name	Virtual Towing Tank	Towing Tank
Resistance	Y	Y
Attitude	Y	Y
Wetted Surface Area (WSA)	Y	Y
hull pressure distribution	Y	N
Maximum wave height	Y	Y

Notably, the virtual towing tank allows also to overcome two well-known limitations of the physical towing tank related specifically to the model scaling procedure. In order to perform the desired analysis, there is:

- the necessity to establish a scaling factor: full-scale hulls are not feasible in most towing tanks;
- the necessity to select which dimensionless fluid dynamic quantity has to be satisfied when scaling: Froude number or Reynolds number. In fact, since the first is related to the square root of the hull length while the second one is related to the length of the hull, preserving one quantity will directly prevent the accordance of the scaled model to the other one.

A practical example of calm waters type of analysis was recently conducted together with one of the project partners with the aim of classifying two hulls that were completely identical in terms of design parameters except for the shape of the bow.

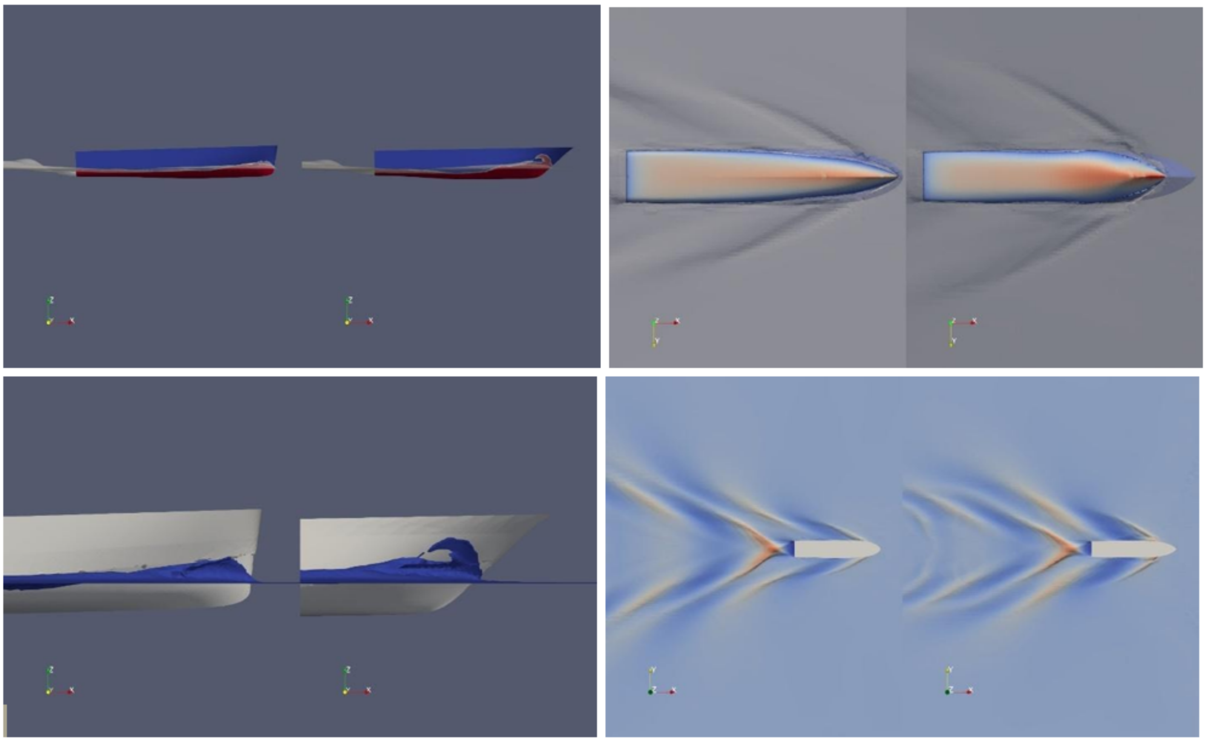

Figure 13 - Virtual towing tank data comparison for sharp and flat bow hulls.

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Using the standard simulation utilities of LincoSim, it was possible to study the two hulls in a virtual ship tank at 1/8 scale and at full scale and then compare the differences in some indicators of interest. Figure 13 and 14 show the geometries and the results of the analysis. It is important to understand how, thanks to standardization and automation, it was possible, with relative simplicity and within 24 hours, to obtain a clear picture of the differences between the two hulls considered. In addition, and herein lies one of the strengths of the virtual version of the ship tank, the variety of data that can be displayed and compared in 2D and 3D is rich, making it possible not only to measure the differences and quantify them but also to visualize and understand the possible causes driving these differences.

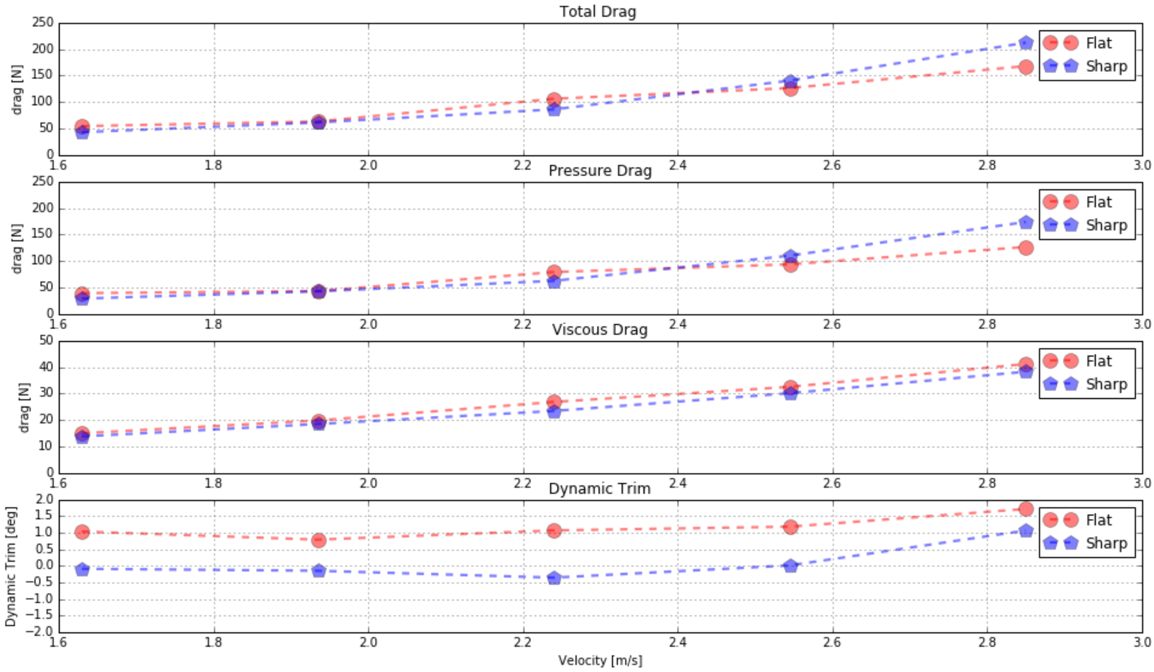

Figure 14 – Quantitative evaluation of flat and sharp bow hulls.

This type of analysis, once the indicators of interest have been identified, can be carried out in a similar way for the hulls defined by the e-SHyIPS use cases. Within WP2, in agreement with the project partners, a workflow was identified to make the best use of the virtual towing tank with reference to the analysis in calm waters, that can be summarized as follows:

1. Assessment analysis: analysis of the hull of interest in the operating range considered with the propulsion system in place (no H2).
2. Hypothesis testing: analysis of hull converted to H2-based propulsion system under defined design hypotheses.
3. Qualitative analysis: 2D and 3D visualization of fluid dynamic indicators.
4. Quantitative analysis: Comparison of indicator values and calculation of deltas.

It is very important to understand how in point 2 (hypothesis testing) there is the possibility to vary several parameters related to the hull, among which, for example, considering the preliminary information obtained from the other WPs:

- mass;

- CoG;
- hull shape.

For each variation of these parameters, a complete analysis can be carried out in the range of speeds indicated by the operational profile of the hull. Therefore, within each variation, a set made of N simulations has to be considered where N generally varies between 5 and 7 speed conditions. In this way, we believe we can quantitatively support the main requirements related to the project by allowing the partners to objectively identify the differences between the current configuration with a standard propulsion system and the hypothetical one with H2-based propulsion.

Depending on the stage of the project and depending of the specific goals of the design stage, more lightweight 0-DoF and 1-DoF simulations can be employed as a more cost-effective tool to more easily explore a wide range of design options.

4.2 Wave performance analysis: requirements analysis

Thanks to the work of the project partners, given the explosive nature of the new fuel, it is necessary to consider new modelling aspects capable of assessing and quantifying in advance the effect that the presence of wave motion can have on hulls. The ability to quantify in advance the effects of wave motion on hulls provides valuable input to WPs dealing with safety and risk assessment to analyze fully realistic configurations and contexts and not to rely only on design assumptions or literature data obtained in similar contexts, if available. Indeed, even IGF code[3], when considering gas fuel tanks and gas fuel system arrangements for wave-induced loads, suggests to perform a complete analysis of the particular ship accelerations and motions in waves. More in details, it is specified that the response of the ship and its liquefied gas fuel tanks to wave induced forces and motions, shall be performed unless the data is available from similar ships.

For the purposes of our analysis, reference parameters for wave design can be obtained from well-established literature with reference to the Seakeeping Standard Series (SSS) including [5], [6], [7].

The range of input parameters identified for the wave motion of our interest, covering real contexts such as navigation, bunkering, and refuelling are listed in Table 2 where we listed the synthetic parameters identified to characterize the wave motion and the ranges of interest. In Table 3 we listed the output parameters that will need to be calculated. In short, sea keeping analysis is used to measure the vessel performances in regular waves through the so-called RAO (Response Amplitude Operator). RAO is a linear operator that represents the input/output (wave/movement) transfer function, being this quantity of key relevance to determine vessel design parameters. In other words, the RAO describes how the response of the vessel changes with wave features.

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[3] IGF Code (sections 6.4.6.3 and 6.4.15.2.2.3): International Code of Safety for Ships Using Gases Or Low Flashpoint Fuels, International Maritime Organization and Mikédzynarodowa Organizacja Morska, International Maritime Organization, 2016.

Table 2 - Input parameter for wave analyses.

Input parameter	Range Values
Wave period	4-20 [s]
Wave amplitude	0-2 [m]
Hull velocity	0-max velocity [Kn]
Wave direction	0-180 [deg]

Table 3 - Output parameters for wave analyses

Output parameter
Max drag
RAO pitch
RAO Roll
RAO heave

As it will be fully discussed in deliverable D2.3, it is worthwhile to anticipate now that the analyses planned for this WP:

- do not include any sloshing effects for the H2 propulsion storage system: according to the literature review performed, hydrogen tank sloshing has internal consequences in the tank thermodynamic response, but it has not an effect on the stability of the vessel [8]. Instead, the whole made of the hull and of the fuel tank as a single rigid body is considered.
- will be carried out considering regular waves as input and eventually superimposing as post-processing procedure different regular wave contributions to infer irregular wave information's; being this kind of procedure a standard in sea keeping analysis.

The identification of these needs, although a great opportunity for growth for the virtual ship tank currently usable for analysis in calm water, also represents a technological and modelling challenge. As a matter of fact, to our knowledge no platform is currently available to perform automated and standardized calculations of hull dynamics including also wave motion. Moreover, if we evaluate the number of the variations of the new input parameters related to wave motion, we can easily understand how the cardinality of the problem tends to become rapidly explosive. In fact, if we consider a permutation of the new parameters involved in the analysis of interest, we understand how for a single hull, we can rapidly reach around hundreds of simulations. To get a more concrete preliminary evaluation of the required cardinality of the wave analysis problem we can fix some lower bound values for a single hull:

- Load conditions: 2 (full and ballast)
- Hull speed: 3 (zero velocity for fueling and bunkering; service cruise velocity, maximum velocity)

- Heading angle: 5; respectively: 0, 60, 90, 150 and 180 degrees.
- Wave period: 7.
- Wave amplitude: 2; min/max values.
- Total: 420 conditions to be analyzed

It is relevant to understand that managing such kind of numerical experiment is not feasible without modeling standardization and process automation and without the usage of HPC storage and computing systems. This is a central point for WP2 activities that motivate the necessity of using an HPC facility.
It is worthwhile also to specify that:

- hull zero-velocity condition with wave analysis will be used to investigate bunkering and fueling conditions;
- hull non-zero-velocity condition and heading at 0 degrees represent the standard wave analysis in the physical towing tank studies.

For these reasons, we will start considering these two specific conditions to be enabled into LincoSim, keeping the other wave requirements to be considered as the second step. Moreover, it is worthwhile to underline that high-fidelity methods are not always necessary to get data output of interest for all the given scenarios. In some conditions, also low-fidelity data output can be used to integrate the overall database ([9]).

5 Conclusions and Perspectives

As shown in the previous sections of this document, the towing tank is the elective experimental facility to perform an a-priory evaluation of hull performance and accurately define all design parameters. Nevertheless, costs and time to results remain an issue especially when early design stage or hypothesis testing type of investigations are involved. The availability of virtualization of such physical facility, the virtual towing tank, supports hull designers in a very effective way shrinking costs and time to result thus opening new opportunities. LincoSim, the virtual towing tank developed and fully validated within the LINCOLN project for calm waters analyses has been identified as a strategic tool also for the e-SHyIPS project where new directions for pre-normative and future normative parameter identification for naval architecture in presence of H2 based propulsion systems are one of the main targets. In the context of design support platform, potential benefits of the virtual towing tank include time/cost reduction, preliminary stages validation, concurrent engineering, and decision making.

As discussed above, although the architecture of LincoSim is potentially generic, the tool has so far been used only to calm water simulations analyses. The necessary data abstraction and standardization of input and output already present in LincoSim is driven by a set of parameters that are significant in the context of this particular type of simulation. The intent of adding new capabilities to LincoSim, accounting for instance for hydrostatic and stability analysis, and/or for analysis in presence of waves, is possible but it requires a concrete revisiting of some components in a non-trivial way. In particular, considering, for instance, simulations with waves, necessary to support the work of WP3 for risk assessment for the explosive nature of H2 systems, it would be necessary to extend the set of input data (e.g., the height of the wave and its period) and even the set of outputs to show to the end-user should be deeply modified. Extensions of this type require significant efforts, but they can clearly strengthen the potential of the platform in the direction of being useful for naval design in a wider sense thus involving a larger audience and potential end-users. For these reasons, the remaining part of T2.2 will be dedicated to this kind of activity.

As a closing remark to D2.2, we want to explicitly discuss the fact that the new extensions will be tested with the aim to support the requirements defined by D2.1 in terms of operational profile for each hull use case and in terms of re-design target to include H2 propulsion systems. Therefore, if some use-case has a re-design target defined as a substantial non-modification of the hull then LincoSim analyses will not be necessary. Similarly, if some of the identified operational profile is defined so that the presence of waves can be excluded, then LincoSim will be accordingly used only for calm water analysis. More general and complete CFD investigations for calm waters and waves will be finally performed only in presence of a substantial hull re-design under the condition of operational profile that will account also for the presence of waves.

Possible standardized strategies to integrate the virtual towing tank within the design process and consequent design choices will be studied in the next phase of the project and eventually used in agreement and collaboration with the project partners.

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