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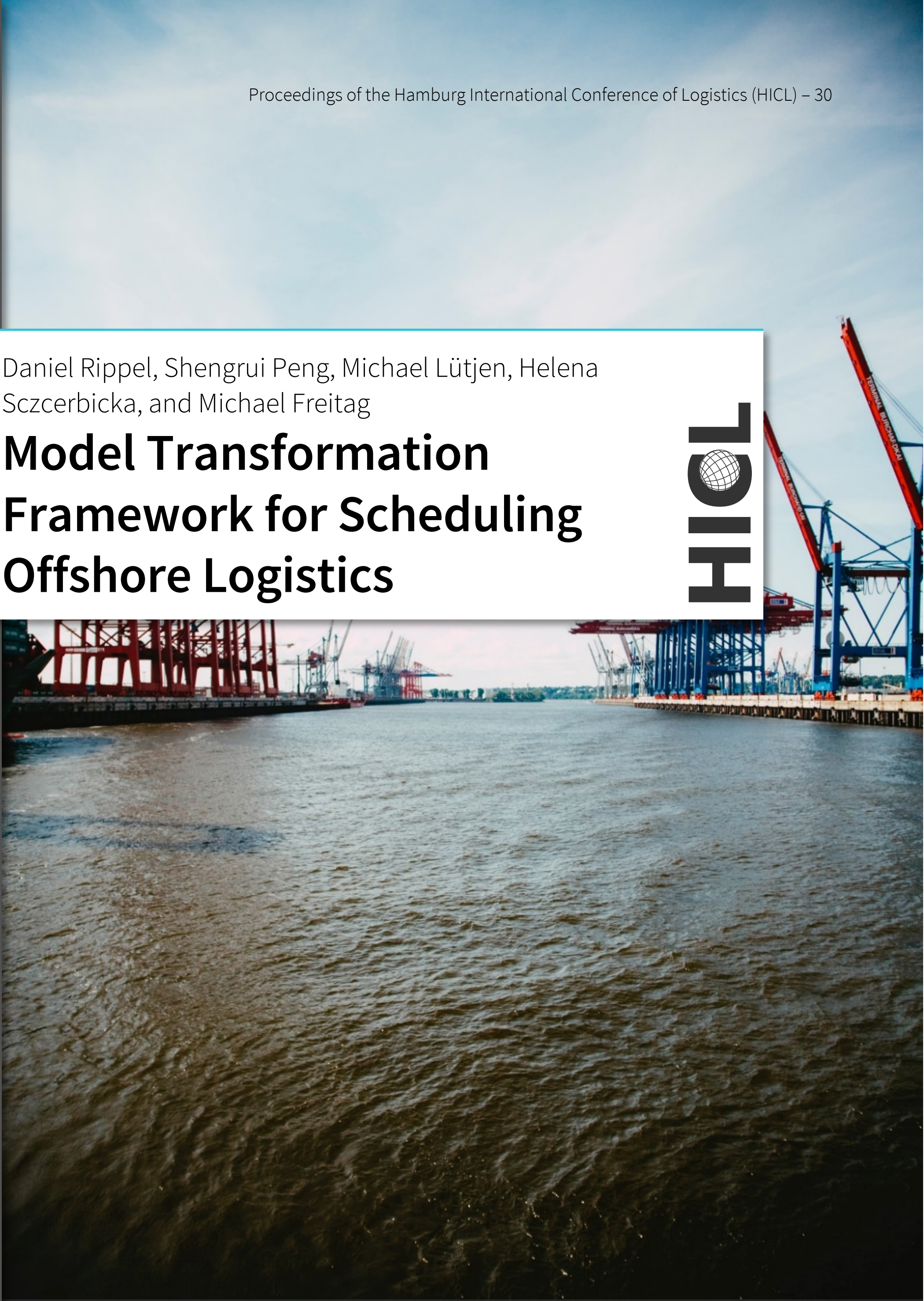

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Model Transformation Framework for Scheduling Offshore Logistics

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Purpose: Wind energy is a promising technology to produce sustainable energy. While higher wind speeds at sea result in higher energy production, they also impede the installation of wind farms. Several authors proposed optimization- or simulation-based scheduling models. This article provides a framework to instantiate different models and discusses their advantages and disadvantages using selected models from the literature.

Methodology: Building upon previous research, which deducted a common meta-model by analyzing current literature, the framework realizes this model using the OMG's Essential Meta-Object Facility Standard. Moreover, the framework uses the OMG's Model To Text Transformation Language for transformations to different models found in the literature and from previous work, to evaluate their behavior given the same base-scenario.

Findings: The results show that the proposed framework achieves an instantiation of different model types, i.e., a mathematical optimization, a multi-agent simulation, and a Petri-Nets-based simulation. The discussion highlights the advantages of these types regarding speed, optimality, and flexibility. As the primary advantage, this framework allows investigating the installation on varying levels, focusing on local resources, processes, or the global system.

Originality: This research aims to operationalize a common meta-model and model transformations between different model formulations by applying well-established standards to realize a basis for using these models during the planning and scheduling of offshore activities. To the authors' best knowledge, no comparable work on the integration of different modeling techniques in the area of offshore logistics exists.

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1 Introduction

Offshore wind energy has evolved into one of the most promising technologies in producing green and sustainable energy, which has already reached a high level of technological maturity (Dolores, et al., 2010). The last decade shows a close to an exponential increase in the amount of energy generated by wind farms world-wide (REN21, 2018). While higher wind speeds at sea result in higher energy production (Breton and Moe, 2009), they also impede crane operations during the installation of such offshore wind farms. Nevertheless, during the first half of 2019, Germany installed over 1350 new offshore turbines with a total capacity of 6.6 GW. Moreover, Germany plans to construct several additional offshore wind farms over the next decade, with an increasing number of turbines and capacity (Deutsche WindGuard GmbH, 2019). This trend, in combination with upcoming projects for the decommissioning of old wind farms (Beinke, et al., 2020), and a continuous increase in the size and weight of turbine components requires enhanced approaches for the planning and scheduling of such projects to avoid high costs and resource shortages, e.g., at the base-ports (Oelker, et al., 2020). Concurrent literature attributes between 15% and 30% of the lifetime costs of an offshore wind farm to logistics during the construction (Lange, Rinne and Haasis, 2012; Dewan, Asgarpour and Savenije, 2015; Muhabie, et al., 2018). As installation vessels contribute one of the highest cost factors, with charter costs of up to 145.000,00€ per day in 2014 (Meyer, 2014), several authors proposed optimization- or simulation-based scheduling models to increase these vessels' efficiency. Thereby, different types of models, e.g., mathematical optimization models or discrete-event simulation models, focus at different aspects of the planning problem, e.g., determining optimal schedules, fleet mixes or start dates.

This article presents a framework for model transformations that aims to instantiate different models from a common base-scenario. In consequence, process planners can apply different models and use their distinct advantages during the planning, without the need to define their scenario for each model seperately. This article follows the hypothesis that model transformation can achieve interoperability between these models and that different executable models provide distinct advantages in terms of their optimality, speed, and flexibility. After presenting the general process of installing offshore wind farms, this article presents an overview of existing models and approaches in concurrent literature. Afterward, this article provides the framework using methods and standards from the Object Management Group’s (OMG) Model Driven Architecture. After defining the framework, this article verifies the above assumption, by instantiating several different models found in the literature and from previous work, i.e., one Petri-Net based simulation model (Peng, Becker and Szczerbicka, 2020), one multi-agent simulation model adapted from (Ait Alla, et al., 2017; Oelker, et al., 2018) and one mathematical optimization model (Rippel, et al., 2019b). Afterward, the article presents the evaluation of these models’ behaviors given the same base-scenario to evaluate if the use of different models actually provides the noted advantages. Finally, the article closes with a discussion of the different models and a conclusion on the general framework.

2 Installation of Offshore Wind Farms

The literature differentiates between several concepts for the installation of offshore wind farms. All of these concepts assume the same supply chain but differ in how components are supplied to the construction site. Thereby, all concepts assume that components are manufactured at their respective production ports. In the conventional (Figure 1) concept, heavy-lift vessels then transport the components to a base port, see, e.g., in (Vis and Ursavas, 2016; Quandt, et al., 2017; Rippel, et al., 2019d). Feeder-based concepts assume a direct delivery of components to the installation site using so-called feeder vessels (Ait Alla, et al., 2017; Oelker, et al., 2018). Preassembly concepts additionally assume a partial assembly of components before they are picked up by the installation vessel at the base port. These so-called jack-up vessels perform the actual installation of the turbines in all concepts. These vessels use retractable pillars to mount themselves unto the seabed, raising themselves out of the water. This capability allows mitigating the influence of rough sea conditions, i.e., of wave height restrictions on installation operations.

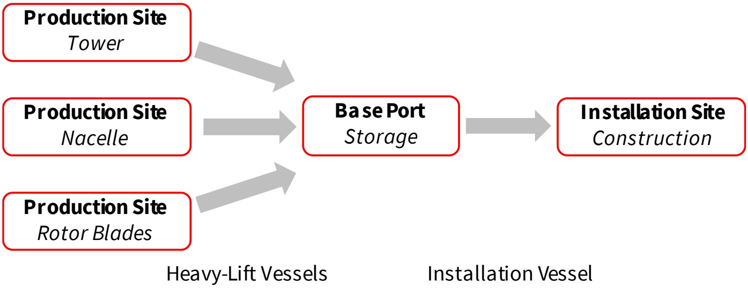


Figure 1: Conventional Installation Concept after (Rippel, et al., 2019b)

The installation of turbines consists of three phases (Vis and Ursavas, 2016; Quandt, et al., 2017). The first and the second phase often take place in different years, as each year only offers some months with reliably stable weather conditions. The first phase comprises the installation of foundations and the infrastructure to connect them to the energy grid. The second phase includes the installation of the turbines. Therefore, installation vessels, equipped with cranes that allow operating in over a hundred-meter height, assemble the tower, nacelle, and blades of each turbine successively. While jacking-up stabilizes the installation vessel and mitigates most of the operations' wave height restrictions, the massive size and weight of the turbines still results in restrictions regarding high wind speeds. Finally, the third phase comprises the commissioning and ramp-up of the wind farm, requiring teams of highly trained and certified technicians.

On the one hand, the installation of wind farms uses highly specialized vessels. In 2014, these vessels had charter costs of up to 145,000€ a day (Meyer, 2014), showing the need to plan and schedule operations efficiently. On the other hand, the process indicates that weather conditions limit the feasibility of offshore operations. While literature shows several different limits (Rippel, et al., 2019a), Table lists the limits used in this article following, e.g., (Oelker, et al., 2018). If, at any time, weather conditions exceed these limits, the installation vessel cannot start an operation or, if it has already started one, it has to abort the operation and restart it later. As a result of these limits and the long duration of operations, the installation process itself highly depends on viable weather forecasts.

Table 1: Duration and limits for offshore operations (Oelker, et al., 2018).

Operation	Base Duration (h)	Max. Wind (m/s)	Max. Wave (m)
Traveling	4	21	2.5
Reposition	1	14	2
Jack-up/-down	2	14	1.8
Load Tower	3	12	5
Load Nacelle	2	12	5
Load Blade	2	10	5
Load Hub	1	12	5
Install Tower	3	12	2.5
Install Nacelle	3	12	2.5
Install Blade	2	10	2.5
Install Hub	2	12	2.5

3 Literature Review - Approaches and Models for the Installation Scheduling

The dependence on weather conditions also reflects in the state of the art in planning and scheduling the installation of offshore wind farms. Vis and Ursavas (2016) state that there exist only a few published research articles on the installation of offshore wind farms compared to other areas like maintenance. Nevertheless, authors have proposed several approaches for the simulation and scheduling of offshore operations. These approaches differ in their modeling technique, aim, and granularity. The remainder of this section presents a short literature review on existing approaches. Thereby, it focusses on the different modeling techniques used to represent the installation process.

Simulation-based models generally focus on the evaluation of specific assumptions or configurations. Muhabie, et al. (2018) present a simulation model to compare the effects of deterministic and stochastic assumptions for weather conditions. Vis and Ursavas (2016) present a simulation study investigating the effects of different preassembly strategies on the overall project efficiency. Ait Alla, et al. (2017) present a multi-agent simulation, implemented in AnyLogic, to compare the efficiency of the conventional and a feeder-based installation concept, further extending the simulation study in Oelker, et al. (2018). Apart from these vessel-centric models, Oelker, et al. (2020) present a simulation study using AnyLogic, which regards available resources inside the base port of Eemshaven in detail. This study highlights that current trends towards an increasing size and weight of components and in the number of concurrent installation projects could lead to shortages in storage space and handling equipment at the base ports. Similarly, Beinke, et al. (2020) present a simulation study that shows a strong increase in the demand for installation vessels over the next years, due to an increasing number of offshore installation and decommissioning projects.

In the literature, two kinds of mathematical models can be found: The majority of models aim at the scheduling of offshore operations at different levels of abstraction. Several other models aim, like the presented simulation models, to assess the efficiency or costs of specific configurations or assumptions. In the context of the later models, for example, Beinke, Ait Alla and Freitag (2017) present a formulation to assess the impact of sharing heavy-lift vessels between several offshore installation projects. Quandt, et al. (2017) present a formulation to evaluate the impact of advanced information sharing between a project's stakeholders. In a mixed fashion, Kerkhove and Vanhoucke (2017) present a scheduling model to determine when additional installation vessels should be deployed or decommissioned based on the workload and assumed weather conditions. Scholz-Reiter, et al. (2010) presents a multi-periodic scheduling formulation to obtain optimized schedules with a daily resolution. To allow this formulation to handle larger scenarios, the authors extended the approach by an additional solution heuristic in Scholz-Reiter, et al. (2011). Ursavas (2017) lately modified the same model and extended it to handle probabilistic weather assumptions. Ait Alla, Quandt and Lütjen (2013) present a time-indexed job-shop formulation for the planning of offshore installations. This model does not provide a detailed schedule but defines how many foundations or top-structures (turbines) can be constructed within a sequence of 12-hour windows, depending on current weather conditions. Irawan, Wall and Jones

(2017) present another Mixed-Integer formulation for the bi-objective optimization of installation projects, aiming to determine an optimized tradeoff between minimal costs and project durations. In more current literature, they modified their model for the decommissioning of old wind farms (Irawan, Wall and Jones, 2019). All of the presented models include weather conditions on a quite abstract level, i.e., in terms of weather classes (good, medium, bad) that are known to the model in advance. In contrast, Rippel, et al. (2019d) propose an approach, which uses a receding horizon technique and a Mixed-Integer formulation to provide optimal schedules based on short-term weather forecasts using an hourly resolution. The authors later extended this approach to include port-side resources as well (Rippel, et al., 2019b). Comparably, Peng, Becker and Szczerbicka (2020) propose a simulation model using Generalized Stochastic Petri Nets and hourly historical weather records to obtain scheduling decisions.

The presented literature review shows that several authors proposed a variety of models and approaches for the planning, scheduling, or evaluation of offshore installation projects. Each of these models and simulations focuses on different aspects of or provides another level of abstraction from the same baseline installation process. The application of different models provides project planners with highly specialized models and tools to evaluate and plan specific aspects of their project. Unfortunately, planners then need to implement and work with various different formulations. Consequently, the next section presents a framework for model transformations, which, in its current state, is capable of generating instances of the same scenario for different formulations, allowing project planners access to a variety of formulations. Thus, this framework provides a simplified way to use different models for the planning of different aspects, e.g., starting dates, project schedules, or capacity requirements. Moreover, different models apply a variety of ways to estimate the influence of weather dynamics, allowing project planners to evaluate their plans under different assumptions.

4 Framework for Model-Interoperability

The framework presented in this article consists of three main components. First, the underlying domain model. This model aggregates the required information for offshore wind farm installation projects. Second, a set of model transformations to generate executable models and, finally, a user interface to edit and specify the desired installation project. This article presents a prototypical JAVA implementation of this framework, using the Eclipse Rich Client Platform (RCP). This platform allows to implement and deploy code-fragments as plug-ins, which guarantees an easy to extend framework and provides access to a multitude of already available plug-ins under open-source licenses.

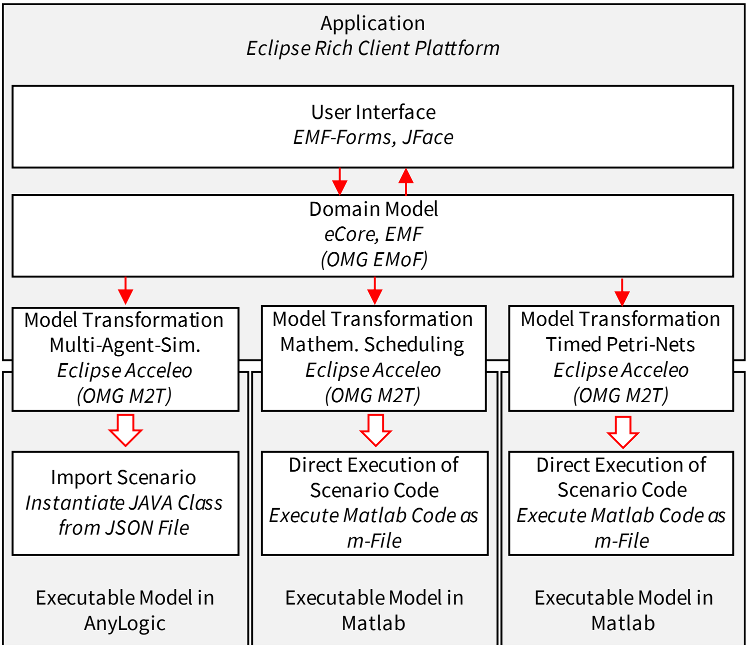


Figure 2: Conceptual design of the framework (top) and the integration with the selected use-cases (bottom)

Figure 2 shows a schematic of the framework's components and its interconnection with selected simulation and scheduling models. Therefore, the gray blocks denote stand-alone applications, i.e., the prototypical implementation of the framework and the respective simulation/optimization tools. The white boxes represent modules, either of the framework (top) or of the respective target model. The figure shows that some of the models need extensions to enable an import of the generated scenarios. For example, the AnyLogic multi-agent model requires an additional class to provide an initial configuration to the scenario, as the original model relied on manual modifications. Besides, Figure 2 indicates the used Plug-ins and Standards in italics for each module.

4.1 Domain Model

The prototype uses a modified version of the domain model proposed by Rippel, et al. (2019c) implemented using Eclipse eCore and the Eclipse Modelling Framework (EMF).eCore thereby represents an implementation of the Object Management Group's Essential Meta-Object Facility (eMoF), while EMF provides capabilities for code generation using an eCore model. The generated code allows managing, loading, and saving of model instances. Additionally, it provides several so-called adapters to simplify the implementation of user interfaces to work with these model instances. Figure 3 presents a simplified overview of the used eCore model. The diagram shows all entities and their interconnections but avoids to show their attributes for the sake of readability. The exported model in Figure 3 also follows the notation of UML Class Diagrams.

The class Scenario constitutes the domain model's central element and acts as a kind of database. Therefore, it contains and manages all other elements, like vessels or operations that project planners could use in specific projects. eCore (Figure 3) shows such containment relations using UML-Compositions. Besides its database of available elements, the Scenario class uses stored BaseOperations to construct process chains for the three main activities: Movement, Loading of Components, and Installation. Depending on the focus of the scenario, e.g., the process chain for installations could include operations required to install foundations or operations required to install top-structures or both. While this article only focusses on the installation of top-structures, this definition of process chains allows more flexibility.

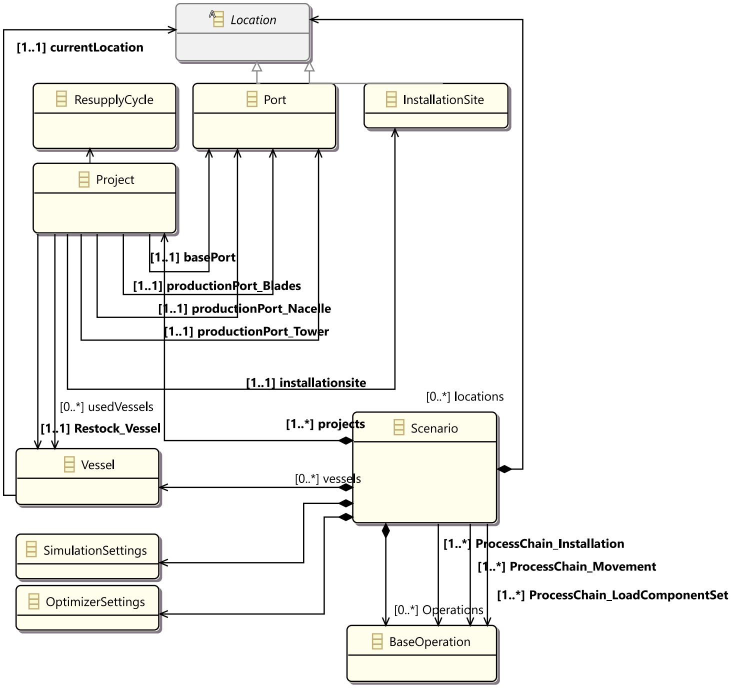


Figure 3: Simplified representation of the implemented eCore domain model as UML-Class Diagram

The following list describes the purpose and information contained for each of the other classes:

BaseOperations represent singular tasks an installation vessel needs to perform. Next to the operations name, this class consists of the operation's minimal duration and its weather restrictions. Thus, it more or less provides the information also given in Table.

Projects represent specific simulation or optimization experiments. Next to containing attributes to specify the project's starting and current dates, they also collect all information on the current state of the project, e.g., how many turbines the wind farm will have and how many already finished. Projects also specify the geographical layout and select vessels from the scenarios database actually to employ in the current scenario. Figure 3 depicts such selections as simple associations.

Locations describe geographical locations relevant to the installation project. Each location provides its longitude and latitude. Moreover, Ports contain attributes to define which resources the installation can access, e.g., the number of loading bays, or storage capacities.

Vessels accumulate all information regarding a specific vessel, e.g., its costs, movement speed, storage capacities, and its current state and cargo. Therefore, the domain model uses the same base class installation and heavy-lift vessels.

Resupply Cycles describe different routes for the resupply of the base port. On the one hand, these specify the order of visited production ports and the duration of loading operations. On the other hand, they also provide operations to calculate average cycle times and resupply amounts per cycle.

Settings aggregate additional settings for specific models. For example, these allow customizing the optimization model's time limits, the decision strategies used in the multi-agent simulation, or the time progression in the Petri-Nets simulation.

Compared to the original domain model, this adapted version does not explicitly include schedules and workforce. None of the targeted models includes workforce and, thus, this domain model also omits it in its current state.

4.2 Transformations

The proposed framework expects all targeted simulation/optimization models to either accept their inputs or entirely consist of text files, e.g., source code, JSON, or XML. This holds for most nonproprietary tools. Consequently, the framework proposes to apply the Open Management Groups Model-To-Text (M2T) standard. The M2T standard relies on providing templates of generated text files for eMoF objects, e.g., for EMF objects of the class project, scenario, or vessel. shows a small excerpt of such a template, which generates Matlab code using EMF objects for the project, scenario, and operations.

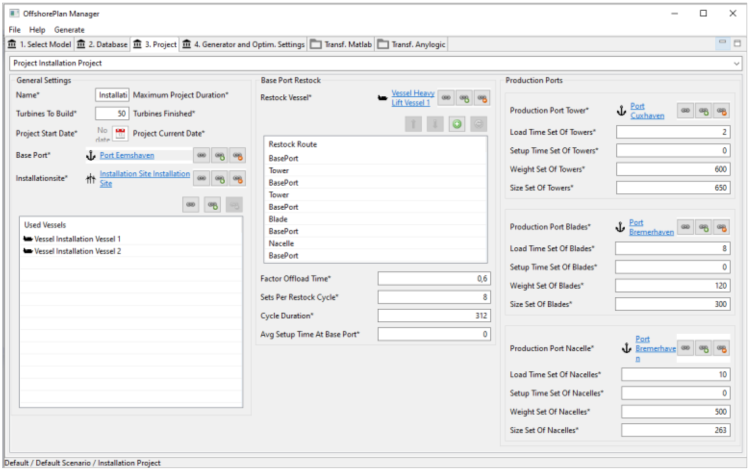
```
%%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% %%%%%                    SCENARIO DATA                           %%%%%
%%% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

scenario.targetPlanTime =    [proj.maximumProjectDuration /];
scenario.OWTsToBuild =   [proj.turbinesToBuild /];

%%% %%%%% Process data %%%%%
[for (op : BaseOperation | scen.Operations ) before ('scenario.opName      = ['  )
                    separator (',\t') after ('];' )]"[op.name /]"[/for]
[for (op : BaseOperation | scen.Operations ) before ('scenario.opData(1,:) = ['  )
                    separator (',\t\t') after ('];' )][op.baseDuration /][/for]
[for (op : BaseOperation | scen.Operations ) before ('scenario.opData(2,:) = ['  )
                    separator (',\t') after ('];' )][op.maxWindSpeed /][/for]
[for (op : BaseOperation | scen.Operations ) before ('scenario.opData(3,:) = ['  )
                    separator (',\t') after ('];' )][op.maxWaveHeight /][/for]
```

Figure 4: Excerpt of an M2T template written in the Object Constraint Language (OCL). Black and green: text to be generated, blue: reference to EMF object attributes, purple: OCL statements.

As the prototype uses the Eclipse RCP and EMF to generate the domain model, it applies another Eclipse plug-in, which already implements the mentioned M2T standard: Eclipse Acceleo. Acceleo integrates directly with the EMF generated models and provides a simple text-based editor to write templates using the Object Constraint Language (OCL). This language allows referencing EMF objects, iterating through lists, or even performing complex calculations using attributes of the underlying model.

4.3 User Interface

The implementation uses yet another Eclipse plug-in, EMF-Forms, to generate and provide a user interface to manage, save, and edit instances of the proposed domain model. EMF-Forms allows generating editors for EMF model elements by visually assembling a set of standard controls, like tables or text fields. It then generates an appropriate JAVA code for the resulting editors and provides these as a new plug-in to be included in an RCP application (Figure 5).



Project Installation Project

Name*: Installati
Maximum Project Duration*
Turbines To Build*: 50
Turbines Finished*
Project Start Date*: No date
Project Current Date*
Base Port*: Port Eemshaven
Installationsite*: Installation Site Installation Site

Used Vessels
- Vessel Installation Vessel 1
- Vessel Installation Vessel 2

Restock Vessel*: Vessel Heavy Lift Vessel 1

Restock Route
- BasePort
- Tower
- BasePort
- Tower
- BasePort
- Blade
- BasePort
- Nacelle
- BasePort

Factor Offload Time*: 0,6
Sets Per Restock Cycle*: 8
Cycle Duration*: 312
Avg Setup Time At Base Port*: 0

Production Port Tower*: Port Cuxhaven
Load Time Set Of Towers*: 2
Setup Time Set Of Towers*: 0
Weight Set Of Towers*: 600
Size Set Of Towers*: 650

Production Port Blades*: Port Bremerhaven
Load Time Set Of Blades*: 8
Setup Time Set Of Blades*: 0
Weight Set Of Blades*: 120
Size Set Of Blades*: 300

Production Port Nacelle*: Port Bremerhaven
Load Time Set Of Nacelles*: 10
Setup Time Set Of Nacelles*: 0
Weight Set Of Nacelles*: 500
Size Set Of Nacelles*: 263

Default / Default Scenario / Installation Project

Figure 5: Screenshot of the user interface to edit projects

5 Application Examples

This section presents an application of the proposed framework for three different models found in the literature or from previous work. This article mainly presents a summary of the simulation/optimization model and the modifications required to enable the respective transformation, if any changes were necessary. Afterward, the next section presents a short discussion of each model's characteristics to highlight the advantages and drawbacks of using a particular model.

5.1 Multi-Agent Simulation

This research uses a slightly modified version of the AnyLogic model presented by Ait Alla, et al. (2017) and Oelker, et al. (2018). The model itself consists of agents for the installation and transport (resupply) vessels, the base port, and the installation site. While the "location" agents mainly store information, e.g., on storage capacities or finished turbines, the vessel agents implement a state diagram to obtain lists of orders, to decide which order to process next and to execute the selected order. The model provides two different decision strategies. The static strategy selects operations by a predetermined priority, i.e., installation operations exceed loading operations, and both exceed movement operations. The second strategy estimates weather-induced waiting times for operations and adjusts the priorities accordingly. The simulation evaluates these operations against current weather data in the planning horizon.

The original model required minor changes to enable model transformations, i.e., an adapter to read the generated scenario file. While it would be possible to generate the complete simulation model using an XML-based template, the prototype generates a scenario file instead. This JSON-formatted file defines relevant parameters like the number and characteristics of vessels or the geographical location of the ports and the installation site. The original model was modified to load this scenario file when the simulation starts. Before, these settings needed to be set during startup using AnyLogic’s parameter interface.

5.2 Mathematical Optimization (Scheduling)

As the second model, the prototype targets the Matlab implementation of the mathematical scheduling model presented by Rippel, et al. (2019b). Therefore, the prototype generates Matlab code, which sets the relevant parameters, like process chains, durations, or vessel characteristics, and executes the model’s main entry-point function. Due to the generation of the scenario as Matlab m-file, the transformation requires no changes to the model.

This model aims to calculate a globally optimal schedule while incrementally performing a simulation of the current weather conditions using a Model Predictive Control scheme and an optimization using a Mixed Integer Linear Program (MILP). This MILP uses a predetermined cost function and a fixed set of constraints. The model itself shows a high level of configurability, e.g., by modifying the number and characteristics of vessels and turbines, the geographical layout of the project, or even the sequence, duration, and restrictions of operations. Nevertheless, modifications of the baseline purpose (scheduling), the cost function, or the used algorithms for handling weather uncertainties are not possible without further code modifications. To incorporate weather, this model uses forecasts for the planning and simulates these plans against the current weather during the planning horizon.

5.3 Petri-Nets Simulation

Finally, the prototype targets a Matlab implementation of the Petri-Nets based simulation model of Peng, Becker and Szczerbicka (2020). Meanwhile, the authors reimplemented the model using the GPenSIM simulator in Matlab. As with the mathematical model, the transformation generates code to set the required model parameters, like process times or the number of vessels, and executes the model's main entry-point function to perform the simulation.

In contrast to the previously described models, this simulation model focuses on the process level and uses historical weather data instead of current data for the simulation. Therefore, it relies on a two-level definition of the process chain. The root-level describes the order of processes for the installation and the resupply of components—the second level models the details of each process, i.e., its weather-dependent duration and its restrictions. The model does not represent vessels directly but by the number of tokens, which traverse along the process chain (Petri-Net). Consequently, this model allows modifying and evaluating the effect of different assumptions about the weather and its related uncertainties on the overall process. In terms of the weather data, the model uses average weather of the past. Thus, given the available dataset, simulating the year 2000, it uses the average weather for each hour of the years 1958 to 1999.

6 Discussion

For the evaluation, this research instantiates all three targeted models with the same scenario. This scenario mostly follows the specifications given in Beinke, Ait Alla and Freitag (2017). This scenario assumes the weather restrictions and durations provided in Table. The logistics network consists of a base port in Eemshaven and production ports in Bremerhaven and Cuxhaven. The scenario applies a single jack-up vessel for the installation and one heavy-lift vessel for the transport. Finally, the scenario aims to install 50 turbines, starting at the randomly chosen date, 01 June 2000.

The models each focus on different aspects of the installation process, ranging from the decision logic of single agents over the handling of process restrictions to the global optimization of schedules. These differences allow project planners and modeling experts to select the most suitable model if they want to evaluate specific assumptions, methods, or strategies. Regarding these aspects, modeling experts can easily modify the appropriate models, e.g., the handling of weather dependencies in the Petri-Nets model, decision strategies in the multi-agent model, or the cost function in the optimization model. Applying the same changes to another one of these models might prove to be more difficult. In contrast, project managers can quickly adapt the scenario, once the modeling experts identified and implemented a suitable method. This second stage allows, e.g., experimenting with different starting dates, cost structures, or amounts of applied resources. The minor modifications required to enable interoperability between the framework and the respective models shows that the first hypothesis holds: Model transformations constitute a suitable tool to unify the modeling efforts by providing a common base model for different formulations.

To further evaluate the three models, this evaluation executed each model using the same base scenario and its default settings. Table summarizes the results in terms of simulation (execution) time, the project duration (optimality of decisions), and the number of unexpectedly delayed operations (handling of uncertainties). All models were executed on the same standard office computer (Ryzen 5 2600 - Six-Core, 16GB RAM).

Table 2: Simulation Results

	Multi-Agent	Petri-Nets	Math. Optimization
Simulation Time	0.51 sec	2.58 sec	1897 sec (31.6 min)
Project Duration	1892 hours	1855* / 1738** hours	1792 hours
Operations with unplanned delays	19	9* / 1**	4

* Only using Data for the current year to enable a comparison with the other models

** Using historic data for the years 1958 – 1999

The results in Table highlight different advantages resulting from the focusses of the different models. While the optimization results in the shortest plans for the current weather conditions (high optimality), it also comes in the highest computational time due to the repeated solving of a Mixed-

Integer optimization (21 times). The multi-agent model results in acceptable plans with short computational times. This formulation excels at its high transparency and flexibility. As it relies on standard JAVA for the decision-making, modeling experts can implement highly advanced decision logics using arbitrary JAVA libraries, e.g., for reinforcement learning or deep neural networks. Finally, the Petri-Nets model also shows short computational times. Regarding the results, it has to be noted that this model does not evaluate its plans against the current weather conditions, but provides an estimation using past weather records. Thus, the original results marked with ** represent expected values. These, in combination with the results of the optimizer, show that the weather in the year 2000 was a little worse than the average weather in the years 1958 until 1999. While the multi-agent simulation and the optimization aim to provide decision support using current weather data and forecasts, the Petri-Nets simulation aims to provide estimates before the project commences. To provide a direct comparison, the table also shows the results of the Petri-Nets simulation, if it only accesses weather data for the year 2000 (marked with *). In this case, the results are comparable to the multi-agent simulation.

7 Conclusions and Future Work

This article proposes a framework that allows a straightforward definition of installation projects for offshore wind farms and is capable of using model transformations to generate instances of several executable simulation or optimization models. Therefore, the framework employs several established standards from the Object Management Groups Model Driven Architecture.

The prototypical implementation of the framework shows that the use of standard tools, e.g., of the Eclipse Rich Client Platform and the associated plug-ins of the Modelling Package, allows a mainly automated generation of the framework. This automation reduces the efforts primarily to the specification of the domain model using a UML-like graphical editor and an implementation of the transformation templates. These templates require the simulation/optimization models to either be specified using text files or to accept textual descriptions as input. This requirement might need changes to the original model, e.g., as shown at the example of the multi-agent simulation. Such modifications and the initial setup of the transformation templates probably require the help of modeling experts. Nevertheless, afterward, the framework enables project managers familiar with the actual installation project to use the targeted simulation or optimization models without further knowledge about their structure or internal algorithms.

The evaluation of the three selected models shows the possible advantages of each formulation depending on the current task at hand. While the mathematical model aims at a global optimization of the schedule, it does not allow modifying aspects like decision strategies or the underlying weather discretizations. In contrast, the Petri Nets model focuses on a process view, which predominantly allows modifying and experimenting with different ways to represent processes, their restrictions, or their duration. Finally, the multi-agent simulation focuses on the decisions of single vessels and provides the opportunity to quickly modify decision strategies by assigning different priorities to single operations. In conclusion, the different models aim at the evaluation of different aspects of the installation process, which might not be viable using a single model due to the required complexity and interplay of these aspects. Although this article only evaluated the approach using three distinct models, it already shows the viability of model transformations to allow process experts access to a variety of models (first research hypothesis). Moreover, these models show comparable performances if provided with the same generated base-scenario. The discussion shows that each of these models focuses on another aspect of the installation process, which allows process experts to evaluate their plans under different assumptions and regarding different facets of their project. This result verifies the second research hypothesis, stating that each model has its particular specialty and that model transformations can render these specialized models available to the process expert without the need to construct and maintain separate model instances. Consequently, this article shows that the usage of different models can prove advantages, especially during the planning phase. The proposed framework enables project managers to specify and modify scenarios in an intuitive way and, after the initial setup, to instantiate different simulation/optimization models to perform a variety of evaluations.

Future work will focus on extending the framework for further models and formulations. This inclusion mainly covers the implementation of additional transformations and the identification and aggregation of model-specific parameters. As part of this extension, future work will integrate weather data and appropriate methods for their conversion into the domain model and the prototype. Currently, this vital baseline data has been converted manually for each model. Moreover, future work will extend the domain model to cover workforce aspects, like personnel planning and qualification. Finally, future work will focus on the development of techniques to retrieve and manage the results of targeted executable models back into the defined scenario. This extension will allow mixing different models during the planning by obtaining some results from one model, e.g., to define required capacities, and passing the new state to another one, e.g., to perform scheduling.

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References

Ait Alla, A.; Oelker, S.; Lewandowski, M.; Freitag, M.; Thoben, K.-D. (2017): A Study of New Installation Concepts of Offshore Wind Farms By Means Of Simulation Model. In: Jin S. Chung, M. S. Triantafyllou und I. Langen (Hg.): The Proceedings of the 27th (2017) International Ocean and Polar Engineering Conference, S. 607–612.

Ait Alla, A.; Quandt, M.; Lütjen, M. (2013): Simulation-based aggregate Installation Planning of Offshore Wind Farms. In: International Journal of Energy 7 (2), S. 23–30.

Beinke, T.; Ait Alla, A.; Freitag, M. (2017): Resource Sharing in the Logistics of the Offshore Wind Farm Installation Process based on a Simulation Study. In: International Journal of e-Navigation and Maritime Economy (7), S. 42–54.

Beinke, Thies; Ait Alla, Abderrahim; Oelker, Stephan; Freitag, Michael (2020): Demand for special vessels for the decommissioning phase of offshore wind turbines in the German North Sea- a simulation study. In: Jin S. Chung (Hg.): The Proceedings of the 30th (2020) International Ocean and Polar Engineering Conference. [accepted].

Breton, S.; Moe, G. (2009): Status, plans and technologies for offshore wind turbines in Europe and North America. In: Renewable Energy 34 (3), S. 646–654.

Deutsche WindGuard GmbH (2019): Status des Offshore-Windenergieausbaus in Deutschland – Erstes Halbjahr 2019. Online verfügbar unter https://www.windenergie.de/fileadmin/redaktion/dokumente/pressemitteilungen/2019/Status_des_Offshore-Windenergieausbaus_Halbjahr_2019.pdf.

Dewan, A.; Asgarpour, M.; Savenije, R. (2015): Commercial Proof of Innovative Offshore Wind Installation Concepts Using ECN Install Tool: ECN.

Dolores, Esteban M.; Javier, Diez J.; López, J.; Negro, V. (2010): Why offshore wind energy? In: Renewable Energy 36 (2), S. 444–450.

Irawan, Chandra Ade; Wall, Graham; Jones, Dylan (2017): Bi-objective optimisation model for installation scheduling in offshore wind farms. In: Computers & Operations Research 78, S. 393–407. DOI: 10.1016/j.cor.2015.09.010.

Irawan, Chandra Ade; Wall, Graham; Jones, Dylan (2019): An optimisation model for scheduling the decommissioning of an offshore wind farm. In: OR Spectrum. DOI: 10.1007/s00291-019-00546-z.

Kerkhove, L.-P.; Vanhoucke, M. (2017): Optimised scheduling for weather sensitive offshore construction projects. In: Omega 66, S. 58–78.

Lange, K.; Rinne, A.; Haasis, H.-D. (2012): Planning maritime logistics concepts for offshore wind farms: A newly developed decision support system. In: Lecture Notes in Computer Science: Computational Logistics 7555, S. 142–158.

Meyer, M. (2014): Reeder von Offshore-Spezialtonnage müssen spekulativer vorgehen. In: HANSA International Maritime Journal 151 (10), S. 54–55.

Muhabie, Y. T.; Rigo, P.; Cepeda, M.; D'Agosto, M. A. (2018): A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies. In: Ocean Engineering 149, S. 279–290.

Oelker, S.; Ait Alla, A.; Lütjen, M.; Lewandowski, M.; Freitag, M.; Thoben, K.-D. (2018): A simulation study of feeder-based installation concepts for offshore wind farms. In: Jin. S. Chung, B.-S. Hyun, D. Matskevitch und A. M. Wang (Hg.): The Proceedings of the 28th (2018) International Ocean and Polar Engineering Conference, S. 578–583.

Oelker, Stephan; Ait Alla, Abderrahim; Büsing, Silas; Lütjen, Michael; Freitag, Michael (2020): Simulative approach for the optimization of logistic processes in offshore ports. In: Jin S. Chung (Hg.): The Proceedings of the 30th (2020) International Ocean and Polar Engineering Conference. [accepted].

Peng, Shengrui; Becker, Matthias; Szczerbicka, Helena (2020): Modelling and Simulation of Oshore Wind Farm Installation with Multi-Leveled CGSPN Approach. In: Jin S. Chung (Hg.): The Proceedings of the 30th (2020) International Ocean and Polar Engineering Conference. [accepted].

Quandt, M.; Beinke, T.; Ait Alla, A.; Freitag, M. (2017): Simulation Based Investigation of the Impact of Information Sharing on the Offshore Wind Farm Installation Process. In: Journal of Renewable Energy 2017, 11 pages. DOI: 10.1155/2017/8301316.

REN21 (2018): Renewables 2018 Global Status Repor, REN21. ISBN 978-3-9818911-3-3, https://www.energia.org/renewables-2018-global-status-report-ren21

Rippel, Daniel; Jathe, Nicolas; Becker, Matthias; Lütjen, Michael; Szczerbicka, Helena; Freitag, Michael (2019a): A Review on the Planning Problem for the Installation of Offshore Wind Farms. In: IFAC-PapersOnLine 52 (13), S. 1337–1342. DOI: 10.1016/j.ifacol.2019.11.384.

Rippel, Daniel; Jathe, Nicolas; Lütjen, Michael; Freitag, Michael (2019b): Evaluation of Loading Bay Restrictions for the Installation of Offshore Wind Farms Using a Combination of Mixed-Integer Linear Programming and Model Predictive Control. In: Applied Sciences 9 (23), ArticleID: 5030. DOI: 10.3390/app9235030.

Rippel, Daniel; Jathe, Nicolas; Lütjen, Michael; Szczerbicka, Helena; Freitag, Michael (2019c): Integrated domain model for operative offshore installation planning. In: C. M. Ringle, W. Kersten und C. Jahn (Hg.): Digital Transformation in Maritime and City Logistics: epubli GmbH (Proceedings of the Hamburg International Conference of Logistics (HICL)), S. 25–54. Online verfügbar unter http://hdl.handle.net/11420/3761.

Rippel, Daniel; Jathe, Nicolas; Lütjen, Michael; Szczerbicka, Helena; Freitag, Michael (2019d): Simulation and Optimization of Operations for Offshore Installations Planning using a Model Predictive Control Scheme. In: N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas und Y.-J Son (Hg.): IEEE Conferences - 2019 Winter Simulation Conference (WSC), S. 1719–1730. Online verfügbar unter https://www.informs-sim.org/wsc19papers/171.pdf.

Scholz-Reiter, B.; Karimi, H. R.; Lütjen, M.; Heger, J.; Schweizer, A. (2011): Towards a Heuristic for Scheduling Offshore Installation Processes. In: S. Maneesh, R.B.K.N. Rao und J. P. Liyanage (Hg.): Proceedings of the 24th International Congress on Condition Monitoringand and Diagnostics Engineering Management. Advances in Industrial Integrated Asset Management, S. 999–1008.

Scholz-Reiter, B.; Lütjen, M.; Heger, J.; Schweizer, A. (2010): Planning and control of logistics for offshore wind farms. In: Liliana Rogozea (Hg.): 12th International Conference on Mathematical and Compuational Methods in Science and Engineering (MACMESE'10). Advances in Mathematical and Computational Methods, S. 242–247.

Ursavas, Evrim (2017): A benders decomposition approach for solving the offshore wind farm installation planning at the North Sea. In: European Journal of Operational Research 258, S. 703–714.

Vis, Iris F.A.; Ursavas, Evrim (2016): Assessment approaches to logistics for offshore wind energy installation. In: Sustainable Energy Technologies and Assessments 14, S. 80–91.