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The LEANWIND suite of logistics optimisation and full lifecycle simulation models for offshore wind farms

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Abstract. The offshore wind sector has achieved significant cost reductions in recent years. However, there is still work to be done to maintain and surpass these savings across current and future farms. There is increased competition to reduce costs within the industry itself. Additional challenges are foreseen at future sites located further from shore, in harsher conditions and deeper waters. Larger turbines and projects also mean new equipment, logistics and maintenance requirements. Moreover, farms are approaching the decommissioning phase where there is little experience. Modelling is a safe and cost-effective way to evaluate and optimise operations. However, there is a lack of comprehensive decision-support tools, detailed enough to provide insight into the effects of technological innovations and novel strategies. To address the gap, the EU FP7 LEANWIND project developed a suite of state-of-the-art logistics optimisation and financial simulation models. They can assess a farm scenario in detail at every stage of the project lifecycle and supply-chain, identifying potential cost reductions and more efficient strategies. This paper introduces the models including: an overview of their scope and capabilities; how they can be applied; and the potential end users.

1. Introduction

The offshore wind industry has achieved significant cost reductions in recent years with a number of projects forecasting a Levelised Cost of Energy (LCOE) surpassing 2020 targets of €100/MWh. In 2016, DONG Energy's bid for the Borssele site implied an LCOE of approximately €68/MWh, excluding transmission costs [1]. Vattenfall's 2016 offshore wind price bid of €49.9/MWh for the Kriegers Flak



project set a record LCOE forecast of €40/MWh [2]. Cost reductions can be generally attributed to the industry's growing maturity leading to technology developments, increased competition in the supply-chain, and supportive policy frameworks, each helping to reduce risk and the cost of capital. However, there is more work to be done to maintain and surpass these savings across current and future farms, ensuring the continued cost-competitiveness of offshore wind in the energy sector. The anticipated fall in LCOE will increase price competition as developers are under pressure to match these forecasts. New markets in East Asia and North America have yet to achieve these targets. In addition, challenges are presented by future sites located further from shore, in harsher conditions and deeper waters. The move towards larger turbines and projects also mean larger equipment requirements and new logistics and maintenance issues. Farms are also approaching the decommissioning or repowering phase, where there is little experience. The first Offshore Wind Farm (OWF) project to be decommissioned only took place in 2016 (Yttre Stengrund, which comprised five 2MW turbines) [3].

Modelling is a safe and cost-effective way to evaluate and optimise operations. However, there is a lack of comprehensive decision-support tools, detailed enough to provide insight into the effects of technological innovations and novel strategies. Since most financial models are developed by consultancies or by wind farm developers [4], there is little information available describing their capabilities. Based on the present literature, while there are a variety that can estimate costs for different aspects of an OWF, current models tend to produce relatively high-level assessments of project costs or only focus on a single lifecycle phase. Therefore, advances can be made in modelling the full capital and installation (CAPEX), operation and maintenance (OPEX) and decommissioning (DECEX) costs. In addition, most models use a simplified LCOE as a metric to compare technologies and innovations but as the industry advances, more sophisticated parameters are being applied particularly to take into account the methods of financing, contractual arrangements, tax policies, risk sharing methods etc. The current models are also generally simulation tools, which do not easily facilitate scenario optimisation, requiring manual manipulation of decision variables per simulation. This can be extremely time-consuming and it exceeds human ability to evaluate all possible solutions.

To address the gap, the EU FP7 LEANWIND project (December 2013-November 2017) developed state-of-the-art decision-support tools including: a set of logistics optimisation models covering the entire supply-chain of an OWF; and a full lifecycle financial cost model. This was done in close cooperation with industry partners and external industry advisors to ensure they could address the key challenges and to validate outputs. Whereas prior publications referenced in this paper describe some of these tools individually, the objective of the present paper is to give an overview of the complete LEANWIND suite of tools. Section 2 summarises the objective and methodologies behind the logistics and financial models respectively. Section 3 describes the capabilities of the models individually, while Section 4 outlines how they can be applied together to obtain the most economically viable and time efficient operational plans for an OWF. Section 5 details the potential end-users and how the models can benefit them in each case e.g. to improve Research and Development (R&D), improved logistics practices and enhanced policy formulation.

2. Methodology

The LEANWIND project sought time and cost savings by optimising existing and developing innovative tools, technologies and procedures. BVG Associates estimated that improving the supply-chain could provide a 9% reduction in LCOE [5]. This is especially true if optimisation is done in the planning phase, where it is cheaper and easier to establish than midway through a project [6]. Therefore, LEANWIND developed a holistic set of logistics optimisation models covering the three main supply-chain stages (prior to/post port; at port; to/from site). These rank a set of supply-chain arrangements across the lifecycle phases.

To simulate novel technologies and strategies in detail and provide in-depth cost analysis, the project also developed a full lifecycle financial model. The model considers the installation, Operation and Maintenance (O&M) and decommissioning of OWFs, and can reduce costs by identifying potential

savings and fostering effective decision-making. Developed for research purposes, it is a non-proprietary, independent financial assessment tool and is relevant to numerous potential users.

The LEANWIND models are divided into two categories: optimisation and simulation. In the simplest terms, the logistics models are optimisation tools while the financial model is a simulation tool. They have independent objectives as follows:

- The logistics models consider multiple decision variables e.g. infrastructure and transport combinations, examining a large number of configurations and ranking the best options for key logistics issues. The objective function is to optimise for cost, although some of the models can also consider time, depending on the user's priority.
- The financial model consists of three lifecycle phase tools that simulate a farm scenario in detail over an hourly time series. It uses the Monte Carlo method, varying selected variables (e.g. costs, weather conditions and component failures) over a large number of iterations to consider uncertain inputs and key risk factors.

While the logistics and financial models can stand alone, they are complementary and are designed to work together to provide the best input in Front End Engineering Design (FEED) stage decision-making.

3. Individual models

3.1. Logistics

The logistics models provide optimised solutions for the supply-chain in the three primary lifecycle phases and in each of the three primary supply-chain stages:

- Prior to/post port: activities prior to the components arriving at the support port (in the installation or O&M phases) or upon leaving the support port (in the decommissioning phase). For the installation and O&M phases, this can consist of manufacturing, transportation, storage, and assembly. In the decommissioning phase, it includes the movement of parts from the port to the recycling or landfill sites.
- At port: selection of the port(s) for each lifecycle phase as well as the optimal layout and usage of the port itself.
- Supply to/from offshore site: the movement of parts from the port to the site for installation and O&M or vice versa for the decommissioning phase.

Table 1 gives a schematic overview of these nine pairings. When executed together, these models are capable of generating a holistic solution for a supply-chain for all lifecycle phases of an OWF. They are further described in subsections 3.1.1-3.1.5.

Table 1. Logistics models and associated lifecycle and supply-chain pairings

	Installation	O&M	Decommissioning
Prior to/post port	PTPIns	PTPOM	IntDis
At port	Portlay, PortIns	PortOM	PortDis
To/from offshore site	VMIns	VMOM	IntDis

3.1.1. Portlay. The Port Layout tool identifies the best layout for an offshore wind port with the objective function of minimising the total transportation cost of the components within the port. As illustrated in Figure 1, the port area is pre-defined and comprises different subareas where the offshore wind turbine components including the nacelle, tower and blade are stored (storage area), assembled (staging area) and loaded/unloaded. Each subarea contains a rectangle of given dimensions for each component. This model is designed for use in the installation phase and has been applied in [7].

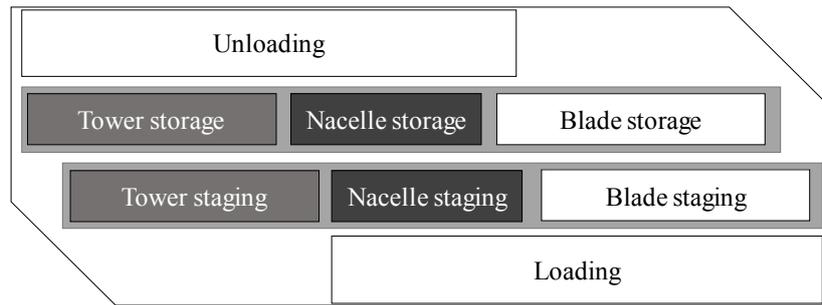


Figure 1. Movement of components within the port

3.1.2. *PortIns, PortOM and PortDis.* The three port ranking models determine the optimal port to support the respective installation, O&M and decommissioning activities from a set of potential options for the selected site. These models measure suitability using a set of criteria relevant to the respective phase including: (i) physical characteristics e.g. quay length (ii) connectivity e.g. road networks and (iii) layout e.g. storage availability. An application of the port selection models is described in [8].

3.1.3. *PTPIns and PTPOM.* The prior to port models for the installation and O&M phases determine the optimal arrangement of the supply-chain (suppliers, manufacturers/plants, and warehouses (ports)) and schedule from the production of turbine parts and components to delivery at port. The objective is to ensure they arrive when needed with minimal cost (transport; inventory/storage and production) and time wastage. The components considered include the foundation, transition piece, tower, nacelle and blades. Components can come from manufacturers/plants or suppliers. Parts are the objects required to assemble main components and come from suppliers. They must be delivered to plants to meet the production schedule of main components. Components and parts can be delivered by land, sea or both. The port warehouses have limited storage. The manufacturers have different production capacities and processing times. Suppliers have a limited availability of parts. The PTPIns and PortIns models are applied in [9, 10].

3.1.4. *VMIns and VMOM.* The port to site model for the installation phase determines the optimal mix and scheduling of vessels, helicopters and bases to support activities. The models can be used to optimise for cost or time depending on user’s priorities. The schedule can be used to provide an indicative plan for installation activities e.g. the number of components that could be installed per day. Figure 2 summarises the input and outputs of the VMIns. A computational study illustrates how the model can be used in collaboration with the PortIns model to provide decision-support with respect to which vessel resources and installation port in [11].

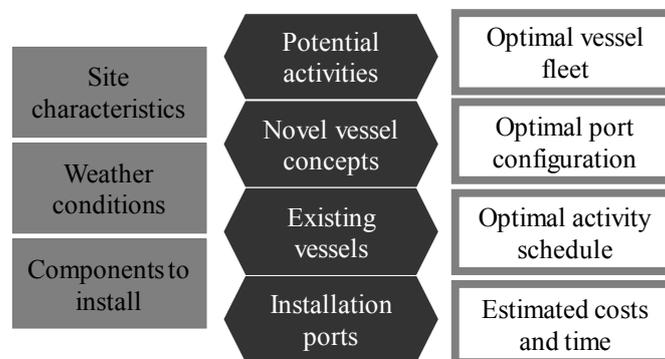


Figure 2. Input and output overview of the VMIns

The transport system during the O&M phase consists of onshore bases, means of transport and offshore bases. The VMOM model considers preventive and corrective maintenance. An estimated duration is associated with each activity, along with a given number of required technicians, spare parts, and vessel resources. Based on the generated maintenance patterns, the model chooses the minimum cost transport combination considering the fixed costs of vessels and bases (e.g. time charter costs); variable costs of executing maintenance patterns; downtime costs; and penalty costs for not executing maintenance activities within the planning horizon. This model is described in [12].

3.1.5. IntDis. The integrated dismantling model determines an initial vessel schedule and flow of components from the site to a set of ports and onto a set of disposal and recycling points when decommissioning an OWF. The objective function is to minimise the total cost of activities rather than time, which is not considered a priority at the end of a project. This model considers the blades, nacelle, tower, foundation and transition pieces. A jack-up vessel dismantles, while a barge transports components to port(s). Components are processed and stored in port until they are transported to dump/landfill or recycling areas. The model considers the capacity of the processing machine, port storage area, and the number of components that can be transported. The tower and foundation are recycled, while blades and the nacelle are landfilled. [13]

3.2. Financial

The financial model consists of a central Microsoft Excel interface, which interacts with three dedicated hourly time series simulation modules implemented in MATLAB. The model architecture is illustrated in Figure 3. The modules each cover a lifecycle phase (installation, O&M and decommissioning) and are probabilistic, employing Monte Carlo simulation to consider stochastic elements such as weather and component failures. Calculating a detailed breakdown of the cost and duration of activities, the modules allow for a detailed assessment of strategies and technologies. For example, they have been used to evaluate the cost-benefit of novel foundation designs and installation strategies; the impact of larger turbines (8MW+); near shore and far from shore sites; O&M strategies including remote presence technologies, the optimal chartering periods for jack-up vessels and implementing seasons for preventive maintenance; novel vessel concepts for each phase; and decommissioning and recycling strategies [14-16]. The model outputs include a full project timeline, energy yield and a comprehensive breakdown of capital and installation (CAPEX), Operation and Maintenance (OPEX) and decommissioning (DECEX) costs. The model provides key financial indicators including the LCOE, Net Present Value (NPV), Internal Rate of Return (IRR) and payback period.

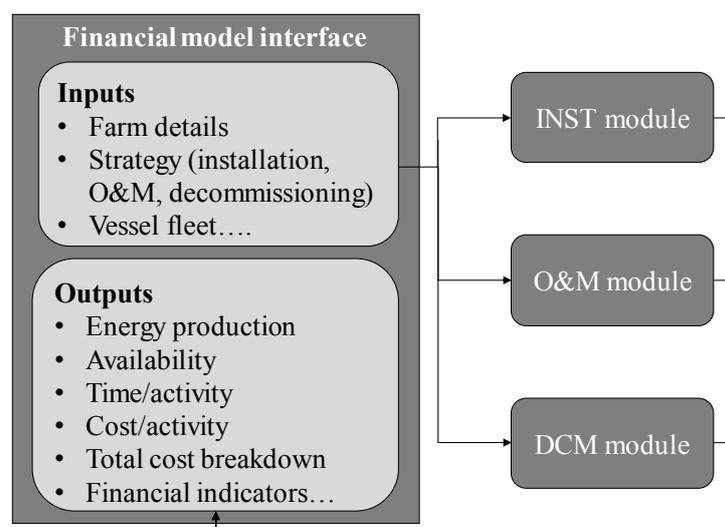


Figure 3. Financial model diagram

The modules were each successfully validated with a) reasonable comparison to case study data and other models; b) significant input from industry on the model input data, assumptions and output data checks; and/or c) sensitivity analysis. Subsections 3.2.1-3.2.4 describe the 4 main components.

3.2.1. Financial model interface. This is the overall controlling model for the system. The user enters the required data for all phase modules through data entry sheets including (among others):

- Simulation information e.g. case study description, the number of iterations etc.
- Wind farm details e.g. water depth, distance to port, average distance between turbines etc.
- Asset details e.g. number, type and rated power of turbine; foundation type, cable ratings etc.
- Available vessels for the three phases
- Crew for the O&M and decommissioning phases
- Project finance assumptions

On completing the inputs, the user initiates the individual phase modules from the central spreadsheet. Once the simulations are complete, results are saved in the spreadsheet where the user can perform further project level financial calculations. The model facilitates detailed financial analysis considering different financing methods (including capital equity, grants and borrowing arrangements/debt); tax; depreciation of assets; savings and deposit interest rates; and subsidies (feed-in-tariff or contract for difference rate). The model produces a cash flow sheet including projected profit and loss, as well as a balance sheet to evaluate debt and equity. The following sections outline the scope of the three phase models hereafter described as the INST, O&M and DCM modules.

3.2.2. INST module. This model considers the installation of the turbine, foundation, substation, substation foundation, export and inter-array cabling. The user can specify or use a pre-defined selection of assets. Different operations are then associated with the installation of each asset. For example, the user can choose to float out and sink the foundation or lift via crane. Table 2 lists the installation strategies available. The module generates and executes a schedule of activities, recording the actual sequence of events, the time spent carrying out each activity, and details of any delays.

The tool calculates the overall time taken per asset and the cost of activities. Outputs include the capital cost of assets; pre-installation transport costs from the manufacturer to the supply port (not included in the time series); the charter and fuel costs for vessels; costs for survey and monitoring; port activities; other balance of plant costs e.g. onshore works.

Table 2. Turbine installation methods

Installation method	Lifts
All components individually	7
2 tower parts; nacelle and hub pre-assembled; 3 blades	6
Tower pre-assembled; nacelle and hub pre-assembled; 3 blades	5
2 tower parts; nacelle; hub and blades pre-assembled	4
2 tower parts; nacelle, hub and 2 blades (bunny ears) pre-assembled; 1 blade	4
Tower pre-assembled; nacelle, hub and 2 blades (bunny ears) pre-assembled; 1 blade	3
Pre-assembled onshore	1
Pre-installed on substructure (float-out to site)	0

The installation module was validated using a number of case studies including C-Power Phase 1: A small scale 30 MW OWF located on Thornton Bank in the North Sea, 30 km from the Belgian coastline. Results were found to closely correlate with the LEANWIND model output of €146 million, only 4.67% less than the expected €153 million quoted for this farm [17].

3.2.3. O&M module. This model analyses a given O&M strategy including corrective, condition-based and predetermined preventive maintenance; the resources available including vessels, personnel

(considering shift patterns), spare parts, and the maintenance base location (either port or offshore maintenance base e.g. “floatel” or “mothership”). The model uses the Monte Carlo method to consider stochastic elements such as e.g. weather and component failures. Based on an hourly time-series input by the user, the model generates a synthetic weather time series for the operational lifetime of the project for each Monte Carlo iteration using Markov chain modelling techniques. The model results include a breakdown of O&M costs e.g. personnel, vessels, spare parts; the wind farm availability; and energy production.

This O&M module was developed from the NOWIcob model and is further described in [18, 19]. During its years of development, it has undergone extensive validation activities including separate industry projects and more specific validation studies. Through these studies, the applicability and accuracy of the O&M module has been tested and improvements have been made accordingly. Industrial studies include a project with a Norwegian offshore wind developer for the investment decision of a real OWF project [19]. This model and the logistics VMOM model have also previously been used together and benchmarked against other state-of-the-art O&M models [20].

3.2.4. DCM module. Figure 4 summarises the decommissioning cost estimates found in the current literature. It is clear that there is a wide range of expectations. With the first offshore wind farms being dismantled, this model is particularly timely to support cost-effective planning.

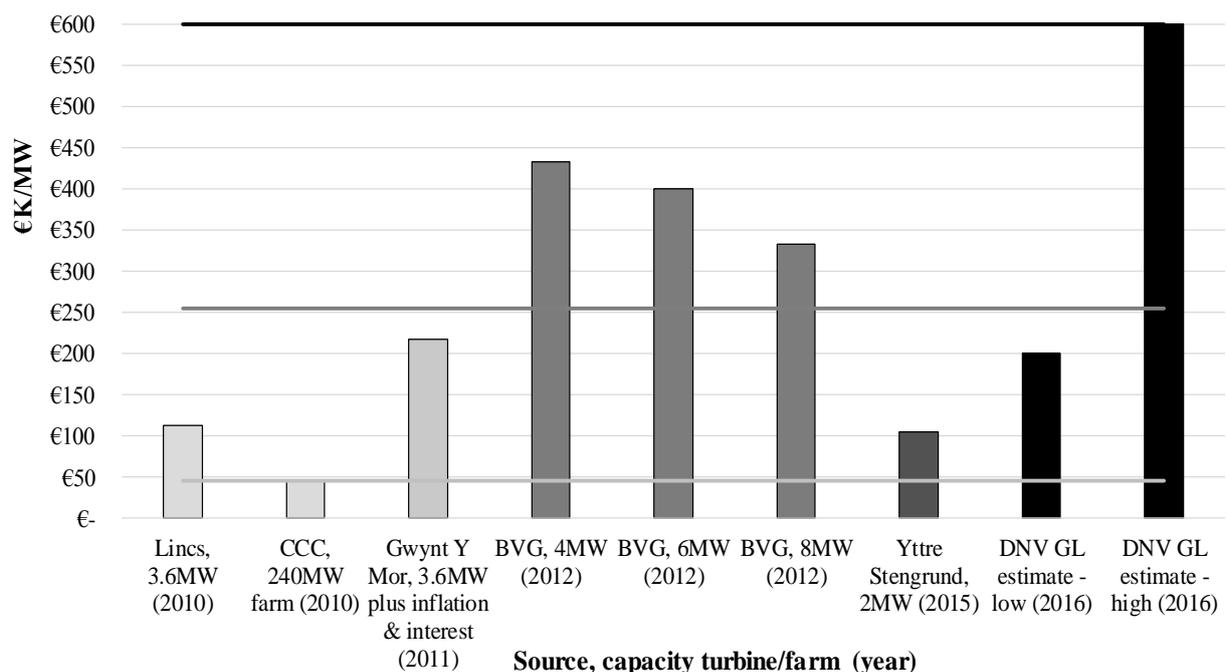


Figure 4. Decommissioning cost estimates [3, 21-25]

The decommissioning and salvage expenditure module (DECEX) simulates a strategy to dismantle the turbine and foundation. Inputs include the component and their materials e.g. tower, steel; component weight; operation durations; up to three destination ports; and landfill or recycling centre locations. The model can also account for the re-sale of components or re-conditioning in the case of repowering rather than fully decommissioning a farm. The user specifies the number of components (e.g. blades, nacelle, gearbox etc.) and order in which they are dismantled. The model can consider strategies with or without a feeder vessel e.g. a barge which would transport materials from site while the larger heavy-lift vessels continue dismantling onsite. The model derives an estimate of

decommissioning costs and the time taken to complete activities. It also calculates salvage revenue from recycling etc. and post-decommissioning costs e.g. for disposal.

Validation of this model is difficult given the lack of experience and is highly dependent on the method used to estimate costs in the current literature. However, the model was run using the installation module case-studies for consistency. Costs were expected to fall within the range estimated by DNV GL of €200,000-€600,000/MW [25]. Results for the C-Power OWF were €513,000 per MW. While at the upper limit of the estimated costs, this and other validation studies correlated well with the best possible estimates for decommissioning cost in the industry at this point in time.

4. Combined application

As indicated in Section 2, the logistics and financial models were developed to be complementary and can be used in an integrated manner to obtain the most economically viable and time efficient solutions to a wide range of logistical and strategic issues. The first step is to determine an optimal supply-chain for a given wind farm scenario using the logistics models. The user inputs the choices they wish to consider, and the models examine different arrangements to determine a selection of promising near-optimal supply-chain configurations for all three phases of the lifecycle. However, most of the logistics models (with the exception of the VMOM) are deterministic, i.e. key risk factors such as weather do not vary. As their focus is to test a large number of supply-chain configurations, they are also less detailed than the simulation models with a small number of parameters/functionalities/assumptions. Thus the near-optimal solutions from the logistic models should in general be evaluated by more detailed simulation models to increase the quality and validate the final and optimised solutions.

Therefore, the top ranking solutions output from the logistics models are used as inputs for the financial model to investigate their potential as well as examining the overall scenario through more detailed analysis. As the financial models consider multiple possible realizations of a project lifecycle, they consider the potential impact of uncertain factors on results (e.g. weather, component failures). Combined use significantly reduces the time-consuming process of optimising a scenario by running numerous iterations in detail with the simulation models.

5. Potential end users

The LEANWIND models are capable of providing decision-support to a wide range of stakeholders. Users could vary from a technology or vessel developer (interested in the impact of their technology on a specific lifecycle phase) to project developers (interested in higher-level investment information). The mapping of offshore wind stakeholders and their interests is complex and, to an extent, still evolving for this significant and emerging sector. The following shows some of the different stakeholders who could utilise the models individually or in combination:

- **Manufacturers:** to guide their facility location policy and optimise the movement and storage of parts. Additionally, if the manufacturer is supplying multiple OWFs, then the potential gains of using a common supply-chain can be investigated.
- **Ports:** to determine their potential for use in the different lifecycle phases; to assess the impact of upgraded facilities and capabilities targeting the offshore wind sector for marketing purposes; and to plan the configuration of space.
- **A technology developer:** to assess the impact of the innovation on costs and time. For example, the models could assess a new turbine concept with improved reliability or the potential benefits of a float-out substructure design over the current industry standard.
- **A wind farm developer:** to determine the optimal supply-chain and to produce detailed forecasted costings to support effective planning e.g. comparing various strategies at each phase or examining the impact of size and type of vessel fleet on project finances.
- **OWF operator:** to investigate the impact of a specific change in circumstances during operations e.g. if a new type of vessel becomes available in the O&M phase.
- **Specialist O&M company:** to optimise their provision and scheduling.

- Specialist vessel providers: to better predict likely installation, O&M and decommissioning strategies and plan future vessel types and number.
- A vessel developer or investor in a new vessel concept: to assess the impact of the design on costs and improved time for installation, maintenance or decommissioning.
- Recycling or landfill centre: to understand and prepare for the need to process material from nearby OWF in the decommissioning phase.
- A project investor or insurance companies: to analyse the possible financial outcomes or key risk factors of a given project or projects.
- Policy makers and funding bodies: to undertake broader cost-benefit analysis such as assessing the impacts of different sites on industry finances; new vessel concepts or foundations or other innovations on industry costs and financial viability; or regional investment in port or transport infrastructure on project finances in that region.
- Academics/Research: to analyse OWF project finances, technical innovations and trends.

6. Conclusion

A comprehensive and complementary set of logistics and financial models were developed. They can be used individually or together to optimise and simulate the full supply-chain and lifecycle of an OWF project. The LEANWIND suite of tools fills a significant gap in the current models available, which cannot support detailed analysis or optimisation at every key stage of an OWF project. While the logistics models focus on ranking an optimum set of supply-chain configurations, the financial model assesses the impact of strategic decisions and technologies on costs and time in detail. Combined use can save considerable computational time, which would be needed to analyse a large set of potentially sub-optimum supply-chain solutions and strategies through the simulation models. The models were designed primarily for the project planning and design phase and to address the current and future challenges faced by a wide range of stakeholders. Through effective and efficient decision-support these models can foster cost-savings in the industry and help secure the continued cost-competitiveness of offshore wind in the energy mix. Several of models have already been applied, either individually or together, and the references included in this paper point to detailed descriptions of the case studies. Separate papers are also planned to publish results reported in [15-16].

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