STATUS REPORT 4

December 15, 2023

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SEA

PREFACE AND CONTENTS

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Preface

This report summarises the work, both planned and executed, the results, and the findings so far in the project SEACo – Safer, Easier and more Accurate Co-simulations. This report is the fourth official status report in the project and will report on the news since the last status report.

The intention with these status reports is to inform the steering committee, as well as the advisory board, about the developments in the project. These status reports are classified as open documents and are freely distributable. The plan is to publish at least two status reports annually.

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OVERVIEW AND OUTLOOK

Project Metrics:

- KSP project
- September 2021 – June 2025
- 19.5 MNOK (5.6 MNOK to industry)
- **2023:** 6.2 MNOK
- 5 technical work packages
- International Advisory Board
- One Ph.D. candidate (NTNU)

Project Leader:

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Safer, Easier and more Accurate Co-Simulations

Project description

During the last few years, the maritime industry has started using co-simulation successfully to boost digital collaboration and innovation based on existing investments and knowledge. Still, several technical challenges remain, and collaboration is inhibited by tools that are often too complicated to use and not unified.

In the SEACo project, we aim to tackle these inhibitors of rapid digital innovation head on. We seek to contribute to more reliable and easier-to-use co-simulations of maritime systems by drawing on the knowledge and the skills acquired over the past decade. To ensure high interactivity and value creation, several key partners from academia and the industry are committed and eager to contribute: SINTEF, DNV, Kongsberg Maritime, Equinor, Aukra Maritime and NTNU.

The project consists of five technical work packages (WPs). A short presentation of each WP will be given in this status report.

Status

The OptiStress project, a sister project to SEACo, was started 1. August. This project is mainly centred around the topics of combining optimisation and system stress testing with co-simulations. The partners in this project are SINTEF Ålesund, SINTEF Ocean, NTNU, DNV, Hav Design, Norwegian Electric Systems and Corvus Energy.

The SECo project had a project workshop 5.–6. September in Ålesund. The topic for the workshop was partner relevance and contributions, and we had lots of discussions about the focused areas in the project. All partners agreed that the project is still quite relevant and addresses important key questions within the scope of co-simulations that are relevant in industrial applications. A list of models was also discussed for the use-case and each partner was given responsibility for specific model deliveries.

Figure 1.1: Workshop 5.-6. September in Ålesund.

A former SINTEF employee, Karl Gunnar Aarsæther, who is now working in University of Tromsø (UiT), is now employed in WP1 as a SINTEF resource. He will continue the work started by Karl-Johan Reite. Hence, the “hold” on WP1 is now lifted.

Magnus Steinstø, the project’s Ph.D. Candidate, who started May 1st, is well underway doing his mandatory subjects at NTNU. His Ph.D. topic will involve all work-packages in the project, but with a main focus on WP3-WP4, also introducing structural analysis and

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Figure 1.2: Open Simulation Platform (OSP) annual conference.

CFD simulations to the work-packages' problem formulations. We will involve him more in the research objectives in the rest of the project period when he has completed most of his mandatory Ph.D. work. As an example, a meeting with the Ph.D. candidate, his supervisors and WP1 is scheduled in December for discussing crane modelling.

The Open Simulation Platform (OSP) conference was held 14. November in Ålesund. The conference was hosted by GCE Blue Maritime and had about 60 attendees. GCE Blue Maritime are willing to also host the conference next year, along with help from the founding partners. Topics that were raised by the industry at the conference was the user-friendliness and availability of simulation models. Co-simulations should be simpler to use for the industry in order to be incorporated in the daily line of work. As of now, the OSP software is not as user friendly and there do not exist complete model libraries with generic models available for use, although some reference models can be downloaded from OSP's website. Hence, projects increasing the industry's modelling and simulation competence, making tools for rapid model prototyping and more user friendly tools for the end-user of co-simulations should be given more attention.

So far, the SEACo project has published one journal article named *"A distributed object-oriented simulator framework for marine power plants with weak power grids"* [1]. The SEACo project has promised 8 publications and 4 specifications in total before the project ends. The leader-team in the project has now started to focus more on the promised deliveries, but it is also expected that the Ph.D. candidate also will contribute. Despite this, the topics raised in the SECo project are important contributors for succeeding with introducing co-simulations in the maritime industry.

Outlook

The Christmas holidays are closing in and SEACo will mainly focus on planning the activities for 2024 before taking a break. The SEACo project has now finished its initial phase and it is both expected, and planned, that the project steps up its pace. We also have a job to do when it comes to increasing the involvement of all project partners as well as the advisory board. However, this involvement should now be initiated on a work-package level. We believe that close collaboration between research institutes and industry, both domestic and international, is crucial for the project outcomes.

IDENTICAL ENVIRONMENTAL CONDITIONS

Work Package Metrics:

- WP number 1
- 14.2% of total budget
- 905 000 NOK in 2023

WP Leader:

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Description

In this work package we will seek to standardise the description of environmental models for current, wind, and waves as used in most maritime co-simulation systems and develop a standardised co-simulation interface for each. Added focus is put on waves because of their higher complexity and fidelity. Transitions between sea states pose an additional challenge, as simply changing parameters causes abrupt changes in the sea state realisation.

For multiple models to share the same environment one typically can either share values (e.g. sharing the surface acceleration for given positions) or formulations (e.g. parameterised predefined models). These approaches have different pros and cons, such as the ability to include vessel-generated waves or estimating values between time steps. It is therefore possible that multiple sharing strategies should be available, to suit different use cases.

Another important issue is to what extent extensions to the standards can be proposed to facilitate more efficient environment sharing strategies.

Status

Progress in this work package has been slow due to an unforeseen personnel shortage. Early in the year, we continued the work from 2022 on choosing a way in which to compactly *specify* an environment, and a way to *realise* a specified environment in an unambiguous manner. What we mean by the latter is that if two or more subsystems are given the same environment description, they should all end up with the same values for variables like surface elevation, current velocity and so on at given points in space and time. We have made a prototype implementation of this in the form of a C++ library named *MarEnv*. The idea is that any model which wants to support "SEACo-conforming" environment sharing can call on this library. (To that end, the library will eventually be released as Free and Open Source Software.)

The environment description, the accompanying algorithms for realising the environment, and the *MarEnv* library interface must at minimum support all the use cases defined by the SEACo project. To that end, we've had one preliminary workshop with users internally in the project to gather initial feedback.

Progress of current activities

Planned
Actual

Identify models: Identify relevant environmental models through literature study and project group discussions. Document the identified environmental models, with pros and cons for use in co-simulation.

Investigate sharing strategies: Identify possible sharing principles and their pros and cons when applied to different scenar-

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ios and models, implement proofs of concepts, and document the most promising strategies.

Implement sharing: Implement the relevant environmental sharing strategies, for the purpose of testing their applicability for co-simulation and widespread use.

Plans for next period

The planned activities for the next period are to:

- gather more user feedback through workshops
- test the implementation in increasingly realistic cases
- improve the methods and implementation based on feedback and own testing
- implement an environment visualisation tool to aid debugging

COORDINATE SYSTEM TRANSFORMATIONS

Work Package Metrics:

- WP number 2
- 16.5% of total budget
- 1 200 000 NOK in 2023

WP Leader:

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Description

In this work package, we seek to establish a method for communicating and solving coordinate system representations between independent models reliably. The aim is to detect whether a given transformation can be safely performed outside the models when time lags cause no issues. In cases where this is not possible, the work packages seek to find the best method for performing the transformation without introducing significant inaccuracy.

Status

To map the challenges with coordinate transformations, interviews were performed internally in SINTEF Ocean. The results provided insight into the challenges related to coordinate system transformations, and it was found that simply mapping the relevant coordinate systems will not be sufficient to address these challenges. As a result, an in-depth study of the requirements and challenges associated with coordinate system transformations were presented which highlights the challenges and possible solutions related to static and dynamic coordinate system transformations.

To further evaluate the needs and requirements for static coordinate systems transformations, a realistic use-case was set up as illustrated in Figure 3.1. This use-case is a well known case in offshore wind turbine maintenance and the goal is to align the DP vessel and the crane/gangway perpendicularly towards the wind-turbine landing spot. This use-case consists of several different coordinate frames, representations and connections between the frames and is therefore effectively demonstrating the coordinate system transformation challenge. FMUs for DP vessel, crane/gangway and turbines have been developed and are ready to be connected through co-simulations.

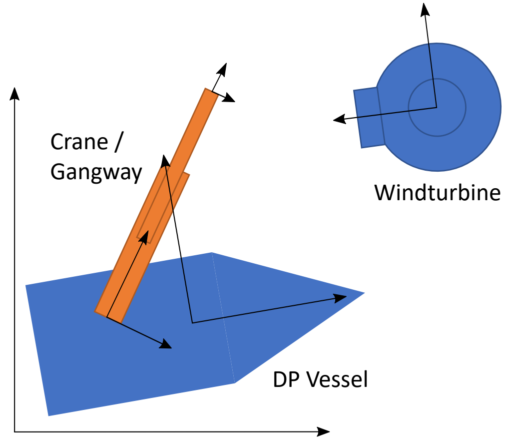

Figure 3.1: Overview of FMUs and coordinate frames in WP2 use-case.

In addition to the use-case shown in Figure 3.1, a simplistic one-dimensional use case is also presented with the aim to truly understand the basics of coordinate transformations. Several small informal workshops have been arranged to get insights to the topic from different users with different backgrounds.

Furthermore, it was found that a closer collaboration with WP3 was needed due to the connection between challenges related to dynamic coordinate system transformations and

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WP Leader:

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tightly coupled systems. The progress has been a bit behind plan, but activities will be ramped up in the coming period.

Progress of current activities

Planned
Actual

Setup static transformation use-case: Create a suitable use-case and solve it with automatic transformations.

Generalise static transformations: Based on the use-case, generalise the solution to make it more applicable.

Setup dynamic transformation use-case: Create a suitable use-case and solve it with automatic transformations.

Plans for next period

The focus for the next period will be to continue the research on static transformations through the use-cases. We will investigate different approaches to describe coordinate systems for FMU signals and to perform the transformations. The most promising option at the moment is to define all relevant reference frames, such as vectorial notations (Euler angles) or quaternions, specific reference frames such as North-East-Down (NED) or Earth Centred Inertial (ECI), and then require that all FMUs specify what type of frame they are using. The system connector can then use this information to connect all the FMUs correctly using predefined available transformations to setup the overall co-simulation.

We will then investigate how these static transformations can be done automatically in a co-simulation setting and formulate the necessary transformations mathematically. The expected outcome is a mapping of the metadata that must be associated with FMUs and their input or output signals to facilitate the automatic detection of coordinate system representations, and the determination for what transformation, if any, must be inserted. Moreover, we will start to investigate dynamic transformations in co-simulations. This topic is highly linked to WP3 and increased coordination with WP3 will help us identify challenges and possible solutions related to dynamic coordinate systems transformations.

MODULAR TIGHTLY COUPLED SYSTEMS

Work Package Metrics:

- WP number 3
- 22.9% of total budget
- 1 400 000 NOK in 2023

WP Leader:

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Description

There are several examples of interesting maritime systems that are *tightly coupled*, such as the connection between a ship's hull and its crane. Such systems are by nature poorly suited for co-simulation, and attempts to do so will usually be riddled with stability and performance issues. Still, the advantages of co-simulation are so many that it is worth investigating how to tackle these issues.

In this work package, we will perform a systematic study of tightly coupled maritime systems. We will examine the effects of different types of simulation techniques and algorithms and consider their suitability in a practical industrial setting. Based on the results, we will develop model interfaces to support modular modelling and co-simulation of tightly coupled systems.

Status

As in WP1, progress in this work package has been hampered by personnel shortage. We have continued studying the toy model shown in Figure 4.1, which was introduced as a highly simplified and idealised abstraction of a ship–crane system. We have tested three methods for resolving the tight coupling between the two masses in the model: 1) inserting a damped spring between the models, 2) using a low-pass filter with derivative effects, and 3) applying a PID controller.

In the process of the study, we ran across an interesting phenomenon which we spent

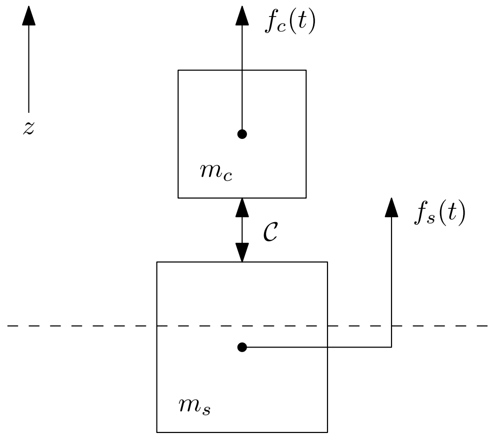

Figure 4.1: Toy model for the ship–crane system. The dashed line represents the "sea level".

some time investigating. We observed a case where a simulation with a fixed-step master algorithm produced a more correct result than the corresponding simulation with a variable-step algorithm that chose a smaller step size. In short, it turned out that errors which accumulated early in the simulation were "frozen in" when the variable-step algorithm abruptly switched to shorter steps. This is shown in Figure 4.2. We were able to identify the conditions under which this happens and which factors influence the magnitude of the error.

In the process, several bugs were found and fixed in the Copylot simulation sandbox, which will also benefit the main track of research in this WP.

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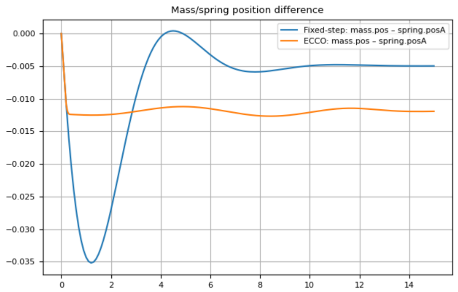

Figure 4.2: Difference between two states that are supposed to be equal in a co-simulation of a damped harmonic oscillator. Blue: fixed-step algorithm; orange: variable-step algorithm.

Progress of current activities

Planned
Actual

Model selected systems : Extending the 1DOF models with higher degrees of freedom.

Perform simulations and analyse results: The 1DOF models have been simulated and to some extent analysed. The work will be continued also incorporating the models with higher degrees of freedom in the study.

Plans for next period

We will continue to study the selected system and methods, also extending the study to involve models with higher dimensionality. The goal will be to understand the advantages, drawbacks, and trade-offs associated with each method in terms of accuracy, simulation speed, stability, and so on. If possible, the simulation results will be compared to analytic studies of the system. Specifically, we will investigate the relationship between *method parameters* (e.g. stiffness and damping), *system characteristics* (e.g. the relative mass and position of ship and crane), and *user requirements* (e.g. accuracy and speed).

MORE ACCURATE AND RELIABLE CO-SIMULATIONS

Work Package Metrics:

- WP number 4
- 21.3% of total budget
- 1 215 000 NOK in 2023

WP Leader:

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Description

The *energy-conservation-based co-simulation method* (ECCO) monitors the flow of energies between models, estimates co-simulation errors reliably, and chooses optimal co-simulation step sizes to control efficiency and accuracy. It poses no additional requirements on the models (such as re-stepping or interface derivatives) and can be used for any power bond connection between models. As such, it presents a promising choice for an easy-to-use and robust co-simulation algorithm. Here, we aim to extend the theory of energy-based co-simulation algorithms to make them more useful and more powerful.

Status

The solid progress in the first half of 2023 (literature review, WP4 workshop, ECCO libcosim implementation, further development of several manuscripts) leading up to the previous status report in June 2023, was followed by a calmer period for WP4 (references to the 2023 Work Plan in parenthesis):

Manuscripts A manuscript with the working title 'On error estimation and step size control in continuous-time co-simulation' that aims to provide practical guidance on how to estimate and control co-simulation errors is under preparation. Though it will require further work to get ready for publication, a lot of high-quality text and material has already be produced for it, and the path towards getting it publication-ready is well-defined.

Submissions Though not directly related to WP4, the manuscript *Higher-order semantics for Functional Mock-up Units* was submitted to the Springer journal *Software and Systems Modeling* just before summer and is currently still under review.

Notes So far, a lot of relevant and interesting work has been produces that has accumulated in many notes. It will still take some time to turn the material therein into manuscripts or specifications. However, in addition to the manuscripts already mentioned, enough results have been obtained for the work on stability and energy-conserving input corrections on one hand, and error estimation and the further development of ECCO, on the other hand, to produce at least two more WP4 manuscripts during the SEACo project period.

Deviations

Despite the progress made, there have been some deviations from the original Work Plan for 2023. Overall progress is still very satisfactory, but there have been significant changes in focus as the work in WP4 progressed: Work on the manuscript on 'Optimal step sizes per coupling' (multi-rate step size control) which was planned for 2023 is still on halt to get another manuscript ('On error estimation and step size control in continuous-time co-simulation')

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ready for publication. This work will be picked up after, however. In addition, we decided to forfeit the investigations into machine-learning and statistics-based approaches to step size optimisation and into energy-agnostic couplings in favour of the other activities, which we deem more relevant for the project and for publication.

Progress of current activities

Planned
Actual

Accuracy: Theoretical study of multi-rate (per coupling) approaches and validations (Task 2)

Stability: Testing different approaches to energy-conserving input corrections (Task 3)

Publication: Manuscript preparation Error Estimation (Milestone 1)

Publication: Manuscript preparation Multi-rate (Milestone 2)

Publication: Manuscript preparation Input Corrections (Milestone 3)

Plans for next period

For 2024, we have several key activities planned (references to the 2024 Work Plan in parenthesis):

libcosim We will continue with the libcosim implementation as the research progresses (Task 4). This will allow us to begin testing different multi-rate schemes (Task 2) as well as energy-conserving input corrections (Task 3).

Accuracy Our research on multi-rate step size control (Task 2) will continue, and we will relate it to existing ideas in the literature to identify potential areas for publication.

Stability We will continue our work on the manuscript about energy-conserving input corrections (Task 3).

Publications We plan to submit three manuscripts for publication in 2024: We will first finish *On Error Estimation and Step Size Control* (Milestone M1), then move on to get one on multi-rate step size control ready (Milestone M2), and finally one on energy-conserving input corrections (Milestone M3). In addition, we will try our best to make sure that the OSP-IS manuscript which is currently under review by *Software and Systems Modeling* will be published successfully.

TESTING AND VERIFICATION

Work Package Metrics:

- WP number 5
- 13.1% of total budget
- 40% of DNV budget used so far (10.2023)
- 900 000 NOK in 2024

WP Leader:

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Description

The assurance of complex systems and operations based on simulation models requires established trust in chosen simulation technologies. Here, we will develop and implement a case study for testing and demonstration of the methodology developed in WP1–WP4. We will also develop efficient methods for independent verification of the fitness of given component models and simulation configurations.

All the aforementioned work packages will provide input to a joint case study specified in this work package, e.g. a marine operation where a load is transferred between two floating platforms, one of which is a ship that carries the lifting crane. This case involves all the project's research areas, as it requires a shared sea environment for the floaters, multiple frames of reference (global, ship bodies, payload), and centres on a quintessential tightly coupled system (ship and crane), all of which pose a significant challenge to co-simulation stability and accuracy. To keep the required models manageable it is planned to implement minimal sub-models as a first stage. When these sub-models work satisfactorily they will be collected into the final use-case model.

Status

In 2022 a basic training on the DNV-RP-0513 'Assurance of Simulation Models' was provided, basic versions of the system conceptual model and the conceptual models of the most important component models were established. The SEACo project contributed also heavily in the OSP conferences of Nov. 2022 and Nov. 2023 (see the previous status report for details). During 2023 the following activities were performed:

Understanding and updating PythonFMU
Related to the initial OSP project a Python package PythonFMU was made and published (see PythonFMU). For both OSP research and OSP projects it is important to be able to construct FMUs "on the fly", where PythonFMU should be a suitable tool. In addition, SEACo wants to test how model assurance work might be done while developing a model, where Python seems to be a suitable starting point. FMUs contain their published (interface) information in the modelDescription.xml file. The information in this file is also needed for model assurance, but also additional information should be addressed and included (e.g. Risk Analysis information) in what we call the *Design Contract*.

Unfortunately the PythonFMU package is currently rather unsupported, as their makers have moved on. In SEACo we are currently providing updates like support for units, support for compound variables (vectors) and extensions with respect to assurance activities. These additional features are supported through the package *component_model*, which will be published as open source pack-

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age and as part of the SEACo project. Extended FMU building abstraction requires also additional changes to the PythonFMU package.

It will need to be decided how the new packages and updated packages are published.

pyCrane As decided in 2022, a crane FMU model has been designed for usage in the SEACo use cases and for permanent storage among the OSP basic models. A first attempt for designing the crane using symbolic computation and Lagrangians has turned out unsuccessful, as the model initialisation time grows exponentially with the number of crane booms and the required results which are to be reported back. A second approach using basic Newton Mechanics has proven successful. The crane model is developed based on the component_model package and packaged as FMU through PythonFMU. A first working version of the pyCrane FMU does now exist. More model testing will be performed through the rest of the year (crane on fixed support).

Progress of current activities

Planned
Actual

PythonFMU updates: This is ongoing work which is basically open-ended. For the SEACo project most issues should be resolved.

component_model development: This is ongoing work which is basically open-ended. For the SEACo project the so-far needed features are implemented.

pyCrane: The first FMU-packaged version of pyCrane exists. Publication towards the end of 2023.

Plans for next period

The following activities are planned for the first half of 2024:

Testing of crane model in connection with vessel When the crane model is mounted on flexible/moving base, most of the SEACo issues (see WP2 to WP4) kick in and need to be resolved. That is also the reason why the crane was chosen in the first place as a use case. We are planning to experiment with that problem and its solution in steps from mounting the crane on a vessel with simple movement to including the crane in the full system, including e.g. also advanced environmental effects. The solutions suggested in the other work packages will thus be tested, scrutinised and verified.

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Collaboration with Aukra Maritime As planned, the crane model shall also be used for industrial purposes. This will be tried out in collaboration with Aukra Maritime.

Follow-up of the other FMUs needed for the planned use case(s). The producers of the other FMUs have been appointed in the SEACo workshop September 2023. During the rest of 2023 meetings with all FMU vendors will be arranged with the goal to ensure that all FMUs become available during 2023, so that use cases can be constructed as test systems for all SEACo WPs. At least one system model (use case) description and a related test report should be available for each WP during the first half of 2024.

Link to the PhD project There is already established good contact with the PhD project. The crane and its related use cases are identified as good starting point in relation to the PhD project. As status meeting is planned for beginning of Dezember 2023 and will be followed up in 2024. Concrete tasks must be agreed upon, but it is expected that the crane model (within the use case), the overall use case model and assurance activities will play an important role. These will then be followed up within this work package.

Identification of efficient assurance methods For an assurance recommendation to have practical value, the employed methods must be efficient. There should never be doubt about the value the assurance activities add to a project. While this vision makes sense, it is hard to achieve in practice. As a continuous activity in the project we will add and test methods and tools which increase the efficiency of assurance methods. The ideas in this respect span from efficient/automatic testing to efficient model documentation. The assurance needs will put special focus on SEACo issues, as specified in the other work packages.

Identification of RP improvements The issues addressed in SEACo (see WP1-WP4) are important for co-simulation in general and especially of marine systems. DNV wishes to keep our RP-0513 updated with respect to important simulation issues. The updates should be twofold:

1. A checklist on how to identify SEACo issues in simulation models
2. A list of test methods to verify that the issues are properly addressed

Assistance in OSP implementations Assist in the implementation of dedicated algorithms for use in the SEACo project within OSP. This work has already begun and will be continued in 2024.

ACTIVITIES, COMMUNICATION, AND DISSEMINATION

This section lists all activities, communication and dissemination throughout the entire project period. Also, additional project information for the status report period, if any, is listed.

Additional resources:
SEACo project card
OptiStress project card
fmiCpp
OSP website
OSP conference 2022: Presentations
DNV-RP-0513
ViProMa website
Other publications
FhSim

Activities

2021

1. Sept.	Project start

2022

20. Jan.	Kick-off (online meeting)
7. Feb.	Advisory board meeting
3. Mars	Presentation of DNV-RP-0513
11. Mars	Steering committee meeting
22.-23. Sept.	Physical workshop in Trondheim, lunch-to-lunch-meeting
31. Oct.	Steering committee meeting
15. Nov.	Annual OSP conference, held in Ålesund, hosted by SINTEF Ålesund

2023

22. Feb.	WP4 workshop in Trondheim
5.-6. Sept	SEACo workshop in Ålesund
(**13. Nov.**	Kick-off in OptiStress, Ålesund.)
14. Nov.	Annual OSP conference, held in Ålesund, hosted by GCE Blue Maritime

Publications

2022

[1] Stian Skjong and Eilif Pedersen. "A distributed object-oriented simulator framework for marine power plants with weak power grids". In: *Journal of Marine Engineering & Technology* 0.0 (2022), pp. 1–13. DOI: 10.1080/20464177.2022.2120171. URL: https://doi.org/10.1080/20464177.2022.2120171.

Additional information

- Karl Gunnar Aarsæther (UiT), a former SINTEF employee, will contribute in WP1 from SINTEF's side.

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