Project funded by the European Commission under the 6th (EC) RTD Framework Programme (2002- 2006) within the framework of the specific research and technological development programme "Integrating and strengthening the European Research Area"

Project UpWind

Contract No.:
019945 (SES6)

"Integrated Wind Turbine Design"

Executive Summary

(WP4: Offshore Foundations and Support Structures)

AUTHOR:	Tim Fischer
AFFILIATION:	Endowed Chair of Wind Energy, Universität Stuttgart
ADDRESS:	Allmandring 5b, 70569 Stuttgart, Germany
TEL.:	+49-711-685-60338
EMAIL:	tim.fischer@ifb.uni-stuttgart.de
FURTHER AUTHORS:	Wybren de Vries (TU Delft) and Andrew Cordle (GL-Garrad Hassan)
REVIEWER:	Fabian Vorpahl (IWES)
APPROVER:	Andreas Rettenmeier (SWE)

Document Information

DOCUMENT TYPE	Executive Summary
DOCUMENT NAME:	UpWind_WP4_Executive_Summary
REVISION:	1
REV.DATE:	10.01.2011
CLASSIFICATION:	R1: General Public
STATUS:	S0: Approved/Released

Acknowledgement

The presented work was funded by the Commission of the European Communities, Research Directorate-General within the scope of the Integrated Project "UpWind – Integrated Wind Turbine Design" (Project No. 019945 (SES6).

Disclaimer

STATUS, CONFIDENTIALITY AND ACCESSIBILITY										
Status				**Confidentiality**				**Accessibility**	
S0	Approved/Released	X		**R0**	General public	X		Private web site	
S1	Reviewed			**R1**	Restricted to project members			Public web site	X
S2	Pending for review			**R2**	Restricted to European. Commission			Paper copy	X
S3	Draft for comments			**R3**	Restricted to WP members + PL				
S4	Under preparation			**R4**	Restricted to Task members +WPL+PL				

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

Contact persons UpWind Work Package 4

Endowed Chair of Wind Energy (SWE) Mr. Tim Fischer, Mr. Denis Matha, Mr. Daniel Kaufer Institute of Aircraft Design, Universität Stuttgart Allmandring 5b, 70569 Stuttgart, Germany Tel: +49-711-685-60338 E-mail: tim.fischer@ifb.uni-stuttgart.de http://www.ifb.uni-stuttgart.de/en	Overall WP-Leader and Leader Task 4.1
DUWIND Mr. Wybren de Vries Offshore Engineering, Delft University of Technolgy Stevinweg 1, 2628 CN Delft, The Netherlands Tel.: +31-15-2787568 E-Mail: w.e.devries@tudelft.nl http://www.duwind.tudelft.nl/	Leader Task 4.2
Garrad Hassan & Partners Ltd. Mr. Andrew Cordle, Mr. Tim Camp St. Vincent's Works Silverthone Lane Bristol BS2 0QD, UK Tel.: +44-117-972-9779 E-Mail: andy.cordle@gl-garradhassan.com http://www.garradhassan.com/	Leader Task 4.3
Dong Energy Mr. Niels Jacob Tarp-Johansen A.C. Meyers Vænge 9 2450 København SV, Denmark Tel.: +45-9955-2494 E-Mail: ntajo@dongenergy.dk http://www.dongenergy.com	
GE Wind Energy GmbH Mr. Po Wen Cheng, Mr. Henk-Jan Kooijman Holsterfeld 16, 48499 Salzbergen, Germany Tel.: +49-5971-980-1169 E-Mail: powen.cheng@ge.com http://www.ge-energy.com	
Germanischer Lloyd Windenergie GmbH Mr. Kimon Argyriadis, Mr. Björn Schmidt Brooktorkai 18, 20457 Hamburg, Germany Tel.: +49-40-36149-707 E-Mail: kimon.argyriadis@gl-group.com http://www.gl-group.com	

Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) Mr. Fabian Vorpahl Am Seedeich 45, 27572 Bremerhaven, Germany Tel.: +49-471-902629-32 E-Mail: fabian.vorpahl@iwes.fraunhofer.de http://www.iwes.fraunhofer.de	
National Renewable Energy Laboratory Mr. Jason Jonkman 1617 Cole Blvd., Golden, Co. 80401-3393, USA Tel.: +1-303-384-7026 E-Mail: jason.jonkman@nrel.gov http://wind.nrel.gov	
Rambøll A/S Mr. Naveen Kumar Vemula, Mr. Henrik Carstens Willemoesgade 2, 6700 Esbjerg, Denmark Tel.: +45-5161-7232 E-Mail: nkv@ramboll.com http://www.ramboll.com/	
Risø-DTU Mr. John Dalsgaard Sørensen Wind Energy Department Frederiksborgvej 399, 4000 Roskilde, Denmark Tel.: +45-4677-5951 E-Mail: jdas@risoe.dtu.dk http://www.risoe.dk	
Vattenfall Vindkraft A/S Mr. Kasper Roed Jensen Oldenborggade 25-31, 7000 Fredericia, Denmark Tel.: +45-3925-3849 E-Mail: kasper.roedjensen@vattenfall.com http://www.vattenfall.dk	
Universität Oldenburg Mr. Martin Kühn Marie-Curie-Str. 1, 26129 Oldenburg, Germany Tel.: +49-441-36116-571 E-Mail: martin.kuehn@uni-oldenburg.de http://www.physik.uni-oldenburg.de	Associate partner of Universität Stuttgart

Table of Contents

1. Scope of the European UpWind Project

1.1 UpWind – general description and objectives

The UpWind project looks towards wind power of tomorrow and towards the design of very large turbines (8 to 10MW) in wind farms of several hundred MW, both on- and offshore. The challenges inherent in the creation of such power stations necessitate the highest possible standards in design, a detailed understanding of external design conditions, the design of materials and structures with extreme strength to mass ratios and advanced control and measuring systems all geared towards the highest degree of reliability, and, critically, reduced overall turbine mass.

Wind turbines greater than 5MW and wind farms of hundreds of MW necessitate the re-evaluation of the core unit of a wind energy power plant, the turbine itself, for its re-conception to cope with future challenges. UpWind develops the accurate, verified tools and component concepts the industry needs to design and manufacture this new breed of turbine. UpWind focuses on design tools for the complete range of turbine components. It addresses the aerodynamic, aero-elastic, structural and material design of rotors. Critical analysis of drive train components are carried out in the search for breakthrough solutions.

In 2003, European companies supplied 90% of the global market for wind power technology.
UpWind helps maintaining that position and realising EU renewable electricity targets for 2010, and to attain the main objective of the Lisbon Agenda. The UpWind Project brings together the most advanced European specialists and experience. The main technical and scientific components of the programme have been fully integrated through a visionary organisational structure, which ensures that scientific research answers industry needs. This has been achieved by organising the project in such a way that the (industrial) integration work packages guide the scientific work to a great extent (vertical integration).

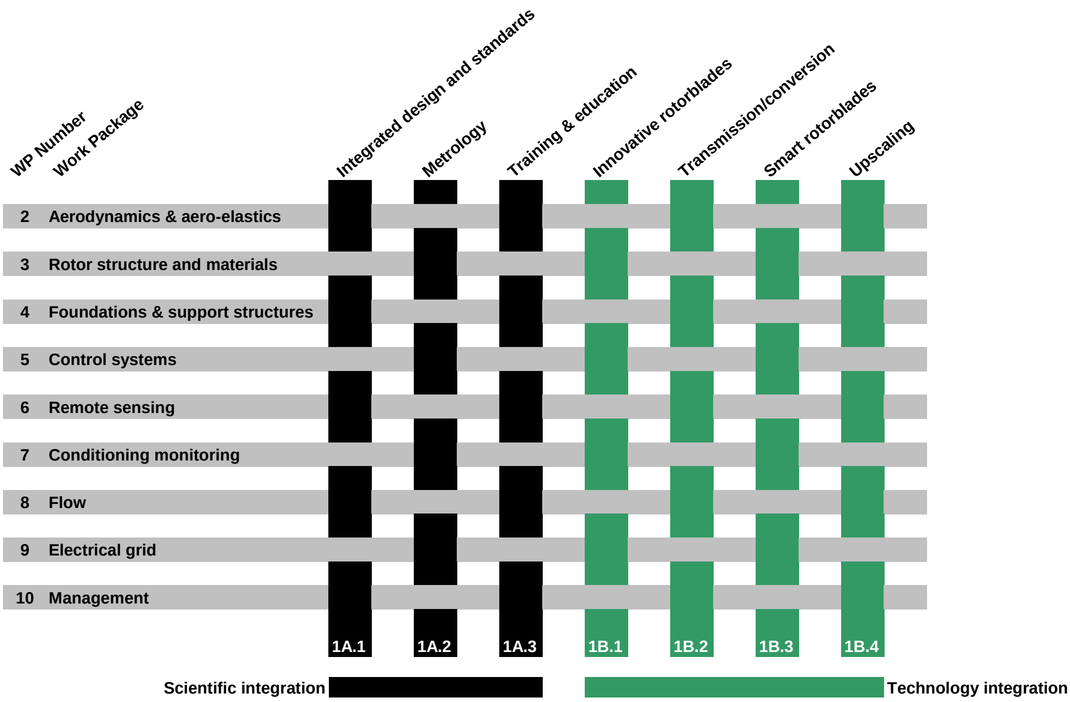


Figure 1: Project matrix structure. Horizontal work packages are “scientific work packages and vertical are “integration tasks“, gathered in work package 1

The findings of the project are disseminated through a series of workshops and through the website www.upwind.eu to the widest possible audience by EWEA which represents members from over 40 countries, and 220 companies, including 98% of manufacturing industry, organisations and research institutions (activity integration).

UpWind develops and verifies substantially improved models of the principle wind turbine components, which the industry needs for the design and manufacture of wind turbines for future very large-scale applications. The wind turbines needed will be very large (>8-10 MW and rotor diameter > 120 m). Present design methods and the available components and materials do not allow such up-scaling. In order to achieve the necessary up-scaling before 2020, full understanding of external design conditions, innovative materials with a sufficient strength to mass ratio, and advanced control and measuring systems are essential. In order to achieve this up-scaling in the most efficient way the following critical areas were identified and addressed in this Integrated Project. Aerodynamics, aero-elasticity, structural and material design of rotors, critical analysis of drive train components and support structures (for offshore applications).These areas are analysed, and new design approaches and concepts developed, as well as supporting technology. As the characteristics of present monitoring and measuring techniques, and control concepts are insufficient the project improves those techniques with the focus on large wind turbine structures. New developments in the field of wind farm lay out, control, and grid connection constraints are translated into design requirements for new wind turbines.

The project has 8 so called “Basic Research Work Packages (WP), listed in the horizontal lines in Figure 1. Each WP stands on its own in the sense that they only contribute in part to the central objectives of the project. The results from these Basic Research packages are needed for use in the “Integration” work packages, whose objectives are fully aligned with the central objectives of the project. There are two types of Integration WP: the first covers science integration, and the second technology integration.

1.2 UpWind WP4 - general description and objectives

The primary objective of the offshore support structure work package (WP4) is to develop innovative, cost-efficient wind turbine support structures to enable the large-scale implementation of offshore wind farms across the EU, from sheltered Baltic sites to deep-water Atlantic and Mediterranean locations, as well as other emerging markets worldwide, such as the US and China. The work package achieves this by seeking solutions which integrate the designs of the foundation, support structure and turbine machinery in order to optimize the structure as a whole. Particular emphasis is placed on large wind turbines, deep water solutions and designs which are insensitive to site conditions, allowing cost-reduction through series production. The project and also the results reflect very much the current state-of-the-art of offshore support structure research. In terms of steel-type support structures, Figure 2 illustrates the current status.

For current offshore wind farms, monopiles are by far the most popular support structure type. For years, tools and design solutions have been available on the market for a number of years. However, for deeper water and/or larger turbines, the fatigue loading is becoming critical and the monopile dimensions are exceeding the current economic feasibility. Therefore, some of the research in WP4 focuses on an integrated optimization process for large offshore turbines in order to achieve optimized designs and/or to extend the applicability of these cost-effective support structure types.

For water depths larger than 30m and large and heavy offshore turbines, braced-structures, such as jackets or tripods, are the current solution. In the past years, different design tools were extended to take the more complex dynamics into account. However, these tools are not fully validated yet and mass production of these structures is still pending. Therefore, the goal of this research field is to assess the possible design solution for large-scale implementation using multi-member support structures. Here the costs of the different possible concepts are very important, beside their manufacturing and installation.

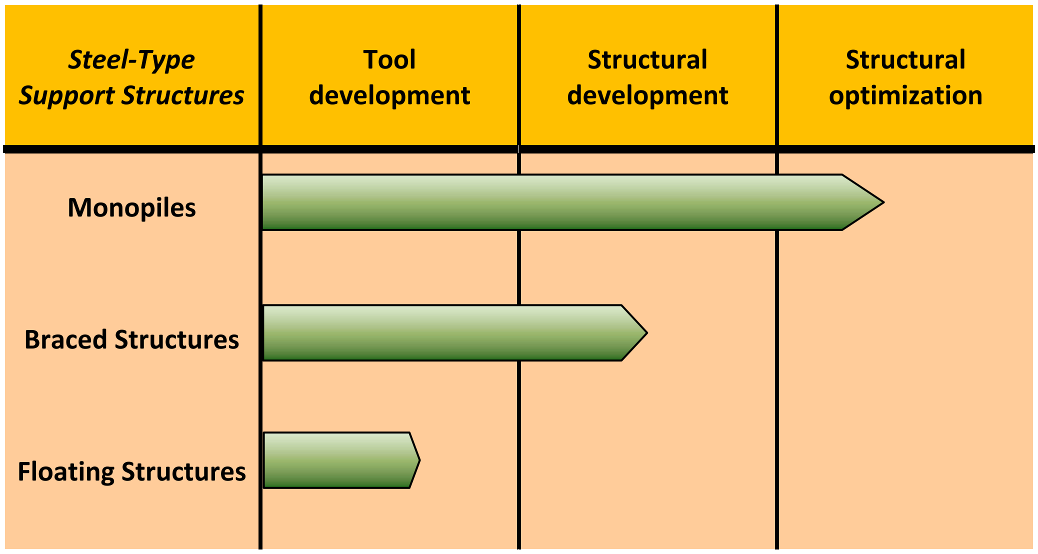


Figure 2: Overview of current research fields for offshore support structures

Finally, due to markets with very deep waters, floating support structures are becoming more and more important. Even if some prototypes are already built, current design tools and standards are not able to represent the complex dynamics and to deal with the different loading characteristics compared to bottom-mounted structures. Therefore, the current research focus is on enhancing available design tools and standardization in order to enable floating structures to become a cost-effective and reliable solution for future deep-water offshore projects.

Based on these current research fields, the work package is divided into three main tasks, which address the challenges described above. The tasks are:

- Task 4.1: Integration of support structure and turbine design for monopile structures
- Task 4.2: Multi-member concepts for deep-water sites
- Task 4.3: Enhancements of design methods and standards for floating support structures

This report is part of a set of reports which together make up the final reporting of Work package 4. The work done in each task is documented in a separate final report. One encompassing report summarises the findings of the WP in an executive summary (this report). The interrelation of the four reports is show in Figure 3.

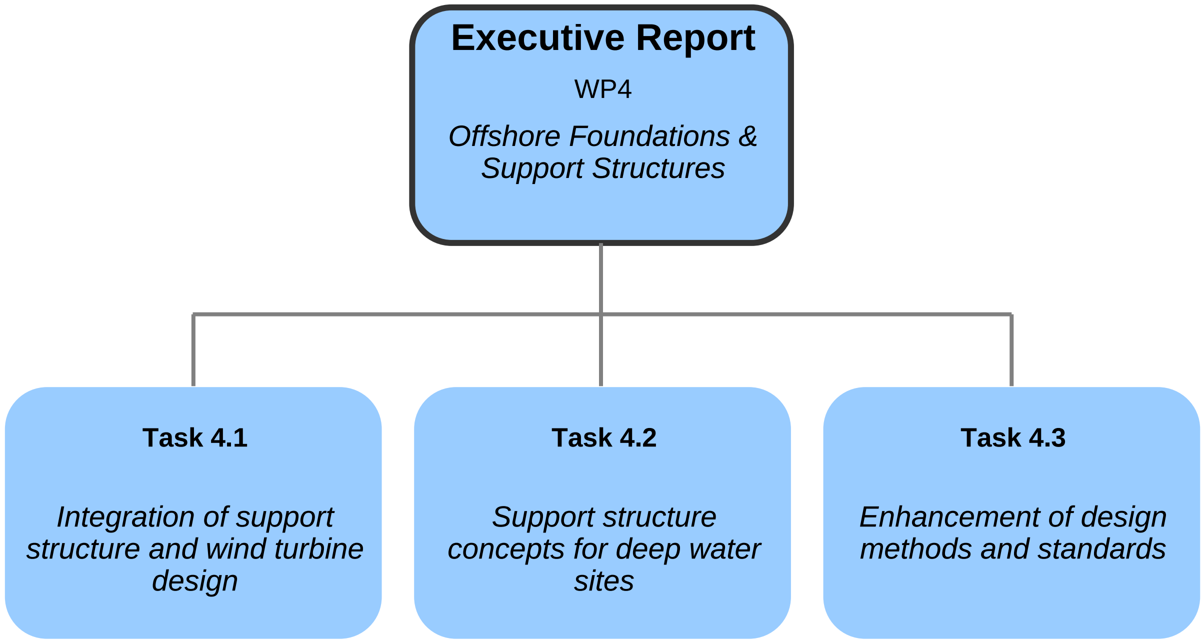


Figure 3: Context of reports in WP4

2. UpWind WP4 - work program and reports

The research activities in WP4 are divided into three Tasks, as shown in Figure 4.

Task 4.1 **Integration of support structure and wind turbine design**	**Task 4.2** **Support structure concepts for deep-water sites**	**Task 4.3** **Enhancement of design methods and standards**
Develop and enhance the integrated design process for offshore wind turbines	***Design innovative bottom-mounted support structures (e.g. truss-type)***	***Design tools and methods for bottom-mounted support structures***
Control concepts for mitigating aerodynamic and hydrodynamic loading	***Analysis of very soft structures (monopile- or braced-type)***	***Design tools and methods for floating support structures***
Compensation of site and structural variability	***Design floating structures***	***Support of the IEC-61400-3 offshore standard***

Figure 4: Three tasks and their main objectives in WP4

Figure 5 presents an overview of the total content of the work package, the associated deliverables and the time schedule for the three tasks. Each task's results are summarized in a separate final report, seen as last deliverable in the time line per task. The stated deliverables are listed again in more detail in Table 1 and if they are public or confidential within the project. All deliverable reports can also be found in the reference list.

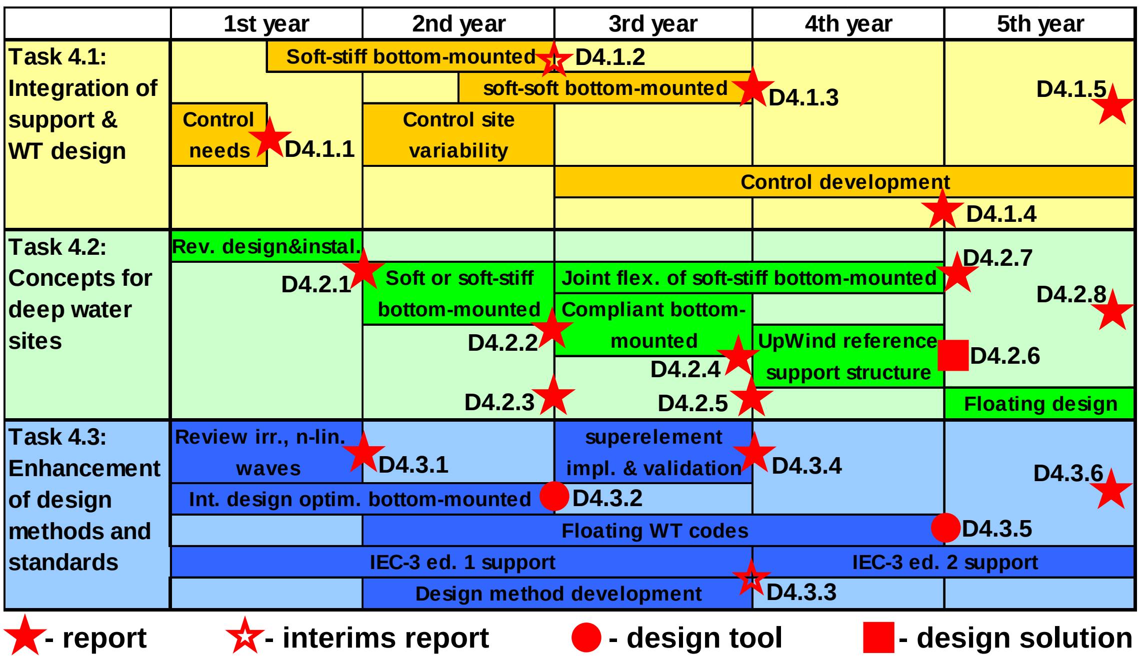


Figure 5: Working plan of WP4

Table 1: List of deliverables in WP4

No.	Month	Task	Description	Responsible	Confidentiality
D4.1.1	6	WP4.1	Definition of control requirements for mitigation of aerodynamic and hydrodynamic loads (incl. increase of aerodynamic damping)	USTUTT	Confidential
D4.1.2	12	WP4.1	Interim report on design integration studies on soft-stiff, bottom-mounted support structures	USTUTT	Confidential
D4.2.1	12	WP4.2	Assessment of bottom-mounted support structure types with conventional design stiffness (MP, TP, J) and installation techniques for a typical deep-water site (35m)	DUT	Public
D4.3.1	12	WP4.3	Irregular, non-linear wave loading of offshore wind turbines: Review of modelling approaches and their relevance for future designs	RISØ	Public
D4.2.2	24	WP4.2	Report on soft or soft-stiff bottom-mounted support structure types	DUT	Confidential
D4.2.3	24	WP4.2	Definition of a cost model for offshore support structures	DUT	Confidential
D4.3.2	24	WP4.3	Design tool for multi-member bottom-mounted support structures	USTUTT	Confidential
D4.1.3	36	WP4.1	Report on design integration studies on bottom-mounted support structures	USTUTT	Confidential
D4.2.4	36	WP4.2	Report on compliant bottom-mounted support structure types	DUT	Public
D.4.2.5	36	WP4.2	Implications of innovative support structures on condition monitoring systems	RAMBØLL	Confidential
D4.3.3	36	WP4.3	Interim report on review of IEC 61400-3 ed. 1 and support on development of ed. 2	GH	Confidential
D4.3.4	36	WP4.3	Report on implementation of a super-element approach in a design tool for braced structures	IWES	Confidential
D4.1.4	48	WP4.1	Report on controller development for mitigation of aerodynamic and hydrodynamic loads	USTUTT	Confidential
D4.2.6	48	WP4.2	Design solution for the UpWind reference offshore support structure	RAMBØLL	Public
D4.3.5	48	WP4.3	Design tool for floating offshore wind turbines	GH	Public
D4.2.7	48	WP4.2	Report on joint flexibilities of soft-stiff structures	IWES	Confidential
D4.1.5	60	WP4.1	Final report for WP4.1	USTUTT	Public
D4.2.8	60	WP4.2	Final report for WP4.2	DUT	Public
D4.3.6	60	WP4.3	Final report for WP4.3	GH	Public

3. UpWind WP4 - major achievements

The main goal of Upwind was to enable large-scale implementation of very large wind turbines. Therefore, the following main project objectives can be formulated:

- Innovations to enable Upscaling
- Enhancement of reliability and reduction of uncertainties
- Lowering of turbine and project costs

Within WP4, the research focus was on the achievement of these goals. In particular, the results can be summarized as follows.

Results in terms of **Upscaling**
In Task 4.1, the studies on load mitigation and the adapted integrated design approach including controls are becoming even more important for future large wind turbines, in particular for offshore.
Larger turbines have higher tower top masses. That is why the water-piercing members of their support structures will increase in diameter to provide sufficient stiffness. This will increase hydrodynamic loading and thus requires more sophisticated control concepts to reduce such loading. Additionally for larger turbines, different design concepts might be implemented, such as two-bladed turbines in a downwind configuration and on full truss towers. Such concepts will impose new requirements in controls and here Task 4.1 offers a range of possible solutions.

Another important result of WP4 in terms of upscaling is the design of a lighthouse reference support structure for a 20 MW offshore wind turbine. Even if the baseline turbine is artificial and probably not an optimized solution in terms of size and mass, the lighthouse structure illustrates what such a support structure would look like by using state-of-the-art design processes and tools. It allows discussions on necessary improvements to enable such large structures to become a suitable solution for future turbines. This includes discussions about fabrication, logistics and installations, but also new materials.

Finally, the activities in Task 4.3 in terms of tool development and benchmarking are important factor for enabling upscaling to very large offshore wind turbines. Here, especially the modelling of joints, as studied in Task 4.3, will become even more important for larger turbines than for current ones, as they are more likely to be placed on braced structures. This also requires more reliable and accurate simulation tools, which will be achieved through the tool developments and benchmarks performed within Task 4.3.

Results in terms of **Reliability / Uncertainties**
Achieving more reliable designs with lower uncertainties is a major criteria for the further large-scale implementation of wind energy. As the offshore trend is moving towards deep water sites due to the limited space at shallow sites, the reference jacket support structure designed for a water depth of 50 m in Task 4.2 is valuable. The structure acts as a reference for future offshore projects in deep water. Since the design is performed with current industry-standard approaches, it enables comparability within the wind community and therefore reduces uncertainties in many ways.
Thus, the structure can be compared with other support structures in project evaluations, and can also serve as a basis for sensitivity studies to reduce uncertainties. These studies can be implementations of certain design load cases and their effects on the structure or details of modelling and their impacts on design/loads. As a first adaption of the reference jacket support structure, the structure serves as baseline design for the currently ongoing IEA Wind Task 30

[20], whose major goal is to validate design tools and to thus reduce uncertainties in simulations.

One of the main focuses of Task 4.3 was the input to standardization, which fits very well with the overall UpWind objectives in terms of reliability and uncertainties. Here WP4 supported the maintenance team of the IEC 61400-3 [22] for the review of the current standard. This also includes the proposals for standard requirements for future floating support structures, which will require new definitions in standards in order to achieve safe and reliable designs.

Additionally, studies have been performed as part of Task 4.3 looking into the definition of current safety standards. As most of the current factors are based on other engineering practice, the studies in Task 4.3 with their special focus on wind turbines will support more reliable assumptions.

Results in terms of **Costs**

Finally all innovations shall result in cost-optimized designs, as this is a major need for the successful increase in installed capacities of wind energy. Here WP4 achieved major steps in terms of reducing costs in all three tasks.

The adapted design process of Task 4.1 illustrates the effectiveness of taking controls into account already in the design process of offshore support structures. The studied concepts have shown high potential for design optimization and thus lower support structure costs. Besides, the potential for reducing costs for materials, the applied control concepts could also be used to enable cheap support structure types to be installed in deeper water.

In Task 4.2, different cost models for support structures were designed. The studied models were done for monopiles and jackets and are able to take different sites (water depth and soil) as well as turbine types (size and mass) into account. The models were validated with publicly available cost data and showed good agreements. Such cost models are important tools to verify designs and they are rarely available in the wind community. Thus, the public availability of the WP4 results will support the overview of costs for the studied support structure types.

Finally in Task 4.3, the tool development and benchmarking which has been performed will enable more accurate simulation results for further optimizations and will lower safety margins in the mid and long term view. This also results in an increased confidence in calculation results, which then allows for reductions in model development costs and computational costs.

In the following, the detailed results of each task are highlighted; not only in the overall UpWind objectives context but in a broader scope.

3.1 Results of task 4.1

The objectives of this task are to mitigate dynamic support structure loading and to compensate for site variability through integration of support structure and turbine design and the use of turbine control. The work focuses on the mitigation of aerodynamic and hydrodynamic loads on the total offshore wind turbine system, as through this an optimized and cost-effective design can be ensured. This can be achieved by integrating the design of the rotor-nacelle assembly (RNA) and support structure in the design process. Hence, the RNA is considered as an active component to mitigate the loads on the support structure.

In a first step, the implementation of control concepts for load mitigation at the support structure imposes a number of general requirements to other components and also the full system, which have to be fulfilled (see deliverable D4.1.1 in Table 1). Examples are:

- Possible additional loading of other components of the RNA especially pitch drives, blades and sensitive drive train components like the gear box should be minimised. This includes checks for increased failure rates of other components by reliability investigations.

- Extra controller action will inherently reduce the energy yield of the offshore wind turbine by operation outside of the aerodynamic optimum and by direct energy consumption of the actuators. As a rule of thumb at least 4 – 5% cost reduction in the total support structure costs (material, manufacturing and installation) is required for compensation of each percent loss in energy yield, assuming a 20 – 25% proportion of support structure related investment of the cost of the energy.

- New control concepts require innovative control algorithms and robust load feedback sensors for structural response and possibly also for environmental conditions like wind and wave parameters.

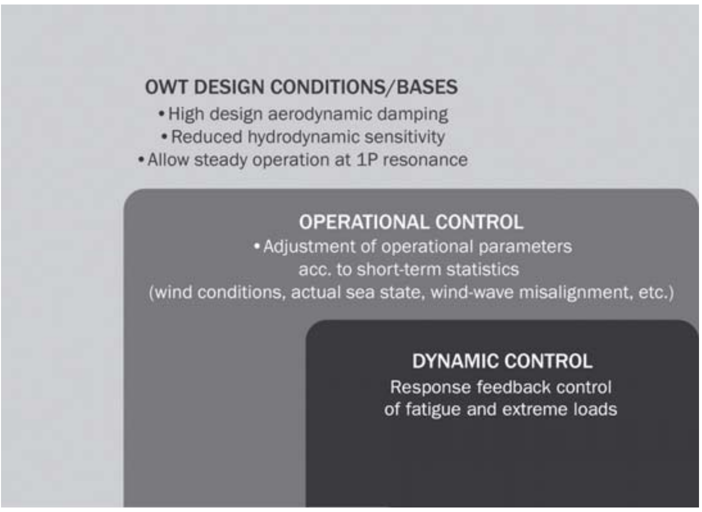


Figure 6: Levels of load mitigation

The implementation of control concepts depends, beside the capabilities of the RNA itself, essentially on the type of support structure and turbine.

For monopile support structures the overturning bending moment at mudline, or in reality some meters below seabed, is the most critical one in cases of fatigue. Here the major impact is of course in the fore-aft motion. The sidewise moment is also considerable, but only site-specific. In cases of strong wind- and wave-misalignment the sidewise quantity can become more important and even design-driving.

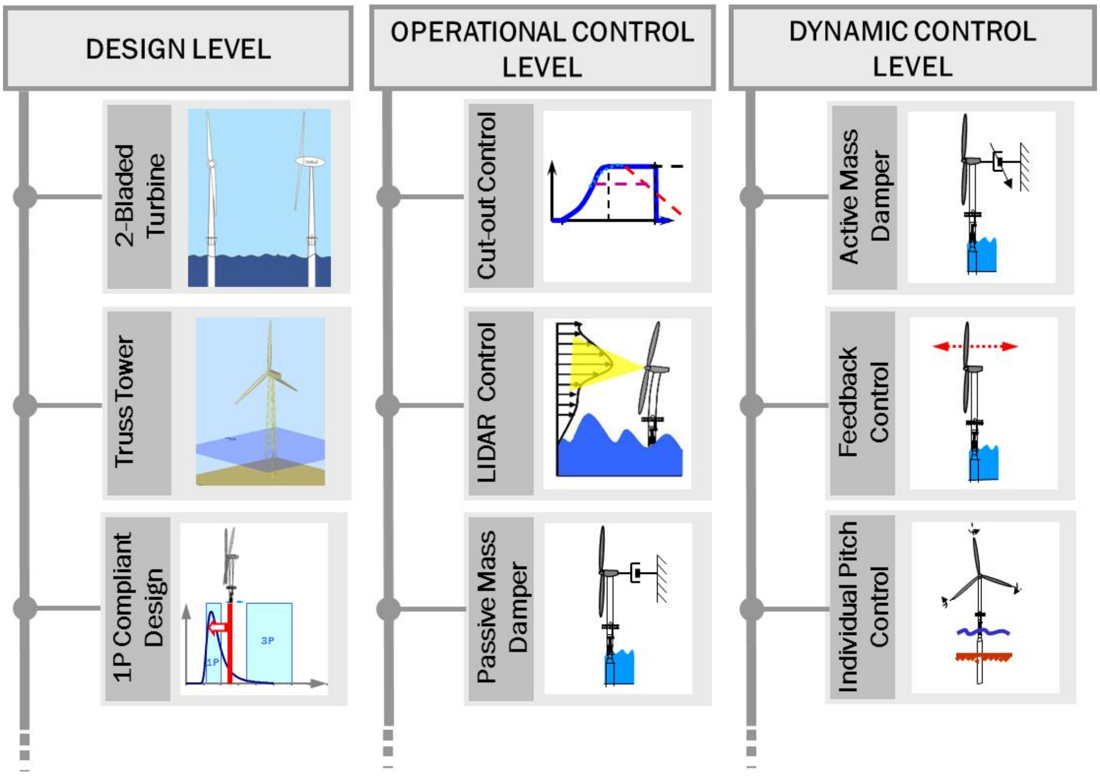


Figure 7: Levels and possible implementation of load mitigation

For multi-member support structures, the tripod is compared to monopiles much stiffer and therefore the dynamics are less pronounced which should limit the prospects of controller strategies for increasing the damping. However, in certain cases load phenomena comparable to monopiles can arise, which demand similar control strategies as for monopiles.
For jackets or truss tower configurations, there are several critical loadings. For jackets one of the critical loading situations might come from torsional loadings. This is somehow different for truss tower configurations, where on the bottom of the structure (close to seabed) the bending or buckling of the elements is critical and closer to the tower top (close to the nacelle) the torsional modes. However, it might even be possible that due to the stiffness and hydrodynamic transparency of such structures, any further concept to reduce dynamic response is useless – useless based on a trade-off between cost reduction for the structure and extra cost for the controller and additional loading of other components such as blades.

Besides the above-mentioned fatigue load cases for bottom-mounted support structures, the extreme loads can be essential for the design as well. Here it is difficult to predict certain operational or dynamic control options to counteract those loadings as several other aspects, such as safety and turbine-specific fault considerations, are also part of the process. However, control options like a safety operational mode in connection with remote sensing or an extended cut-out with a connected tower feedback controller might be options, which are worth to evaluate.

For load mitigation of the support structure, different concepts are possible and can be distinguished at three different levels according to the time scale involved. The levels can be identified in the design, operational control and dynamic control level as seen in Figure 6.

On the design level, the objective is to include load mitigating aspects already in the design of the offshore turbine itself or the wind farm layout. In the operational control level, the goal is to use already available operational control capabilities in order to reduce the loading on the support structures. Finally, different advanced dynamic control systems are available to damp the loads on an offshore wind turbine actively. In Figure 7, the three levels of load mitigation are listed again together with some examples for implementations.

Table 2: Studied concepts within Task 4.1

Design Level	Operational Control Level	Dynamic Control Level
Two bladed turbines	Soft cut-out	Tower-feedback control
Full truss-tower solutions	LIDAR control	Active idling control
Park configuration	Rotational speed window	Individual pitch control
Site-variable design	Passive structural damper	Active generator torque control
Robust design		Semi-active structural damper

Within the scope of Task 4.1, several concepts were evaluated as seen in Table 2. These concepts were evaluated in different reports in Task 4.1 (see deliverables D4.1.2 to D4.1.4 in Table 1). In particular, the conclusions of the performed studies are as follows:

DESIGN LEVEL

Two bladed turbine design

For current offshore turbine types, usually three bladed designs are used, as the concept has the best dynamic properties due to its symmetric layout. For future large turbine concepts, the blades are getting much larger and therefore play a major role in terms of costs. Besides, installation and maintenance of these farms are a factor in the cost-effective design of offshore projects. Therefore, a two bladed offshore-specific turbine design can be one design solution of the future, as the reduction of the number of blades lowers the costs for maintenance and holds a significant potential to be more cost effective in the production process. Two bladed offshore turbines are also easier and faster to erect, which brings a considerable cost reduction to the expensive offshore installations.
Still two bladed concepts face different critical loading phenomena compared to their three bladed competitors. But by connecting other concepts like individual pitch, downwind configurations or truss-type support structures, most of the disadvantages compared to three bladed designs can be eliminated and enables the two bladed concepts to be a competitive solution.

Truss-tower configuration

The usage of truss towers for offshore wind turbines still have some major drawbacks like much higher costs for fabrication and maintenance, which takes the advantage of saving material compared to solutions with tubular towers. The critical loadings for truss towers can be mitigated by using control concepts like individual pitch. In a combination with an offshore-specific turbine concept, such as two bladed machines, these structures can become a competitive solution for future projects. Especially their high stiffness might enable stiff-stiff design solutions beyond the critical turbine operation ranges and impacts from waves.

Park configuration

Offshore wind farms are nowadays mainly planned according to minimizing the wake effects and thus maximizing the power output. But a wind farm layout with minimized wake effects does not necessarily mean the lowest loading on the turbines. Especially half wake situations do not have a high effect on power losses, but on the turbine loading due to increased torsional effects. Therefore, an approach could be to take both into account when planning an offshore wind farm, turbine power and loading. Of course, there are further influences defining certain locations for turbines, such as minimizing the cost for cabling or local soil conditions. Still, an integrated park configuration approach could lead to optimized designs in a global cost point of view.

Site-variable design
For some monopile designs in larger water depths, for poor soil conditions and/or larger turbines the support structure design might not be driven by the wind and wave loads but mainly driven by the requirement of sufficient dynamic stiffness in order to achieve a fundamental eigenfrequency at least 10 % higher than the rated rotational frequency of the machine (1P).

Instead of performing very costly support structure designs individually for each location, it might be more cost-effective to design a larger group of support structures by not taking the worst site and turbine conditions into account for the design-group, but an intermediate site or even the best conditions. If in such a case loading is not driving for the softest structures but for the exclusion ranges of certain rotational dependent turbine frequencies, there is a range of concepts available to avoid upcoming problems. By using different operational control concepts like rotational speed windows or even dynamic control concepts like semi-active structural damper devices, an overall trade-off for the whole offshore wind farm can be achieved. Finally one might think about site-specific turbines, which are able to adjust their rotor speeds to higher values in order to enable designs out of 1P resonances.

Robust design
Within this project, the main emphasis is on advanced turbine design and control concepts in order to achieve a cost-effective offshore wind turbine design. In order to complete the conceptual evaluations, an opposite concept is also possible. This concept excludes all advanced systems and reduces the amount of components in the turbine. Therefore, this concept is called robust design. Due to the lower amount of components, less failure shall occur or the investment costs shall be lower as well as costs for operations and maintenance. This leads in conclusion to lower levelized production costs, which are a measure of costs of a turbine per produced energy output.

Different to robust concepts from the past, which were fixed-speed, stall-regulated turbines, the solution for coming robust designs could be a stall-regulated concept with a variable-speed direct drive electric system and controlling generator torque so that the power output is kept stable beyond rated wind speed. This concept still includes on the one hand all advantages of a robust design with its rigidly mounted blades and fewer components for bearings and pitch actuators and on the other hand it provides a stable power curve and better controlled loadings. Additionally, due to its variable-speed characteristics provided by a controlled torque from the direct drive generator, the power losses before rated wind speed can be reduced. This also includes longer operations in the turbine’s optimal tip speed ratio. Especially for offshore wind farms far away from shore, such a system design for minimized failure, maintenance and maximized reliability and availability can be a competitive solution.

OPERATIONAL CONTROL LEVEL

Soft cut-out
This concept involves an extension of the power production range to higher wind speeds. As for the extension a reduced power level is targeted, it is often called soft cut-out. The range of normal operation for wind turbines is generally within a wind speed range of 4 to 25m/s. In some rare cases the cut-out wind speed is enlarged to higher values. If the turbine is once

beyond this level and shuts down, a switch back into the power production mode is only possible with a hysteresis and after a significant lower wind speed. Onshore this concept is reasonable, but offshore the common cut-out procedure might cause relatively high hydrodynamic excitations since no aerodynamic damping is present after a shutdown event. These adverse conditions become even more critical because high waves will persist even when the wind has already calmed down due to the time lag between mean wind speed and sea state conditions in a storm. Here the soft cut-out strategy can be suggestive, which has the goal to maintain a reduced power level beyond the former cut-out wind speed so as to use the aeroelastic response for damping the wave responses. Of course, due to the extended power range the loads on the RNA will increase, but due to the low probability of occurrence of such high wind speeds, the effects are low. On the other hand, the wave excitations can have a significant impact, even if the probabilities are low, by what such a concept can be beneficial. The important decision-maker for applying a soft cut-out is the type of loading at the given offshore site. As mentioned before, for sites with high amounts of hydrodynamic loading, such as possibly for monopiles in deep water, the extended power range can have a very positive effect on the support structure loads. But if a site has only a small amount of hydrodynamic fatigue loading and is mainly driven by the aerodynamic loads, such as possibly for monopiles in shallow waters, the concept can even have a contrary effect and it increases the overall support structure fatigue loads.
A further advantage of the soft cut-out are its effects on the energy output. First of all an extended power range will lead to a higher energy yield, which can be site-dependent between 0.5 - 1.5 %. Furthermore the concept provides stability to the electrical grid. As future large offshore wind farms will provide a large amount of electricity to the grid, a rapid drop-down in cases of wind speed changes due to strict cut-out behaviours can lead to breakdowns of a whole electrical system.

LIDAR control
This concept includes the use of light detection and ranging devices (briefly LIDAR). Here the LIDAR device can be used to detect critical extreme loads, such as gusts. By knowing the arising gust, the turbine can switch into a safety mode or can directly shut down. Thus, critical extreme loads can be reduced. Of course, the LIDAR device can also be included in a dynamic control system, where, based on the measured incoming wind speed signals, the gust loads are reduced by pitch actions while keeping the turbine in normal operations. However, for this approach an operational security, reliability and accuracy has to be established.

Rotational speed window
A well-known concept is the so-called rotational speed window. If due to design or, for example, changes in soil conditions the support structure eigenfrequency is in certain cases in resonance with a rotational frequency, this can be avoided by skipping this rotational speed range during operations. In such a case the rotational speed is fixed right before reaching the critical resonance frequency with the result of increasing torque. As soon as a certain torque level is reached, the rotational speed is let loose with the result of a fast increase of rotational speed and a reduction in torque. This fast event is then used to run quickly through the critical resonance.

Passive structural damper device
The enhancement of structural damping is another option for operation control. This can be achieved by including a structural damper device into the operation of the offshore wind turbine. Here a passive damper device can be implemented into the turbine in order to reduce loads. An example can be a clamped mass at the top of the tower for damping the support structure’s first eigenfrequency. These concepts are well-known from civil engineering and are yet not often used for modern turbines even if they contain a high potential. The advantage of such a system is that it is always operational, even if the turbine is non-available. And as for the soft cut-out, if a turbine is at a site with high hydrodynamic fatigue loading, non-availability and the connected loss of aerodynamic damping can have a significant effect on the support structure lifetime. In

such a case a passive mass damper would still be operational and would damp the hydrodynamically induced excitations. Besides, in the turbine's operational cases it can increase the amount of damping in the system.

DYNAMIC CONTROL LEVEL

Tower-feedback control

For mitigation of the fore-aft movement of a support structure, the main control goal is to enhance aerodynamic damping by pitching the blades accordingly to the measured tower top accelerations in order to provide a counteracting thrust for the tower vibrations. A classical concept is a tower-feedback controller. The advantage of this concept is that is does not require any additional components, as it uses already available pitch drives and is implemented by updating the controller itself. Furthermore, the additional control actions do not impose further checks for extreme loads, as the additional pitch actions are just slightly higher than at normal operations. The drawback of the concept is that any additional pitch actions increase RNA loads, such as for blade, hub, yaw, drive-train and pitch drives. But the increases in RNA loads are small and can be within the design limits if the controller is tuned smoothly in connection to the normal power production controller.

Active idling control

A further approach to decrease the fore-aft loads at the support structure is an active idling controller. In normal idling operations of a pitch-controlled turbine the blades are pitched to feather (85° to 90°) and are not or slowly turning. But in order to enhance aerodynamic damping of the rotor, the pitch angles can be reduced, which results in a higher rotational speed of the idling rotor. A small increase in idling rotor speed can already increase the effect of aerodynamic damping in a beneficial manner for the support structure. Of course, the rotor speed has to be kept small in order to keep blade and other RNA loads in a reasonable order of magnitude and to secure a safe operation of the turbine. This is done by changing the pitch angle actively according to the present wind conditions. However, some increases in RNA loads cannot be excluded, but they can be kept low if the set rotational speed level is not too high. As an example for a modern 5MW turbine design, a idling rotor speed of just 3rpm can already provide a considerable amount of aerodynamic damping. This active idling control concept combines very well with the tower-feedback controller. If the turbine is operating, the tower-feedback controller is active. In cases of non-availability of the turbine, the active idling controller can take over. However, if the reason for the non-availability is based on a failure in the turbine, it is not assured that the active idling controller can still be operated.

Individual pitch control

For the reduction of side-to-side motions of the support structure, which are mainly caused by wind and wave misalignment, the usage of individual pitch control is a reasonable concept. Here the blade pitch angles are changed according to the tower top accelerations. Through activating the individual pitch controller and therefore by having different pitch angles per blade, the concept generates a resulting edgewise shear force. This force is in normal operations for a collective pitch turbine cancelled out between the three blades, but in the case of the individual pitch controller it actively controls a component of the sideways force on the hub. The side-to-side mode is more directly linked to the side-to-side displacement than to the tower top rotation, so in this sense the individual pitch concept can provide more effective damping than the active generator torque concept. However, the individual pitch concept can mainly be effective at full power, where the aerodynamic torque varies a lot with the change in pitch angle. In partial loading and when the blades are near or at fine pitch, the effectiveness is low. This is a drawback of the individual pitch controller against the active generator torque system, as the latter concept is effective for all wind speeds. Furthermore, large misalignments between wind and waves, which cause the main sideways vibrations, occur more often at low wind speeds. Another disadvantage of the pitch-controlled concept is that it slightly increases the fore-aft component of the support structure loads and of course blade and pitch drive loads. Besides, it requires more sophisticated safety systems and extreme load checks, as the three blades operate at different angles during turbine operations.

Active generator torque control

As mentioned before for the individual pitch controller, there is another concept available for reducing side-to-side loadings on offshore support structures. The concept is based on the use of the coupling of the drive-train torque with the side-to-side support structure mode; this is why it is called active generator torque control. Effective damping is achieved when the control action leads to a force on the structure that couples with the mode of vibration that is to be damped, and acts in anti-phase with the modal velocity. The generator torque directly affects the torque applied by the shaft onto the gearbox. As the first support structure side-to-side mode includes some rotation of the tower top, and so of the gearbox, the generator torque therefore directly couples with the relevant mode of vibration. Therefore, the concept is called active generator torque control. The drawback of the concept is that it increases power fluctuations and loads in the drive-train, which might be critical for the gearbox. However, the blade loads are unaffected and yaw and hub loads are even decreased.

Semi-active structural damper device

After discussing load mitigation for certain support structure modes, there is also an integrated option. The passive mass damper device discussed for operational control can be extended to a semi-active system. Here the damping of the device can be actively controlled in order to match certain load events – fatigue and extremes. Here the solution can be based on using a magneto-rheological damper that is able to change its damping coefficients extremely fast. The benefit of this system is that it is very light as it is mainly designed out of three braces including the damper elements. But as for the passive device, the system imposes additional costs.

Table 3: Qualitative fatigue load influences on system quantities by applying dynamic control concepts

	Energy output	Power fluctuations	Support structure		Blades	Hub	Yaw	Gearbox	Pitch drives	System costs	Additional ULS case check[1]
			Fore-aft	Side-to-side							
TFC[fa]	➡	➡	⬇	➡	↗	↗	↗	↗	↗	➡	
AIC[fa]	➡	➡	↘	➡	↗	↗	↗	↗	↗	➡	●
IPC[ss]	➡	➡	↗	⬇	↗	↘	↘	➡	⬆	➡	●
AGTC[ss]	➡	⬆	➡	⬇	➡	⬇	↘	↗	➡	➡	
ASCO[fa, ss]	⬆	↗	⬇	↗	↗	↗	↗	↗	↗	➡	●
SAMD[fa, ss]	➡	➡	⬇	⬇	➡	➡	➡	➡	➡	⬆	●

TFC - tower-feedback control , AIC - active idling control , IPC - individual pitch control , AGTC - active generator torque control , ASCO - soft cut-out including TFC and AGCT , SAMD - semi-active mass damper

fa – controller tuned to work for fore-aft support structure vibrations

ss – controller tuned to work for side-to-side support structure vibrations

[1] – application of this control device might impose new requirements for extreme load checks

Table 3 illustrates as a summary the effects of the dynamic control systems on the offshore turbine and the associated cost impacts. Depending on the case-specific loading, an appropriate control concept or set of concepts can be chosen. This was done in a final demonstration study in Task 4.1 ((see deliverable D4.1.5 in Table 1). The case of a 5 MW turbine concept on a monopile in 25 m deep water was studied, which is a challenging design selection due to the significant impact of hydrodynamic loading and the required large piled structure.

In this study, the load reduction was used to optimize the structure in terms of cost. In the reference case, the support structure weight was 923 tons, while the optimised case led to a 838 tons design (9.2% mass savings). However, the application of such control concepts could also extend the application range for monopiles to deeper sites, as this concept will probably still be competitive against other more complex structures, such as jackets or tripods. In this study RNA loads are kept in reasonable magnitudes, which was also the reason for not achieving a higher amount of material savings.

In conclusion, all studied concepts showed that offshore-specific controls can be effective in reducing hydrodynamically-induced loading on offshore support structures. Here the amount of mitigation is very much dependent on the importance of hydrodynamic loading with respect to the overall fatigue. Finally, it depends on the selection of control concepts according to the chosen turbine and support structure type, but also offshore site.

The demonstration has shown the effectiveness of the integrated design approach by including load mitigation concepts for offshore support structure designs. In the future, where turbines are getting larger and heavier and the planned sites deeper, the need for such load mitigation concepts will increase in order to achieve cost effective designs.

3.2 Results of task 4.2

The aim of task 4.2 is to develop support structure concepts for large offshore wind turbines and deep water, including bottom mounted very soft and floating structures .

To meet this objective, first a survey of existing and proposed support structure concepts has been done. To establish the practical limitations and requirements for offshore wind turbine support structures, a review has been made of the fabrication process and installation methods for support structures. A description of the design methodology applied for monopile and multi-member structures is presented, including a review of design criteria.

Based on these findings reference designs for a monopile structure in 25 m water depth and a jacket structure for 50 m deep water have been made. Sensitivity analyses showed how the loads and required dimensions for these structures vary as functions of the main environmental parameters and for key turbine parameters. Using these findings the mass and costs could be determined for a variety of conditions, leading to cost models for the monopile and jacket structures.
To look beyond the established concepts an analysis has been performed of more innovative bottom-fixed support structure concepts, including a tripod, a three-legged jacket, and a hybrid monopile-truss structure.

Finally, conceptual studies for support structures with fundamental frequencies outside the conventional soft-stiff range have been performed, first for compliant fixed structures, secondly for floating structures. Also a design solution for a support structure supporting a fictitious 20 MW turbine is presented.

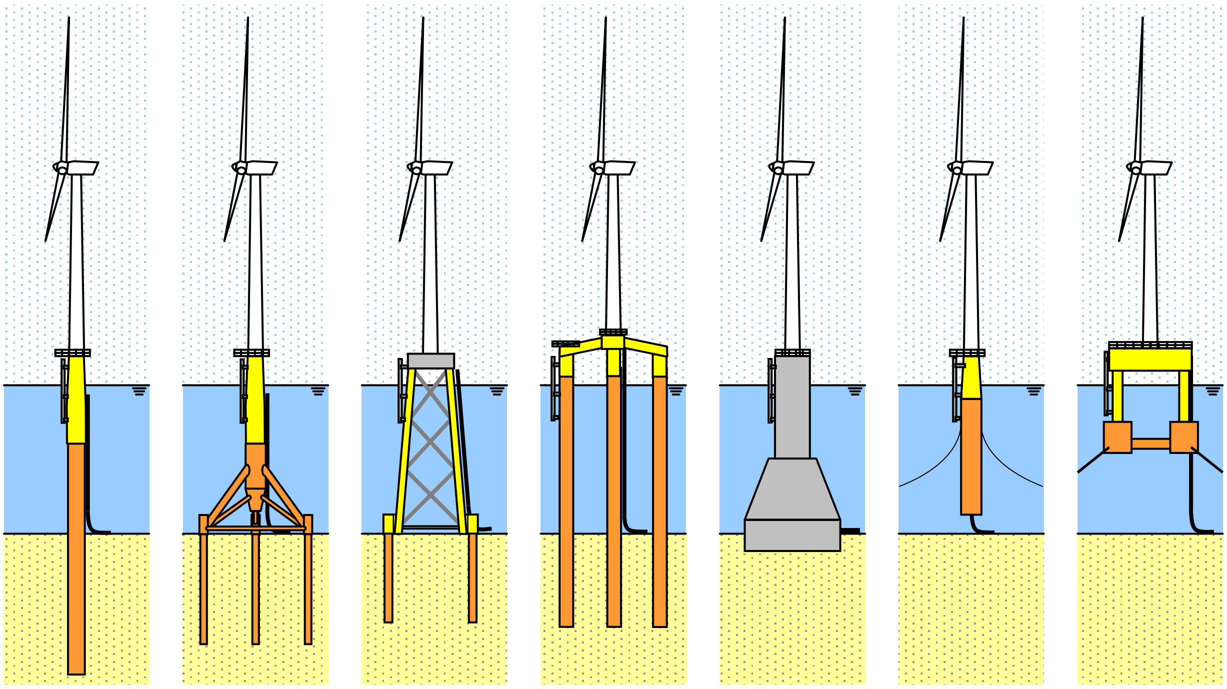


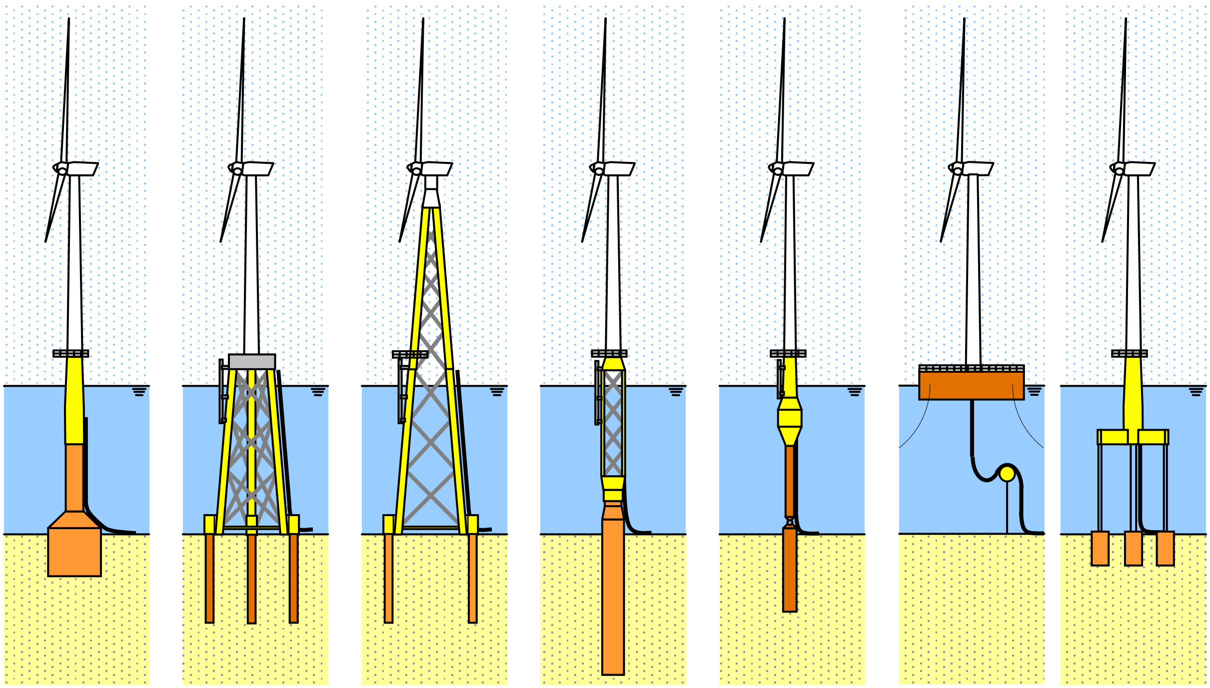
Figure 8: Existing support structure concepts

The results for task 4.2 have been documented in the Final report for WP4.2 (see Deliverable D4.2.8 in Table 1). The work in this task can be divided into three parts, starting with a review of support structure concepts, fabrication ad installation issues and the design process. This part is followed by an assessment of bottom mounted support structure concepts. Finally support structure concepts with fundamental frequencies outside the soft-stiff range are described. The results and main conclusions are presented hereafter and follow the general content of the Final report for WP4.2.

Part I A review of support structure concepts, fabrication and installation issues and the design process

An overview of support structure concepts
With the number of offshore wind farms rapidly increasing, in a wide variety of site conditions and using different turbine sizes, many concepts for support structures have been proposed, some of which have been realised. Existing structures include fixed steel structures, concrete gravity foundations and floating structures (see Figure 8).

- Monopile
- Tripod
- Jacket
- Tripile
- Gravity based foundation
- Spar floater
- Semisubmersible floater



Suction can monotower | *3-legged jacket* | *Full truss structure: 3 or 4 legs* | *Monopile - Truss Hybrid* | *Compliant structure* | *Barge floater* | *Tension leg platform*

Figure 9: Proposed support structure concepts

Alternative support structure types have been proposed, of which several may be suited for deep waters (see Figure 9).

- Suction bucket monotower
- Three-legged jacket
- Full truss structures

- Hybrid monopile-truss structure
- Compliant structure
- Barge floater
- Tension leg platform

In the early stages of the project an assessment of the aforementioned support structure types was performed using an evaluation matrix filled out by a number of participants of the work package (see Deliverable D4.2.1 in Table 1). The monopile appears very suitable for water depths below 25 m, but for increasing water depths it becomes progressively less suitable, while the jacket support structure performs relatively constant for all water depths. Floating structures perform best in deep water. These results helped to perform effective qualitative and quantitative assessments in later stages.

Fabrication and installation issues

The manufacturing processes for monopile structures and for multi-member structures such as jackets are substantially different. Monopile structures consist of large diameter elements that are heavy, but relatively simple to produce and assemble.

While the jacket structure consists of much smaller elements, the fabrication of joints requires more effort and assembly of the structure involves the welding of many connections.

After the primary structure is assembled, it requires blasting and the application of a protective coating. Subsequently secondary items such as boatlandings, J-tubes, ladders and platforms are mounted.

For these reasons the costs for producing a monopile structure is in the order of 2 €/kg, whereas the production costs for a jacket substructure are in the range of 4-6 €/kg. The fabrication of conical sections is more costly, therefore the costs of towers can be estimated at 2-3 €/kg.

Also the installation process varies significantly for the different support structure concepts. The installation of monopile structures involves driving a single large diameter pile into the soil. Subsequently, the transition piece is installed on top of the foundation and fixed by means of a grouted connection. For jacket and tripods 3 or 4 smaller diameter piles are to be installed. These may be pre-or post installed. The substructure is lifted onto the seabed and the connection with the piles is made by filling the annulus between pile and leg or pile sleeve with grout.

The turbine tower is installed, generally in two pieces and bolted. Finally the rotor-nacelle assembly is installed, sometimes with two blades pre-attached and lifting the final blade in place separately or by installing the nacelle first and the pre-assembled rotor later.

For the installation of support structures limiting factors are the lifting capacity and transport capacity of installation vessels, the ‘reach’ of the cranes to install rotor-nacelle assemblies and the energy and size of piling equipment and transit times.

Design methodology

Based on a review of design standards, design cases and practical experience, the design process is described (see Deliverable D4.2.8 in Table 1). It starts off by establishing the site data and turbine parameters in a design basis. An allowable natural frequency range is defined. Subsequently, the initial geometry is determined, based on rules of thumb and practical experience. Important data that must be defined are the elevation of the interface between the tower and the substructure.

On the basis of the environmental conditions, a set of design load cases are defined including a large number of combinations of wind speeds and directions, wave heights, periods and directions. Subsequently, the extreme loads on the structure are determined. These are used to determine the penetration depth of the foundation piles. With the extreme loads yield and stability checks are performed. The wall thicknesses of members that do not pass these checks are increased. Finally, a fatigue assessment is performed.

Part II Assessment of bottom mounted concepts with conventional stiffness

Monopile reference structure

The monopile reference design has been carried out for a shallow water site with conditions that lead to hydrodynamic dominated fatigue. As such the monopile reference design was well suited to demonstrate the load mitigation and control strategies from task 4.1. The reference design approach included two stages. First, a preliminary design was made, based on superposition of hydrodynamic loads and predetermined aerodynamic loads. In the final design stage a fully integrated time domain analysis was performed for a large number of load cases, including extreme event and fatigue analyses.

The resulting design comprises a foundation pile with a bottom diameter of 6 m and a conical section tapering to a top diameter of 5.5 m. The embedded length is 24m and the total length is 54 m. The transition piece has an outer diameter of 5.8 m and a total length of 18.7 m. A tower of 68 m length is used, leading to a hub height of 85.2 m. The overall mass of the primary steel for the foundation pile is 542 tonnes and 147 tonnes for the transition piece. The required wall thickness for the monopile and transition piece is driven by fatigue, whereas the penetration depth is driven by extreme loads and natural frequency requirements.

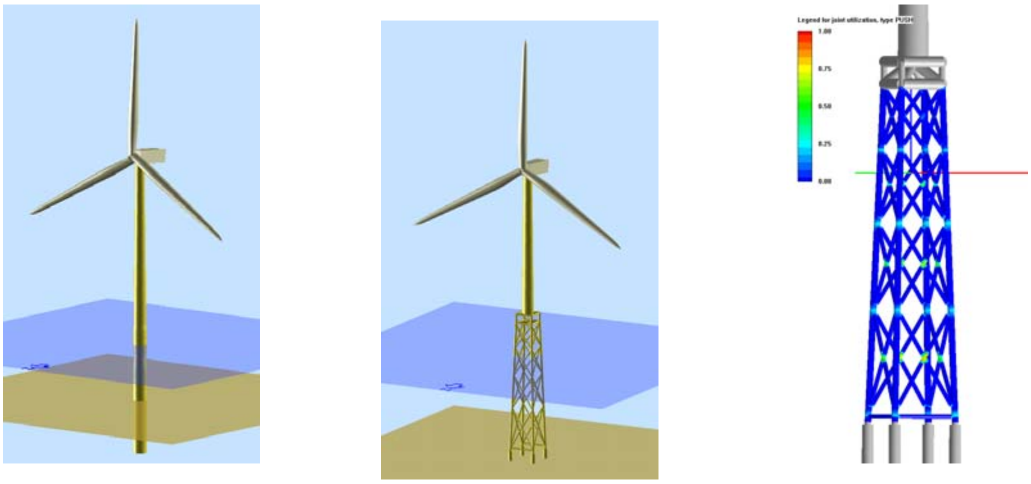


Figure 10: Monopile (left) and jacket reference structures

Jacket reference structure

The Upwind reference jacket structure (see Deliverable D4.2.6 in Table 1) is intended to demonstrate a design solution for a support structure for an offshore wind turbine in 50 m of water and may be used for comparison with other support structure concepts and the demonstration of the sensitivity to environmental conditions and to structural parameters. The jacket structure designed in this task is used as a reference structure in the IEA Wind Task 30 Offshore Code Comparison Continuation project OC4 [20].

A parameter study in which the jacket bottom width was varied and the remaining dimensions of the jacket foundation were kept constant yielded a suitable preliminary geometry. After completing a preliminary design based on simplified loads for extreme event and fatigue, the detailed design was performed. In this phase, time series of aerodynamic loads were combined with wave time series to establish the dynamic response to extreme event and fatigue load cases. The structure was optimised to fulfil the requirements for natural frequency, strength, stability and fatigue life. The final design shows that the critical locations for the ultimate limit state are in the X-braces at the jacket base, whereas for fatigue the critical joints are the connections of the top X-braces to the legs.

The interface level and hub height are set at 20.15 m and 90.55 m above MSL. A concrete transition piece is applied with length and width of 9.4 m and 4 m height. Due to the large water depth at this site, four levels of X-braces are implemented in order to comply with the requirement of the minimum angle between chord and brace. A jacket bottom width of 12.0 m is chosen. The mass of the concrete transition piece is 666 tons, while the overall mass of the primary steel for the jacket structure is 983 tonnes, the piles accounting for 438 tonnes and the jacket substructure contributing the remaining 545 tonnes.

Cost models

A cost model has been established for monopile foundations (see Deliverable D4.2.3 in Table 1). This allows for quick assessment of the impact of changing turbine parameters on the support structure costs. The model has been set up to determine the overall mass of the support structure based on a limited number of input parameters for the environment and the turbine. Parameters for the turbine are rotor diameter, rotor speed, and turbine mass. Environmental parameters included in the model are water depth, wave height and soil conditions. The dimensions of the support structure are determined on the basis of the natural frequency and a stress check for combined wind and wave loading. The overall costs are calculated based on material costs in which costs for the manufacturing are included.

A validation of the model has been performed using support structure mass data and the corresponding environmental data and turbine parameters of two existing projects and the monopile reference design. The results match the mass of the actual projects and the reference design within 10 %.

A similar costing tool has been made for a jacket structure and is described in the final report for task 4.2 In this model the mass of a jacket support structure is determined as a function of the water depth, turbine size and soil conditions. This shows that the mass of a jacket structure increases approximately linearly with water depth. Limited data is available for verification, but comparisons with the jacket reference design and with a jacket design for the Alpha Ventus wind farm show that the resulting masses determined with the cost model are within 10% of the masses of the compared designs.

Analysis of alternative soft-stiff support structure concepts

Apart from the reference designs for the monopile and jacket structures, several other support structure concepts have been assessed. Preliminary designs were made for a tripod, a three-legged jacket, and a monopile - truss hybrid in 50 m water depth. Also a monopile structure has been designed as a reference. The reference jacket structure is also included in the comparison. The results of this analysis show that the three legged and four legged jacket structures are best suited for the conditions considered. The three-leg jacket concept shows a lower overall mass than the reference jacket, but the detailing of leg-to-brace connections is critical due to the narrow angle between the braces at the leg. The monopile-truss hybrid structure is only marginally heavier than the four-leg jacket. Compared to an equivalent monopile it experiences significantly lower hydrodynamic loads than and is also significantly lighter. The tripod is significantly heavier than the jacket structures and the monopile-truss hybrid structures. It accumulates high fatigue damage at the connections of the legs and braces to the central column. Finally, the monopile is the heaviest structure, also experiencing high fatigue damage, mainly due to hydrodynamic loading.

Part III A conceptual analysis of structures with non-conventional stiffness

Compliant structures

Up till now support structure types with fundamental frequency in the soft-stiff range have been assessed. A different approach is to design a structure in the soft-soft range. For offshore wind turbines this means that the fundamental frequency is approximately in the wave frequency range with high energy content. A way to circumvent this is to design the structure to have a

fundamental frequency below the wave frequencies with appreciable energy. This approach has been applied before in the oil and gas industry, where such structures are called compliant towers.
The aim of this part of the research was to identify possible concepts that suit the conditions for large turbines in deep water and to indicate areas for further research (see Deliverable D4.2.4 in Table 1).
In order to achieve sufficient flexibility for a compliant structure to locate its first natural frequency inside the soft-soft range and below wave frequencies with high energy artificial soft spots are required. However, it is difficult to achieve strength and stability requirements for such a structure at the same time. Therefore additional restoring force is required. A study in which an extended monopile, a compliant piled tower and an articulated buoyant tower have been evaluated showed that it is possible to design an articulated buoyant tower as a compliant structure in 50 m water depth. The mass savings compared to a soft stiff design for the same conditions were found to be approximately 100 tons in this preliminary assessment. For the other two concepts it has not been found possible to achieve a compliant design for the considered conditions, as the strength and stability requirements cannot be satisfied simultaneously with the natural frequency requirements.
Compliant structures for offshore wind turbines could be effective in intermediate water depths, where bottom-mounted structures may no longer be viable and floating structures might still need too much buoyancy to be cost effective.

Floating structures

A comparison of several floating support structure concepts has been made which includes a tension leg platform floater, a spar buoy and a barge floater. The concepts have been compared based on statistics, extreme event analysis, instabilities and fatigue life evaluations. The simple design of a barge floater may prove to be cost effective for benign sea conditions. The spar buoy is better suited for harsh sea conditions, but its deep draft and the large ballast make the structure relatively expensive. Regarding ultimate strength and fatigue considerations, the tension leg platform appears to perform best, but the installation procedure and the large mass makes it an expensive structure type. The results of these comparisons help to resolve fundamental design trade-offs between these floating concepts

Support structure design for a 20MW turbine

A design for a jacket foundation for a 20MW turbine has been made. The 20 MW turbine used is the result of the application of classic upscaling coefficients rather than more realistic values as e.g. obtained from turbine development trends over the last years, leading to a very heavy, unrealistic design. Due to the low rotor speed of the 20 MW turbine the upper boundary of the 3P range is at 0.306 Hz. Therefore a stiff-stiff design is considered, rather than the conventional soft-stiff approach.
The foundation design is considered reasonably only in relation to the given tower and RNA configuration. Nevertheless, the designed foundation structure is very large and not expected to be a good representation of future jacket foundation structures for 20MW turbines. The resulting jacket structure has a top width of 28m and a base width of 42m. The overall structure mass, including piles, transition piece and jacket is 5610 tons. The associated first natural frequency is 0.297 Hz. As such the structure’s first natural frequency falls within the 10% safety margin at the upper end of the 3P range. However, it is shown that it would be possible to achieve a design with a first natural frequency in the stiff-stiff range when the RNA mass and rotor diameter are scaled in more line with technological developments. Other possibilities for enabling the application of 20 MW wind turbines offshore is by employing lattice towers instead of the tubular tower used in this design.
Equipment and facilities for fabrication, transportation and installation of the designed foundation components are available even nowadays. Limitations arise in connection to the installation of the given tower and RNA components due to the large hub height as well as for fabrication of the tower segments due to the large diameter.

3.3 Results of task 4.3

The development of innovative support structure concepts and offshore wind technology in tasks 4.1 and 4.2, both bottom-mounted and floating, requires enhancement of the capabilities of existing design tools and methods with respect to the description of wind turbine, support structure and site characteristics as well as the rapid processing of many similar designs. The objectives of task 4.3 are to enhance integrated design tools for the automated design of large numbers of structures at deep-water sites, and to actively support the development of dedicated international standards which specify best practice for the design of offshore wind farms (e.g. site-specific design, aerodynamic and hydrodynamic impact, low-risk structures, floating concepts).

PART I – Design Methods for Bottom-Mounted Support Structures

1. Integrated design tools

Historically aeroelastic simulation tools have been developed for onshore wind turbine simulations. It is possible to adapt these tools for offshore applications, but in order to calculate the loads on bottom-mounted multi-member support structures like tripods and jackets, the existing design tools and methods must be extended and enhanced. Three different approaches to performing integrated design load calculations for fixed-bottom offshore wind turbines with complex support structures are presented.

The first approach is the coupled aero-elastic and FE method. After the second year, a new design tool for integrated simulations of multi-member offshore wind turbine support structures was completed. For the bottom-mounted part, the finite-element-based code FECOS with hydrodynamic loading capabilities was employed, which was coupled to the Flex5 simulation code for the modeling of the rotor-nacelle assembly (see Deliverable D4.3.2 in Table 1). Flex5 has also been coupled with Poseidon and ASAS to enable accurate simulations of offshore wind turbines with complex support structures. The advantages and disadvatanges of these methods are presented.

The second approach is the combined multibody/modal method. One example of this approach is the GH Bladed software tool. An overview of the GH Bladed code is presented, including a summary of the recent development into a multibody representation of the structural dynamics.

The third approach is the full finite element method. One example of this approach is the ADCoS-Offshore software tool. An overview of the ADCoS-Offshore code is presented, including a description of the coupling between the core ADCoS code and ASAS to allow for simulation of offshore wind turbines.

2. Benchmarking of design tools

Benchmarking exercises are important to validate design tools against each other. A number of WP4 members were involved in the OC3 code comparison project under IEA Wind Task 23, in which a monopile and a tripod support structure were modelled and compared using the coupled tools partly developed in Upwind WP4. This included basic comparisons of frequencies and masses, together with time histories and auto spectra derived from simplified load cases. For the following IEA Wind Task 30, the WP has provided a reference jacket model for the continuation of the comparison work with a more complex structure (described in Section 4.2). Again, several WP members are involved in the new IEA Wind Task and gave support on the jacket structure modeling. The goal will be, as for the monopile and tripod in the IEA Wind Task 23, to reduce uncertainties between different design tools in the wind energy community and therefore enable more accurate designs in the future. For jacket structures in particular such a code-to-code comparison is important, as it seems to be the support structure type of the coming years in medium to deep waters.

In addition to the above interface with the IEA Wind Task code comparison projects, benchmarking exercises have been performed for the tools presented in chapter 1. Three fully integrated tools are applied in the analysis - namely Flex5-Poseidon, GH Bladed and ADCoS-

Offshore, all of which can be used for simulating arbitrary bottom mounted offshore wind turbines. The benchmarking exercises carried out in this chapter are performed with the NREL 5MW baseline wind turbine mounted on the UpWind Reference Jacket support structure designed by Rambøll.

3. Advanced modelling approaches

There are a number of features unique to multi-member support structures, in particular the presence of complex joints, which require enhancement of design tool capabilities and techniques.

As a first step, investigations were carried out to determine the influence of joint can modeling on the global dynamic simulation of a jacket support structure. The NREL 5MW baseline wind turbine was used, mounted on the Upwind Reference Jacket support structure. The mass difference due to joint can modeling is approximately 1.7% w.r.t. the offshore wind turbine as a whole and the differences concerning the first 18 natural frequencies are under 0.8%. These are minor differences that are not expected to lead to significant changes in the loads in more detailed investigations. Therefore it is concluded that it is an acceptable assumption to carry out further investigations on the UpWind Reference Jacket structure with a basic model neglecting joint cans.

A superelement technique for braced support structures was developed, to enable a more detailed modelling of joints in multi-member space-frame support structures. This was implemented in the design tool ADCoS-Offshore, a nonlinear finite element code for the modelling of bottom-mounted offshore wind turbines (see Deliverable D4.3.4 in Table 1). Detailed FE models of the required components were generated in ANSYS, and the degrees of freedom reduced into a super-element mass and stiffness matrix file suitable for inclusion into ADCoS-Offshore (see Figure 11). The stiffness properties and displacements were checked via comparisons with ANSYS models, and good agreement was obtained. The results of the studies showed the importance of these modelling techniques, especially for structures with large joints such as tripods.

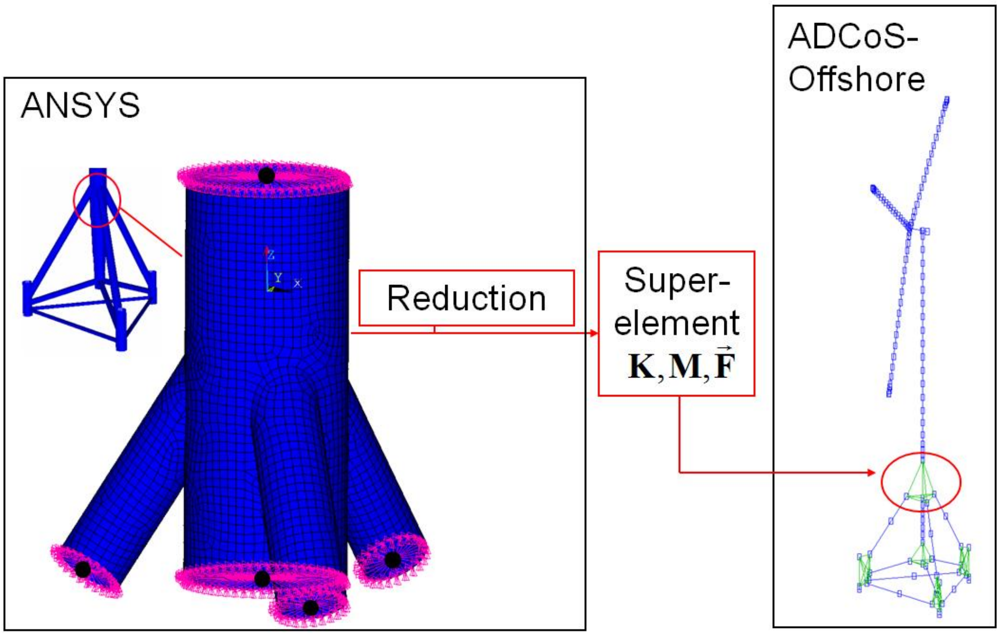


Figure 11: Superelement approach in ADCoS-Offshore. The central joint of a tripod is condensed and the superelement is included in the overall turbine model for time domain simulation.

4. Development of design requirements

As offshore wind turbine support structures become more complex, the design standards used in the industry must undergo corresponding development. It is important that both normative requirements and informative methodologies are updated and improved with respect to the more advanced kind of braced support structures which are increasingly being used to support offshore wind turbines. As part of WP4 the development of the IEC 61400-3 international design standard for bottom-mounted offshore wind turbines was actively supported. A review of various models for irregular, non-linear waves suitable for design purposes was performed, in order to judge their relevance for future offshore wind farms (see Deliverable D4.3.1 in Table 1). An interim review of the first edition of the IEC 61400-3 standard was performed, including recommendations for the development of future editions (see Deliverable D4.3.3 in Table 1).

A reliability-based investigation was performed into the required safety factor / Fatigue Design Factor (FDF) values to be used for fatigue design of steel substructures for offshore wind turbines. Design and limit state equations are formulated and stochastic models for the uncertain strength and load parameters are described. The results indicate that for fatigue critical details where the fatigue load is dominated by wind load a FDF value equal to approximately 2.5 is required – slightly smaller FDF values can be used for single wind turbines. If wave load is dominating a larger FDF value is required, approximately 3.5. The differences are mainly due to additional uncertainty due to wakes in wind farms and implicit safety included in the wind load model by using a 90% quantile for the turbulence in deterministic design.

The number of design load cases required for full offshore support structure design is potentially very large, and this can become even more impractical when complex multiple-member support structures are considered. Recommendations are given for the implementation of a reduced set of offshore wind turbine design load cases according to the IEC 61400-3 standard for the preliminary design of jacket support structures.

Finally, a design load case parameter analysis was performed for the UpWind reference jacket support structure. The relative influence of a number of key fatigue and extreme design load case parameters was investigated, in order to identify the sensitivity of jacket support structure design to these parameters. The fatigue loading on the structure was found to be dominated by the wind, with a relatively low contribution from the hydrodynamics. This is reflected in small changes in DEL when marine parameters are varied (tide height, wind/wave misalignment) compared to large changes in DEL when wind parameters are varied (wind class). The parameter which has the most effect on fatigue loading is the structural natural frequency. This demonstrates the importance of placing the natural frequency in the right range when designing a jacket support structure. The parameter which has the most effect on the extreme loading on the structure is the wave period of the 50 year maximum wave. This should be set to the lower bound to give conservative load results.

PART II – Design Methods for Floating Support Structures

1. Integrated design tools

Consideration of the floater kinematics and additional aerodynamic, hydrodynamic and mooring line effects on floating offshore wind turbines (FOWTs) imposes entirely new requirements for integrated design calculations in the time domain (see Figure 12). In order to accurately model these effects, existing design tools and methods require significant development and enhancement.

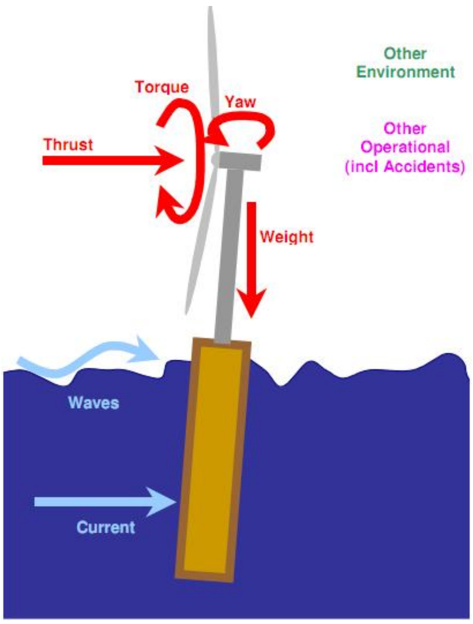


Figure 12: Principal design loads on floating offshore wind turbine

A review of the current state-of-the-art in floating wind turbine design tools was performed, giving an overview of modelling techniques for FOWTs and the advantages and disadvantages of the various approaches (see Deliverable D4.3.5 in Table 1). The following development needs for floating design tools were identified as the main areas in need of more research:

- Testing and validation of floating design tools using measured data and further code-to-code comparisons
- Further research into aerodynamic and hydrodynamic theories applicable to FOWTs, specifically rotor-wake interaction for turbines with large low-frequency motion and second order hydrodynamics for floating bodies with large displacements
- Studies into the effects of mooring line dynamics on floating wind turbines, including an analysis of the importance of dynamics for different mooring system configurations and water depths.

2. Benchmark of tools

Benchmarking exercises have been performed to validate the existing floating design tools. A number of UpWind WP4 members were involved in Phase IV of the OC3 code comparison project under IEA Wind Task 23, in which a floating offshore wind turbine was modelled on a spar-buoy platform. A summary of the results from this project is presented.

The GH Bladed code has been developed from a simple modal representation of structural dynamics into a multibody representation, which enables more accurate modelling of the large displacements and increased number of degrees of freedom experienced by floating wind turbines. The testing and validation of the new code structure is presented (see Figure 13).

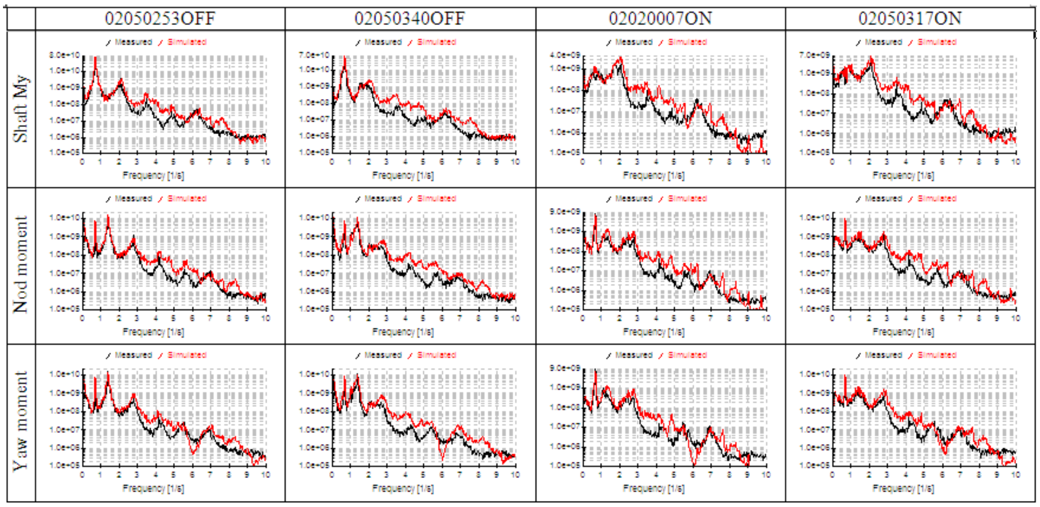


Figure 13: Example of Bladed v4.0 multibody validation against measurements (spectra for tower top loads)

3. Advanced modelling approaches

Advanced modelling methods and techniques are required for detailed studies of particular aerodynamic, hydrodynamic and mooring line effects unique to FOWTs. New developments and methodologies for the analysis of FOWTs are presented.

Regarding aerodynamics, the large low-frequency platform motions experienced by floating offshore wind turbines result in flow conditions which are considerably more complex than those experienced by conventional onshore or fixed-bottom offshore wind turbines and are not captured by BEM. Significant pitch and surge motions lead to a change in the interaction between the rotor and wake. Dynamic stall and yawed inflow models also have increased importance for FOWTs. The limitations of BEM and the capabilities of CFD and potential flow methods (PFM) for FOWT simulation are discussed. First indicative results and comparisons from new aerodynamic (PFM, CFD) models are presented.

For modelling of non-slender floating platforms potential theory is required in order to correctly determine the local pressure force and global wave loads due to diffraction and radiation.. Significant platform movements require inclusion of wave radiation forces, and non-cylindrical elements demand modelling of added mass-induced coupling between hydrodynamic force and support structure acceleration. Second-order linear hydrodynamics may also become important for FOWT simulations. The results of detailed comparisons between first and second-order hydrodynamic models for simple floating body configurations are presented. The development of non-linear potential flow based methods is outlined, and the importance of vortex induced vibrations for FOWT simulations is discussed.

Different techniques for the representation of mooring line dynamics on a full system level and their impact on global system loads were investigated, including quasi-static, look-up table, FEM and MBS methods. A review of currently available mooring line codes was performed. Results and comparisons from different mooring line models (quasi-static, look-up table, MBS,) for different floating body configurations are presented.

4. Development of design requirements

A literature review of current design standards relevant to offshore floating structures has been performed, together with comments on applicability to floating offshore wind turbines, in order to provide input for the standardization of floating wind turbines.

Recommendations are presented for possible extensions to the IEC 61400-3 standard to enable applicability to deep-water floating wind turbine designs, including the implementation of additional/different design load cases. Issues that need to be considered when defining DLCs for FOWTs include:

- Potential large motions of the RNA
- Influence of low frequency motions on the control system
- Influence of heave motion on air gap and rotor clearance
- Influence of wave drift forces on mean response, e.g. for catenary moored systems
- Longer simulation requirements and how this relates to wind/wave stationarity
- Inclusion of low-frequency components in wind and wave conditions
- Importance of radiation and diffraction effects as well as wind/wave misalignment
- Mooring and riser systems as new component with associated failure modes
- Inclining, stability and watertight integrity requirements
- Safety factors (including non-redundant mooring systems)

4. Recommendations for future work

Through the work in WP4 several new results were achieved, but also a range of further open questions and topics were raised. In particular, the work in WP4 enables the following recommendations for future research in the scope of offshore wind support structures:

1.) Integrated design process and load mitigation
   - Develop and evaluate more control concepts in terms of their use for load mitigation, especially with respect to other support structure concepts (e.g. LIDAR-based controls for floaters or control concepts for extreme event control at jacket structures).
   - Include more detailed information about soil characteristics, such as soil damping, and evaluate effect on design

2.) Bottom-mounted support structure designs
   - Design and optimization of transition pieces, especially for complex structures like jackets.
   - Evaluate full truss-tower solutions for deep water (maybe in combination with two-bladed, downwind configurations).
   - Validate design tools with measurement data

3.) Floating support structures
   - Evaluation of critical design load cases for floating structures.
   - Enhancement of modelling techniques for aerodynamics, hydrodynamics and mooring for floating design tools.
   - Establish a new IEC 61400 standard for floating structures.
   - Develop more sophisticated controls for floating structures.
   - Further tool validations.

5. Anticipated benefits and cooperation with other projects

During the operation of WP4, the work package has cooperated with different national and international programmes as illustrated in Figure 14.

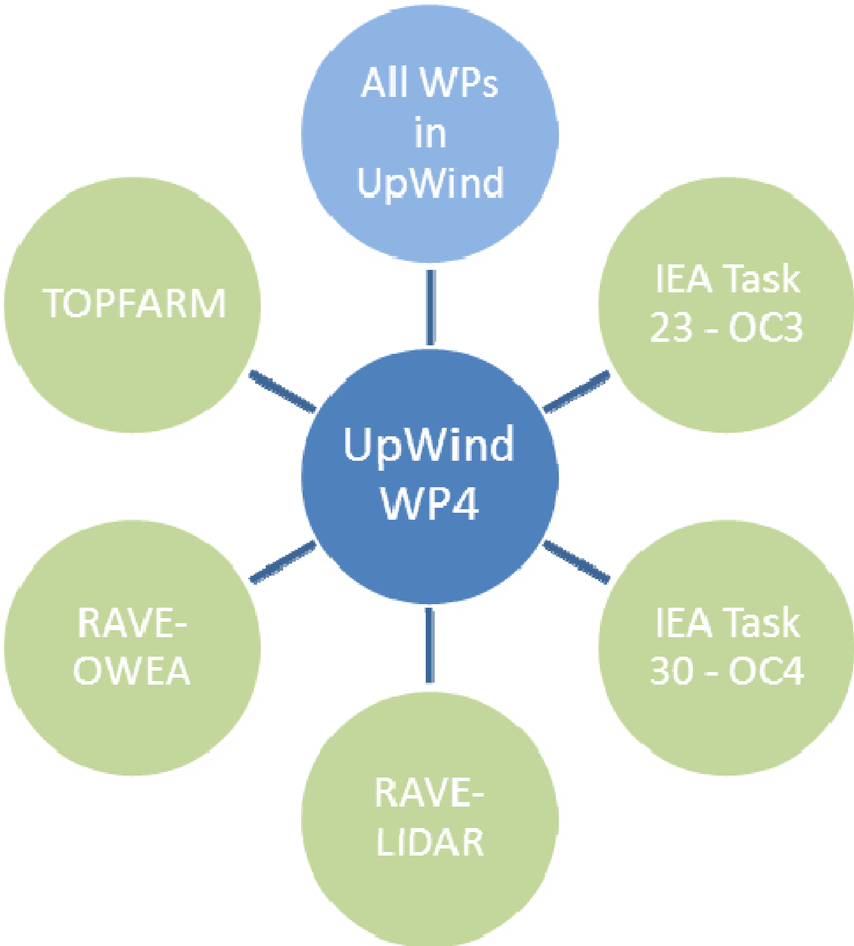


Figure 14: Cooperation of WP4

Most of the interactions were based on the exchange with other work packages in the Upwind project. Due to the integrated context of the overall project, a continuous exchange of results took place in order to achieve the overall targets as discussed in chapter 3.

Beside interactions within Upwind, there was also a strong link to the IEA Wind Task 23 (OC3) and 30 (OC4) for the whole project duration. This especially involved the provision of a baseline support structure, the reference jacket, for the code-to-code comparison in IEA Task 30, and also the application of developed design tools for multi-member, bottom-mounted and floating support structures in the validation work of OC3 and OC4.

In the context of bottom-mounted, multi-member support structures and here especially the influences of different modelling techniques, collaboration with the RAVE project (OWEA) took place [23]. In the scope of new control devices for load mitigation, a further cooperation with the RAVE research group of LIDAR technology was established.

Finally, a link between the two European funded projects TOPFARM and Upwind was established in the context of optimized wind farm configurations for offshore wind farms in terms of power output and load distributions.

Beside the cooperation with other programmes, the results of WP4 will be and are already being used in the wind community for different purposes. In general, WP4 contributed to the following general outcomes:

- Preparation of training material for PhD courses
- Publicly available jacket design [14]
- Publicly available design basis [21]
- Public cost models for monopiles and jacket support structures [18]
- Several conference and journal publications

Additionally, several possibilities for future industry and research applications can be seen, which are in particular:

- Use of recommendations for current and future IEC offshore standards
- Use of the design basis in the Dutch North Sea for project evaluations
- Application of the jacket structure for comparisons, sensitivity studies and code validations
- Application of the cost models
- Using recommendations of evaluated load mitigation concepts for optimization of future offshore wind farms
- Use of fully-integrated design tools for bottom-mounted and floating support structures

6. References

(1) Fischer, T., Kühn, M. and Passon P.: *Definition of control requirements for mitigation of aerodynamic and hydrodynamic loads*, UpWind deliverable D4.1.1, Stuttgart, 2006.

(2) Fischer, T., Kühn, M. and Passon P.: *Interim report on design integration studies on soft-stiff, bottom-mounted support structures*, UpWind deliverable D4.1.2, Stuttgart, 2008.

(3) De Vries, W.: *Assessment of bottom-mounted support structure types with conventional design stiffness and installation techniques for a typical deep-water site*, UpWind deliverable D4.2.1, Delft, 2007.

(4) Tarp-Johansen, T.-J., Agyriadis, K., Carstens, H., v.d. Tempel, J., Camp, T., Cheng, P.W. and Passon, P.: *Irregular, non-linear wave loading of offshore wind turbines: Review of modelling approaches and their relevance for future designs*, UpWind deliverable D4.3.1, Roskilde, 2008.

(5) De Vries, W., Fischer, T. and Haverkort, A.G.: *Report on soft or soft-stiff bottom mounted support structure types*, UpWind deliverable D4.2.2, Delft, 2008.

(6) De Vries, W. and Carstens, H.: *Definition of a cost model for offshore support structures*, UpWind deliverable D4.2.3, Delft, 2008.

(7) Passon, P.: *Design tool for multi-member bottom-mounted support structures*, UpWind deliverable D4.3.2, Stuttgart, 2008.

(8) Fischer, T. and Kühn, M.: *Report on design integration studies on bottom-mounted support structures*, UpWind deliverable D4.1.3, Stuttgart, 2009.

(9) De Vries, W.: *Report on compliant bottom mounted support structure types*, UpWind deliverable D4.2.4, Delft, 2009.

(10) Passon, P.: *Implications of innovative support structures on condition monitoring systems*, UpWind deliverable D4.2.5, Esbjerg, 2009.

(11) Cordle, A.: *Interim report on review of IEC 61400-3 ed. 1 and support on development of ed. 2*, UpWind deliverable D4.3.3, Bristol, 2009.

(12) Vorpahl, F.: *Report on implementation of a super-element approach in a design tool for braced structures*, UpWind deliverable D4.3.4, Bremerhaven, 2009.

(13) Fischer, T.: *Report on controller development for mitigation of aerodynamic and hydrodynamic loads*, UpWind deliverable D4.1.4, Stuttgart, 2010.

(14) Vemula, N.K., de Vries, W., Fischer, T., Cordle, A. and Schmidt, B.: *Design solution for the UpWind reference offshore support structure*, UpWind deliverable D4.2.6, Esbjerg, 2010.

(15) Cordle, A.: *Design tool for floating offshore wind turbines*, UpWind deliverable D4.3.5, Bristol, 2010.

(16) Vorpahl, F.: *Report on joint flexibilities of soft-stiff structures*, UpWind deliverable D4.2.7, Bremerhaven, 2010.

(17) Fischer, T. (editor) : *Final report for WP4.1*, UpWind deliverable D4.1.5, Stuttgart, 2011.

(18) De Vries, W. (editor): *Final report for WP4.2*, UpWind deliverable D4.2.8, Delft, 2011.

(19) Cordle, A. (editor): *Final report for WP4.3*, UpWind deliverable D4.3.6, Bristol, 2011.

(20) Vorpahl, F. and Kaufer, D.: *Description of a basic model oft he „Upwind reference jacket“ for code comparison in the OC4 project under IEA Wind Annex XXX*, Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), 2010.

(21) Fischer, T, de Vries, W. and Schmidt, B.: *Upwind design basis*, Stuttgart, 2010.

(22) IEC 61400-3 Ed. 1, *Wind Turbines – Part 3: Design requirements for offshore wind turbines*.

(23) http://rave.iset.uni-kassel.de