STATUS REPORT 3

June 29, 2023

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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 third 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.

Contents

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

This year started with a physical workshop for WP3 and WP4, which was held in Trondheim in February, right before Lars T. Kyllingstad, the WP3 leader, went on parental leave. Stian has taken on the responsibilities for WP3 in the meantime, before Lars returns in August.

Also, an application for a supporting project named *OptiStress* was sent in in the middle of February. The project got funded with expected project start August 1st. The OptiStress project proposal is mainly centred around the topics of combining optimisation and system stress testing with co-simulations.

Moreover, WP1 is currently on hold from SINTEF Ocean's side due to a sick leave, but different actions will be discussed after summer in order to speed up the progression.

Magnus Steinstø, the project's Ph.D. Candidate, started May 1st. He has previously been working in DNV and, hence, been involved in the SEACo project, mainly in WP5 developing a crane model. However, 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 CFD simulations to the work-packages' problem formulations. Although he will be working with the topics in the project, an initial delay is expected due to required classes and credits.

The C++ modelling framework *fmiCpp* has gained more attention, and a group of researchers in Åbo Akademi University have started using it as a co-simulation modelling framework, along with the Open Simulation Platform simulation master algorithm. Also some of the project partners have started experimenting with the framework as well.

The research centre SFI MOVE[1] had its final conference in the end of May, marking a project period of 8 years coming to an end. A project named *Onboard Decision Support System* (ODSS) has been closely connected to the SEACo project using co-simulation for observation and prediction purposes alongside operations onboard offshore vessels. In the final

[1] https://www.ntnu.edu/move

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SEACo

Safer, Easier and more Accurate Co-Simulations

Figure 1.1: Presentation of AMADEA at the final SFI MOVE conference.

conference, Stian presented the final results from the ODSS project, a software architecture for ODSS named *AMADEA - Adaptable Maritime Decision Support Architecture*.

The project leader, Stian, left SINTEF Ocean for a new position in SINTEF Ålesund June 1th. However, he is still taking on the responsibility as project leader, and the change in position is not expected to affect the project in any negative direction.

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], and two more publication are in the pipeline. The first one treats the topic of variable time step size control in co-simulation master algorithms (WP4). The second one is continued in SEACo but initially started on in *DTYard*[2] and describes the development of OSP-IS. The latter is ready for submission to a relevant journal. There is also work in progress in WP3 which is expected to result in at least one manuscript, and activities in WP4 have resulted in yet another manuscript that could be made ready for publication in 2023/24.

Another SEACo autumn workshop is in the planning stage. This workshop will focus on bridging the work-package topics, and will be structured in parallel group work sessions. Also, the SEACo project team hope that another Open Simulation Platform conference will be planned and hosted this year, and hence will be contributing to its realisation. However, to make it happen, other financing sources than SEACo must take the main costs, both in planning hours and in direct costs. More information about OSP and possible conference dates can be found on the OSP website.

[2] *Digital Twin Yard - An ecosystem for maritime models and digital twin simulation* (2019–2022), also funded by the Research Council of Norway (grant no. 295918) and industry partners.

Outlook

The summer holidays are closing in and SEACo will mainly focus on planning the rest of this year's activities before taking a break. The SEACo project has now finished its initial phase and it is both expected, and planned, that the project will step up its pace.

For the rest of 2023 we plan to involve the industry partners and the advisory board more than before. 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

The initial objective of WP1 has been to establish the short and long term requirements of potential users, as well as exploring various methods and concepts for meeting these requirements. A central task has been to establish and consider various concepts for sharing a common environment. Last year, a preliminary plan for the work package was laid out. In short, this included:

- Sharing environment information between FMUs using the FMU port system, specifically using string ports and serialisation.
- Creating a development environment facilitating visualisation and co-simulation testing.
- Creating a publicly available library which implements predefined methods which an FMU can use for realisation of environment processes also between macro time steps.

Implementation of the public library, preliminary named *MarEnv*, as well as the development environment was started last year and is planned to continue this year.

Progress of current activities

The research activities in this work-package was planned to be continued in the autumn this year, mostly due to the start-up of the project's Ph.D. candidate and coordination of resources in other ongoing projects. The tasks, as well as the progression in this work-package are therefore unchanged in comparison to the previous status report. Due to an unexpected lack of resources (man hours) in SINTEF this spring a contingency plan is under development in order to stay on track with the research tasks at hand after the summer.

IDENTICAL ENVIRONMENTAL CONDITIONS

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SEA

Safer, Easier and more Accurate Co-Simulations

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 scenarios 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

First, we will finish the contingency plan for keeping the progress of this work-package on track. Resources in SINTEF Ocean have been allocated from the autumn on to boost the research activities in the work-package. Moreover, Lars will be back from maternity leave, and will, in addition to leading WP3, support and contribute in WP1 where needed. Furthermore, in the scope of research activities, we will continue to focus on establishing proofs of concepts. This will enable us to test and iterate on the principles for sharing environment information between FMUs in a co-simulation. It will also be beneficial for implementing the resources we aim to provide for model developers to facilitate their adherence to the developed standards. To facilitate easier debugging, and as a possible result in its own right, we will, as earlier planned, implement an environment visualisation tool. This will enable us to visualise both environment aspects (waves, winds, currents) and how multiple FMUs simultaneously reacts in this environment. We will implement the developed methods for sea state realisation into this, and develop methods for sharing information about ocean currents and bathymetry. We will also start the work on methods for realistic and synchronously transitioning between sea states.

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). And, if not, to find the best method for performing the transformation without introducing significant inaccuracy.

Status

Initially, the work in WP2 focused on mapping the most common system boundaries (interface signals) and their most common coordinate system representations. This mapping was envisioned to be conducted via structured interviews with relevant actors. Interview questions were developed and tested 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. The results of the preliminary interviews lead to an in-depth study of the requirements and challenges associated with coordinate system transformations. The work has, therefore, focused on identifying 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 perpendicular towards the wind-turbine landing spot. This use-case will 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 wind turbines have been developed and are ready to be connected through a co-simulation.

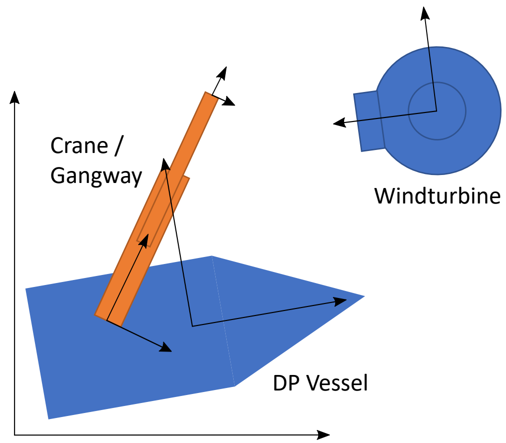

Figure 3.1: Overview of FMUs and coordinate frames in WP2 use-case.

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

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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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.

Plans for next period

The focus for the next period will be to continue the research on static transformations through the use-case. We will investigate different approaches to describe coordinate systems for FMU signals and to perform the transformations. One option is to choose 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 to set one FMU's coordinate system as a master that all other coordinate systems must be transformed into. This approach requires a method for choosing an appropriate master coordinate system, which could be solved via establishing some hierarchy of coordinate systems. Another option is to identify a global coordinate system and require that all subsystems transform their signals into this coordinate system. For each type of data exchanged there would then be a generic transformation between two coordinate systems.

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. At the end of the next period, 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 and exhaustive 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

Last year, we selected, based on a "mind mapping" excersise during the SEACo workshop, a ship-crane system for our methodological study of how to solve tight model couplings in co-simulations. As a starting point we formulated a model of it which was highly abstracted and idealised—just two point masses moving in one dimension as shown in Figure 4.1—but which captured the essential internal dynamics and external drivers to a sufficient degree. Nevertheless, the system of simplified models still was able to represent the problem that the ship and crane both have the same causality,

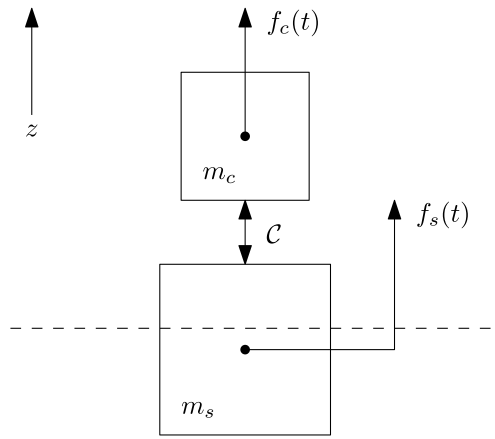

Figure 4.1: Toy model for the ship–crane system. The dashed line represents the "sea level".

and hence, are not directly connectable in a co-simulation setup. That is, in the "default implementation" both models expect a force as input and return the resulting motions as output, and are therefore incompatible.

We also selected a number of methods for resolving this implicit model coupling: 1) inserting a damped spring between the models, 2) using a low-pass filter with derivative effects and 3) a PID controller, to fix causality issues. These three methods were implemented and compared to each other and to a baseline monolithic implementation, as seen in Figure 4.2. Note that the first two methods are quite similar. Originally, also a fourth method was planned, namely implementing Baumgarte stabilisation. Nevertheless, this idea was put on hold because it required much informa-

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Work Package Metrics:

- WP number 3
- 22.9% of total budget
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WP Leader:

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S(E)(A)

Safer, Easier and more Accurate Co-Simulations

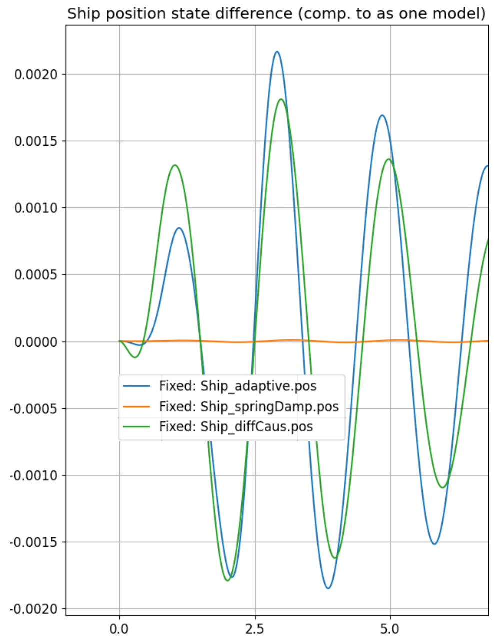

Figure 4.2: Simulation results showing a comparison of the ship position state based on a toy model of the ship–crane system and a monolithic approach.

tion about the models themselves, which contradicts the black-box principle. An example of Baumgarte stabilisation for lumped cable models can be found here for reference.

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 degrees of freedom. 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

Since the last status report in December 2022, we have made significant progress (references to the 2023 Work Plan in parenthesis):

Literature We have completed the literature review on master algorithms (works related to ECCO and multi-rate step size control), which was a pending task from 2022. This has provided us with a comprehensive understanding of the current state of the field and has informed our ongoing work.

Workshop In February, we held a technical workshop on ECCO in Trondheim (Subtask 1.1 and 2.1), where we worked in groups on multi-rate scheduling (accuracy) and energy-conserving input corrections (stability) and continued our work on the ECCO libcosim implementation with DNV (Task 4).

libcosim Specifically, we implemented and validated (single-rate) ECCO with the quarter car benchmark case (Milestone 4.1) during the workshop.

Stability A significant amount of work has been done on energy-conserving input corrections to improve co-simulation stability (and, secondarily, accuracy which is preferably controlled via step size). We have tried many different approaches to this problem (which is underdetermined), several of which gave promising preliminary results.

Manuscripts We have continued to update our technical notes to document the work and as a basis for future publications.

Deviations

Despite the progress made, there have been some deviations from the original Work Plan for 2023: Quite some time went into finishing a manuscript describing previous work not directly related to WP4 on the Open Simulation Interface Specification (OSP-IS) and identifying potential journals for publication. This delayed the work on the manuscript on "Optimal step sizes per coupling" (multi-rate step size control) which is planned for 2023 (Milestone 1.1). However, the OSP-IS manuscript does count towards the SEACo publication tally, if published. In addition, we decided to halt

SEA

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Work Package Metrics:

- WP number 4
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WP Leader:

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the investigations into machine-learning and statistics-based approaches to step size optimisation (Task 2) and into energy-agnostic couplings (Task 3) in favour of the other activities, which we deemed more relevant for the time being.

Progress of current activities

Planned
Actual

libcosim: Implement ECCO with the quarter car benchmark case (Task 4)

Accuracy: Theoretical study of multi-rate (per coupling) approaches and validations (Task 1)

Stability: Testing different approaches to energy-conserving input corrections

Publications: Manuscript preparation (Milestone 1.1)

Plans for next period

For the rest of 2023, we have several key activities planned (references to the 2023 Work Plan in parenthesis):

libcosim We will continue with the libcosim implementation, specifically focusing on the Quarter Truck test case and validation (Task 4). This will allow us to begin testing different multi-rate schemes (Task 1).

Accuracy Our research on multi-rate step size control (Task 1) 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 correction.

Publications We plan to submit at least one manuscript for publication in 2023. This will either be on multi-rate step size control (Milestone M1.1) or on energy-conserving input corrections for which much material has already been collected. In addition, the OSP-IS manuscript for which we already received positive feedback from *Software and Systems Modeling* will soon be submitted.

TESTING AND VERIFICATION

Work Package Metrics:

- WP number 5
- 13.1% of total budget
- 835 000 NOK in 2023

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.

Status

As of 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 conference of Nov. 2022 (see the previous status report for details). During 2023 the following activities were performed:

Understanding and updating PythonFMU Related to the 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. It will need to be decided how this can lead to an update of the official package.

Crane FMU 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

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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 as such works now. It remains to package the the model into an FMU and then try it out together with other components in the SEACo use case(s). Hopefully the packaging will be concluded during the coming weeks.

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.

Crane FMU: As stated, only the FMU packaging remains including the packaging of improvements like including units and ranges in the FMU.

Plans for next period

The following activities are planned for the second part of 2023:

Testing of crane model in use case 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.

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). So far the producers of the other FMUs are only loosely appointed, no delivery dates are specified and the planned assurance activities are unclear. This need to be clarified between the project participants. DNV can then, together with SINTEF, be responsible to follow up on these activities. It is important that the project gets a working system model in place as soon as possible.

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Link to the PhD project where relevant The project has now appointed a PhD candidate and he is currently in his initial phase. During autumn it is expected that he will take part more actively in the SEACo project. Concrete tasks must be agreed upon, but it is expected that the crane model (within the use case), the use case model as such 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 2023.

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
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

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

- Lars T. Kyllingstad will be back from parental leave in August.

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