Studie naar haalbaarheid van en randvoorwaarden voor drijvende offshore windturbines

ECN, MARIN, Lagerwey the Windmaster, TNO, TUD
MSC

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Executive summary

The project “Studie naar haalbaarheid van en randvoorwaarden voor drijvende offshore windturbines (Study to feasibility of and boundary conditions for floating offshore wind turbines)” (“Drijfwind”) is carried out by ECN, MARIN, TUD, TNO and Lagerwey the windmaster under coordination of TNO. The project has received financial support from NOVEM under contract number 224.721-0003.

To obtain the overview of what has been done so far on floating wind turbines a literature study has been carried out. All project partners have gathered public literature and also non-public literature which has been made available for the project partners. All found literature is collected on a CD-ROM. Via an hyperlink based index easy access is given to the articles. If the article itself is not available, a reference is given where to find the complete article.

With the aid of the literature study the criteria, boundary conditions, references etc. for the floating offshore wind turbines are formulated. During the project, numbers and boundary conditions are added or adjusted.

By means of brainstorm sessions with all partners, a number of concepts for floating offshore wind turbines have been derived. For some of the concepts main dimensions are determined.. Use has been made of the knowledge based system Quaestor. This system relates weight, costs, dimensions, stability etc. with each other to find an optimum solution.
Feasible concepts which have been further analysed with respect to static stability are a.o. the ‘pill-box’ buoy concept, the spar-type and the tri-floater.

The ‘pill-box’ and spar-type seem not to be feasible due to the large size and the resulting costs.

The tri-floater concept appears to be static and dynamic stable and has been further analysed. Motion response calculations have been made.
Thereafter a more thorough analysis has been made to the strength and to the costs of production and installation. The mooring system has been taken care of.

An electrical system analysis has been made for a 500 MWatt wind farm with 100 turbines. Several energy system types are looked at. Up to a distance of 140 km from the coast, the individual variable speed system with an 150 V AC seems to be the cheapest option. For more than 140 km from the coast a park variable speed system with an 141 kV DC connection is the cheapest option.

An analysis has been made of the integral maintenance cost of an offshore wind farm. By means of component failure rates, repair time ‘weather windows’, choice of transport equipment etc. the maintenance strategy has been defined. This results in an overview of the maintenance costs.
When using lightning protection, the maintenance costs per year for one turbine are 277 kEUR at a distance of 100 km from the coast.
Due to component failure and maintenance the availability of a wind turbine is reduced with 33 days, which results in an availability of 91% per year.
From a cost analysis it became clear that towing a floating turbine to an harbour for large maintenance operations, seems not to be cost effective.

Project leader:	M.J. Wolf
Visa:	M.P.M. van der Meer

Summary

Chapter 3 Literature study
To obtain the overview of what has been done so far on floating wind turbines a literature study has been carried out. All project partners have gathered public literature and also non-public literature, which has been made available for the project partners. All found literature is collected on a CD-ROM.

Chapter 4 Terms of Reference
With the aid of the literature study the criteria, boundary conditions, design conditions, references etc. for the floating offshore wind turbines are formulated. During the project, numbers and boundary conditions are added or adjusted.

Chapter 5 Concepts generation with Quaestor
Some initial calculations performed within the DRIJFWIND knowledge base show that the single “pill-box” buoy concept without pretension is not feasible as free floating buoy and requires buoy diameters as much as 37 m for a 115 m turbine. Smaller buoy sizes are only possible when a tension leg concept is applied. This implies to some extend that the single buoy/single turbine concept is not feasible at all since a tension leg concept does not allow the buoy + turbine to be towed to a harbour facility for maintenance. From a perspective of motions, the “pill-box” floater is not feasible since in particular the vertical motion response is within the high-energy region of the wave spectrum.
The multi-floater i.e. triple-floater concept is feasible in terms of stability and its structural weight is smaller if compared to a single floater. However, the size of the structure becomes quickly too large for a single turbine. The requirement of a movable platform implies a requirement for stability afloat, say during the passage from shore to the wind farm. A hybrid solution could be a jackup, which is a fixed structure when on location and a floating one related to transport and maintenance. The jackup, however, is not feasible due to its high construction cost.
The course approximations in the DRIJFWIND knowledge base allowed to rapidly focusing on the technically feasible concepts. In order to select/optimise the presented concepts in terms of both economical and technical aspects, it is absolutely necessary to fill in the white spots discussed in section 4.2. Based on the concept variations performed in DRIJFWIND, the triple floater concept was selected as basis of a point design, performed by MSC [MSC, 2002].
The DRIJFWIND knowledge base in QUAESTOR proved to be a useful tool to establish the focus of research performed within this project. The DRIJFWIND knowledge base forms an extendable and easy to maintain body of knowledge on floating wind farms and is open to extensions and enhancements that results from future research

Chapter 6 Motion response analysis of a floating wind turbine
Various concepts were selected for review using the QUAESTOR programme. The most promising concept, a tri--floater, was further investigated with respect to its motion behaviour in waves. The motion characteristics in regular waves were established using a linearised potential flow panel programme called DIFFRAC. The wave conditions that were selected for this study were taken from near shore locations like meetpost Noordwijk ,K13 and data from the European Centre of Medium Weather Forecast (ECMWF) in Reading UK.

Due to the nature of the wave climate near shore also wave climates were generated using wind-wave generation models (SWAN).
For the floating wind farm limiting conditions of maximum 10 degrees rolling or pitching were assumed.
From the statistical analysis it is observed that for the various wave conditions studied the rolling and pitching criteria were not exceeded in the 20 years lifetime of the floater.
From the motion behaviour one may therefore conclude that the tri-floater concept is a viable alternative for a floating wind farm.

Chapter 7 Analysis of Tri-floater
The trifloater has been designed for a turbine of 5 MW and for the environmental conditions of the Southern North Sea.
A further design criteria was a maximum heel (static + dynamic) of 100 both in operational as in survival condition. This heel corresponds with the strength of the lower part of the tower.
The dimensions of the unit are as follows:
– distance between column centers 68 m
– column diameter 8 m
– column height 24 m
– column draft 12 m
– steel weight (without wind turbine) 1150 t
– displacement (incl mooring and wind turbine) 2480 t

The material dimensions of floaters and bracings are common in the shipbuilding and offshore industry. The stability has been checked for intact and damaged condition in accordance with international rules. The motion behavior has been checked for a wide range of frequencies and directions. The motion and stability have been optimized to arrive at a maximum heeling angle of 100. The accelerations are moderate and within the limitations as indicated by the turbine manufacturer.

A conventional 6 lines mooring system has been designed. Due to the limited water depth of 40 – 50 m, the mooring system is heavy and expensive.
The cost price per unit has been estimated:
– construction in Europe 7 million Euro
– construction in Asia 6 million Euro
A price reduction due to the series effect of 100 units might be 1 million Euro per unit. A study into a special mooring system might result in a further cost reduction of 1 million Euro per unit.
The cost price does not include the wind turbine itself, nor the electrical connection to the sea floor.

An artist impression of the tri-floater is shown in the next figure.

Chapter 8 Electrical infrastructure
An important aspect in the determination of the feasibility of an offshore wind farm is the choice of the electrical system, necessary to collect the power in the farm and transport it to shore. This report describes how this choice was made for the Drijfwind concept. Based on the results of the ERAO project the two most promising system types for Drijfwind have been chosen: individual variable speed and park variable speed. For these options, two park layouts based on platforms with 1 and 5 turbines have been investigated. These layouts correspond to different cable layouts inside the park: string and star. The second parameter investigated is the distance between the wind farm and the shore. The *EEFARM* computer program has used to calculate the electrical and economic performance of these options.

Based on economics only, the best choice for the Drijfwind 500 MW wind farm will be the Individual Variable speed system for distances below 140 km and the Park Variable speed system for distance above 140 km. Differences in controllability and stability of the two options may influence the choice, but has not been investigated.

Chapter 9 Electrical infrastructure

On behalf of a feasibility study for remote offshore wind platforms, which have a distance to shore in the range of 50 km and up, the maintenance costs in order to safeguard the availability of these systems has been estimated.

An issue that is of particular interest in this study, is the question to what extent it is profitable to perform “on site” maintenance in comparison with “on shore” maintenance for which the floating platform needs to be shipped.The factor that towing of a platform is subjected to a weather window leads to the result that “on site” maintenance is favourable for practically all failure mechanisms, since this weather window is supposed to present a clear barrier.

Specific “on shore” activities such as recovering of the platform or clustered activities within a “substantial overhaul” have been assumed to be unnecessary due to a maintenance free platform and the use of reliable components.

The cost calculations assume the availability of exchange parts, the costs of which are managed by using renewed cost-intensive components that have failed. Efficiency measures such as opportunity based maintenance or implementation of clustered corrective maintenance actions, have not been incorporated in the model since the failure rates are limited. This factor therefore determines the maintenance costs only to a limited portion of the accuracy of estimation.

Uncertainties with respect to the maintenance demand, resulting from the fact that no detailed design is present, are to be controlled by incorporating a RAM specification and assessment within the design phase of the final construction. In a RAM assessment the final design is evaluated with respect to its maintainability (with function loss during a specific time) and the resulting availability (capability to produce), by using the reliability performance data of the specific components.

The reliability data that are applicable for supposedly “maintenance free” components in order to safeguard the assumptions made within this study, are determined by a failure rate of ultimately $4*10^{-4}$ (yr^{-1}). This guideline in combination with availability criteria is applicable during the actual design phase.

The maintenance costs for a platform are estimated to 2,2 % of the investment costs (offshore position: 100 km).

This implies a reduction of 35 % of the actual “capital production” to be expected during a year.

In this calculation the capital effects of the realised CO_2 reduction have been omitted.

Contents[1]

1 Detailed list of contents is provided at the beginning of each Chapter; page numbering combines chapter number and page number within chapter.
2 The summary is a collection of the summaries given at each chapter.

1 Introduction

Currently several plans for offshore wind turbine fields are in progress. Near the coast of Egmond, two fields are being developed. Near the coast of Sweden and Great Britain two fields are just completed.
Until now, most of the studies focus on fixed offshore wind turbines in shallow water. It is expected that this soon will be economical feasible.
The main reasons for applying fixed turbines are:
- proven technology for fixing the poles in the ground
- easy connection of wires from the turbine to the shore
- few effect of current and wind on the motions of the pole

Of course there are some adverse aspects:
- restricted to shallow waters
- (re)moval is difficult
- Expensive installation

Only a small amount of investigations have been done on floating wind turbines, which showed that, due to economical reasons, it is not feasible yet.
Because (other) floating concepts are not thoroughly investigated, this study focuses on new concepts which are technical and economical feasible.
The advantages of floating turbines are that they can operate in deeper water and (re)moval is feasible. Unknown aspects are:
- motion of the unit due to current, waves and wind
- installation
- design (stability)

Issue
In this project, a framework for developing a floating offshore wind turbine field will be established. The technical and economical feasibility of floating Offshore Wind Energy Converter Systems is assessed.
The existing fixed wind parks will be taken as reference. Aspects to be assessed are the floaters, electrical system, installation and operation and maintenance. The parameters will be put in a model in the knowledge based program Quaestor. New concepts will be made and evaluated against criteria derived from existing parks.

Partners
The project is executed by 5 companies, which ensures that all the necessary knowledge is available. There is one industrial partner (Lagerwey de Windmaster) and four research partners. (TNO, MARIN, ECN and Delft Technical University). The industrial partner gives the practical needs and limits, whereas the research partners provide theoretical background and new concepts. In addition, an offshore consultant agency (Marine Structure Consultants, MSC) has taken part in the project.

2 Outline

The project has been subdivided into several main subjects. Each subject is discussed in detail in a separate chapter. Due to the fact that the chapters are written by different project partners, as if it is a report on its own, some recurrence can take place. Each chapter will have its own appendices and references.

The following outline has been used. In chapter 3 the literature study will be discussed, while in chapter 4 the terms of reference are given, which are mainly based on the literature study. The generation of concepts and the use of Quaestor is discussed in chapter 5. One of the most promising concepts is further investigated in chapter 6 and 7. The choice of the electrical system is presented in chapter 8 and the aspects related to Operation and Maintenance are discussed in chapter 9. Chapter 10 presents the calculation of the levelised production cost. Conclusions and recommendations are given in chapter 11. In the table below the chapters with the report references are given.

Chapter	Report reference
3	Henderson A.R., *Feasibility Study for Floating Offshore Windenergy (Drijfwind) Literature review*, TU Delft, Section Windenergy, September 2002
4	Bulder B., *Feasibility study "Drijfwind", Terms of Reference'*, September 2002
5	van Hees M.Th., *Drijfwind in Quaestor*, MARIN, report no. 16602-2-KBS, September 2002
6	Huijsmans R.H.M., *Motion response calculations of a floating wind turbine*, MARIN, report no. 16602-1-RD
7	Snijders, E.J.B., *Concept design floating wind turbine*, MSC ref P 10499-3940, September 2002.
8	Pierik J.T.G., *'Drijfwind' Electrical System, Conceptual design and costs*, ECN-CX—02-025, February 2002
9	Wijnants G.H., *Integral maintenance cost estimate for Remote Offshore Platforms*, TNO-Bouw report, 2002-CI-R2130, 13 September 2002

3 Literature study

Foreword

The results of the Literature Review as part of the DRIJFWIND project are reported on within this document.

The report has been published by TUDelft, Section Wind Energy.

The work reported here forms part of the Feasibility Study for Floating Offshore Windenergy (DRIJFWIND) project, which has received partial financial support from NOVEM under contract 224.721-0003 awarded under the TWIN-2 program and has been undertaken by Delft University of Technology, ECN, Lagerwey, MARIN and TNO under the co-ordination of TNO.

Delft, September 2002

Contents

3.1 Introduction

With bottom-mounted wind turbines promising to become a common feature across the shallow seas of Northern Europe, the question arises of what the prospects are for the generation of power in the deeper waters both there and elsewhere in the world.

This report reviews recent floating offshore wind energy studies and includes an inventory of the more important reports and papers that will help the reader gain an understanding of the subject. To date, such activities have been limited to feasibility and design studies, with the high cost of the floater and in particular of the mooring systems, inhibiting the realisation of any of the proposed concepts up to now.

Last year saw the construction of the first offshore windfarms using MW sized wind turbines, as a precursor to the very large windfarms that are planned to be built over the next few years in the shallow seas surrounding Denmark, Sweden, Germany, Netherlands, Belgium, Britain and Ireland. These windfarms will consist of tens to hundreds of such MW-sized turbines and for the first time, it will be possible to build a wind-energy power station with a similar output as a conventional plant. Offshore wind energy will become a major source of energy across large regions in northern Europe and the trend of companies from the traditional energy industries becoming involved will continue. This is likely to lead to further attempts to introduce novel technology onto the market as these organisations attempt to apply their knowledge to the problem of generating large amounts of electricity from the wind, both cheaply and reliably. An important question is whether they will be successful and for this paper, whether offshore engineering companies will be able to do so for floating windfarm concepts.

To date, a limited amount of effort has gone into developing and evaluating various floating windfarm concepts, which is briefly summarised below. Several very different concepts were developed since the early 1990s, including:

- In the United Kingdom, Garrad Hassan and Technomare co-operated in the evaluation of a single turbine concept, located on a spar-buoy and kept in position using eight-point catenary moorings [10]. This was a fairly detailed study and aspects such as type of wind-turbine (downwind, free-yawing with very-high tip-speed), multiple vs. single turbine structures, sharing of anchoring systems and tower design (lattice type to reduce wind loads and overturning moment) were investigated. The costs were estimated to be inhibitatively expensive at around twice that of bottom-mounted alternatives.
- Also in the United Kingdom, a group at University College London investigated the possibilities of locating several turbines on a single structure with the potential advantage of reduced motion response and shared moorings (hence reduced anchoring costs). This concept was developed in a PhD [4] and an EPSRC research project (in which the author was responsible for the wind-turbine and floating structure aspects; [5]) to develop research tools and evaluate the idea in greater detail. The main conclusions were that it would be excessively expensive as well as difficult to construct to withstand the wave loads in regions with an attractive wind resource.

- In Italy, a group in Milan investigated placing a single turbine on to a toroidal-shaped float, positioned with tensioned moorings. The complex shape was chosen to minimise wave motion response but had the disadvantage of being difficult and expensive to build (1).
- More recently, also in Italy, a proposal has been made to locate electrical generating and desalination plant on a floating pontoon to provide temporary supplies to island communities during the holiday season [3]. This could possibly develop into a niche market for floating windenergy.
- In Japan, the JOIA (Japanese Ocean Industries Association) is co-ordinating a group of interested parties to evaluate the potential for floating wind energy in that country; the first phase was completed in 2001 [8] and further work continues with the results of the next stage expected to be complete during this year (2002) and with the ultimate objective being to develop a prototype by the end of the decade. Regarding which concepts would be most suitable for the relatively deep waters around Japan, preliminary conclusions are broadly similar to those identified in this paper.

The Inventory of Literature that follows divides the documents into six sections, representing respectively:

- Wind Energy
- Offshore Wind Energy
- Floating Wind Energy
- Offshore Engineering
- Patents
- Miscellaneous

A number of comprehensive review reports and policy documents on ***wind energy*** have been written over the last decade and those felt by the project members to be most relevant have been included in the literature review list.

In addition several review and policy reports have been written over the last few years specifically on ***offshore wind energy***, including the Concerted Action on Offshore Wind Energy in Europe (CA-OWEE) final report, *Offshore Wind Energy - Ready to Power a Sustainable Europe* [2]. In addition there been reports by DEWI (commissioned by Greenpeace) focusing on the German sector of the North and Baltic Seas and by Borderwind (also commissioned by Greenpeace) focusing on the British seas, and a number of research reports and PhDs (specifically on bottom mounted offshore wind energy) have been published including the Opti-OWECS [7] and COSLOW [9] project report and PhDs by Kühn [6], Cheng (end of 2002) and van der Temple (2000) all at TUDelft.

Turning to ***floating offshore wind energy***, the breadth of research is of course less extensive than for the bottom-mounted counterpart, however PhDs include those by Simpson, Halfpenny and Henderson at University College London and summaries of research projects include the FLOAT and JOIA projects detailed above are available. It has not been possible to obtain the complete project reports because of confidentiality restrictions, however the publicly available conference and journal papers have been included.

A number of ***offshore engineering*** documents are also included, with review documents to provide windenergy specialists an introduction into the subject. The variety of environmental conditions and operational challenges facing the offshore oil and gas industry has led to a similarly wide range of technical solutions. Generally there is initial resistance against any new concept, unless it can demonstrate an economic improvement of at least 20 per cent against proven solutions. Once proven however such concepts are often widely applied, for example the TLP concept, which was first constructed in the mid-eighties and today is frequently used.

Patents are another source of information, describing potentially viable concepts, inspiration for concept generation and indication of the general level of activity. Patent activity for floating offshore windenergy concepts has increased recently to a level of several patents each year. It should be noted that the majority of patented ideas are impractical and indicate a lack of knowledge of the fields of either windenergy engineering or offshore engineering or sometimes both.

The final section, ***Miscellaneous***, deals with aspects of potential benefit to this project are not relating directly to any of the technologies.

Sources include PhDs, research project reports, journal and conference papers and trade magazine articles from both wind energy and Offshore Engineering fields.

This report is accompanied by a CD-ROM, which contains a number of the documents identified here in pdf format.

3.2 Literature Inventory

This section lists the documents identified as being of greatest interest by the partners within the project. A number of the documents are available on the accompanying CD-Rom in pdf format.

Type	Title	Author	Source	Year
	3.2.1 Wind Energy			
Reports	Wind Energy - The Facts	EWEA	European Commission - Directorate for Energy	
	Wind Force 10 - A blueprint to achieve 10 per cent of the world's electricity from wind power by 2020	BTM Consult	EWEA, Forum for Energy and Development (Denmark) and Greenpeace	1999
	Wind Force 12 - A blueprint to achieve 12 per cent of the world's electricity from wind power by 2020	BTM Consult	EWEA and Greenpeace	2002

Type	Title	Author	Source	Year
Journal paper	Wind energy technology and current status: a review	T. Ackermann & L. Söder	Renewable and sustainable energy reviews; V4; pp 315-374	2000
Lecture Notes	Electrical Systems for Wind Energy Conversion	S. W. H. De Haan	DUWind Offshore Wind Energy Course	2001
Recommendations	Estimation of Cost of Energy from Wind Energy Converters Systems	Tande & Hunter	IEA Recommended Practices	1994
	Guidelines for Design of Wind Turbines (2nd Edition)	DNV & Risø	Risø	2002
Book	Wind Energy Handbook	Burton, Sharpe, Jenkins & Bossanyi	John Wiley ISBN 0-471-48997-2	2001
	3.2.2 Offshore Wind Energy			
Reports	**Concerted Action** on Offshore Wind Energy in Europe [1]	Henderson (coordinator)	TUDelft *et al*	2001
	Prospects for offshore wind energy	BWEA	BWEA	2000
	Offshore wind energy in the North Sea - technical possibilities and ecological considerations - a study for Greenpeace Germany / Netherlands	DEWI	DEWI, Greenpeace	2000
	Opti-OWECS - structural and economic optimisation of bottom-mounted offshore wind energy converters; Final Report, Volumes 0-5	M. Kuhn *et al*	TUDelft Report No. IW-98139R	1998
	Cost Optimisation of Large-Scale Offshore Windfarms, Final Report, Volumes 1-4	Olsen, F.A., *et al*	SK Power Report	1999

[1] available at http://www.offshorewindenergy.org

Type	Title	Author	Source	Year
Ph.D. Thesis	Dynamics and design optimisation of offshore wind energy conversion system	M. Kuhn	TUDelft	2001
Journal paper	A Brief Review of offshore wind energy activity in the 1990s	R. J. Barthelmie	Wind Engineering, Volume 22 Number 6 page 265	1998
Conference Paper	Possibilities for off-shore applications of wind turbine systems in Europe	Jos Beurskens	Hussum	1999
	Steady State Electrical Design, Power Performance And Economic Modeling Of Offshore Wind Farms	J.T.G. Pierik, M.E.C. Damen, P. Bauer, S.W.H. de Haan	EWEA STC Brussels	2001
	Offshore Windparken: Elektrische concepten, Energieopbrengst en Kosten	Jan Pierik, Michiel Damen, Paul Bauer and Sjoerd de Haan	Vision Gebruikersdag, 12 Dec 2001	2001
3.2.3 Floating Wind Energy				
Conference, Seminar & Journal Papers	FLOAT - a floating offshore wind turbine system	Tong, Quarton & Standing	BWEA	1993
	Elomar - a moored platform for windturbines	Bertacchi et al	Wind Engineering Vol 18, Nr 4, p189	1994
	technical and economic aspects of a floating offshore windfarm	Tong	*Proceedings of the OWEMES Seminar*, Rome Feb 1994	1994
	a Technical feasibility study and economic assessment of an offshore floating windfarm	Halfpenny	European windenergy Conference 1995	1995
	floating offshore wind energy	Henderson & Patel	BWEA	1998
	Design of floating foundation for installation of wind-turbine	Roy	DEWEK	2000
	moored floating platforms for wind-turbines	C. J. Satchwell	Royal Aeronautical Society Conference: Offshore wind power mega-projects	1988

Type	Title	Author	Source	Year
	Prospects For Floating Offshore Wind Energy	A. R. Henderson & J. H. Vugts	European Wind Energy Conference 2001, Copenhagen	2001
	Floating offshore wind farms - an option?	A. R. Henderson *et al*	*Proceedings of the OWEMES Seminar*, Syracuse 2000	2000
	Multiple Unit Floating Offshore windfarm (MUFOW)	N. Barltrop	DTI	1993
Ph.D Thesis	Analysis Tools for Large Floating Offshore Wind Farms	A. R. Henderson	University College London	2000
Magazine Article	Offshore applications for wind power [2]		Energy World Bulletin from the Institute of Fuel	May 1995
Promotio nal Literature	ILIOS concept	T. Hiruma		1996

3.2.4 *Offshore Engineering*

Type	Title	Author	Source	Year
Conference Paper	Technology trends and future opportunities in Ocean renewable energy	C. Dudgeon	Oceanology International 94	1994
Conference Paper	Design of optimum offshore structures based on long-term wave statistics[3]	Clauss F. G. & Birk, L.	OMAE 98; p 0521	1998
Journal Paper	'Dynamic tension in risers and mooring lines: an algebraic approximation for harmonic excitation'	Aranha,J.A. P. Pinto, M.O.	*Applied Ocean Research*, vol.23, no. 2.	
Journal Paper	Approximate Formulae for Calculating the Motion of Semi-subs	van Santen	Ocean Engineering, Vol 12 Nr 3, pp 235-252	1985

[2] Micro turbine on Amoco Oilrig
[3] optimising the form of a semi-sub to minimise motion

Type	Title	Author	Source	Year
	Offshore Technology - advances at the dawn of a new millennium reviewed from a UK perspectives	Lyons	Proc IMechE Vol 214, Part E	2000
Extracts from Books	25 Years in the North Sea[4]	M H Patel	Offshore Engineering Handbook	1991
	Analysis and design of catenary Moorings systems	Patel & Brown	Advances in Underwater Technology, Vol 13	1987
	Offshore Structures (summary of different types of offshore structures)	Angus Mather	from Offshore Engineering - An Introduction	2000
Books	Offshore structures, volume 1; conceptual design and hydromechanics	Clauss, Lehmann and Ostergaard		
	Offshore Hydrodynamics [5]	J.M.J. Journée & W.W. Massie	Delft University of Technology	Jan 2001
Certification	Rules and Regulations for the Construction and Classification of a Floating Offshore Unit at a Fixed Location	Lloyd's Register		1999
	Rules and Regulations for the Classification of Mobile Offshore Units	Lloyd's Register		1996
	Rules and Regulations for the Classification of Fixed Offshore Installations	Lloyd's Register		1989
	Rules and Regulations for the Construction and Classification of Submersibles and Underwater Systems	Lloyd's Register		1989

3.2.5 Patents

Type	Title	Author	Source	Year
Patents	summary of floating offshore wind energy & related patents	Henderson	internet search	2001
	Artificial Wind turbine island	H. Lagerwey	WO9902856 / EP0995035 / NL1006496	1999

[4] introduction to floating offshore concepts as used in the oil and gas industry
[5] Available at http://dutw189.wbmt.tudelft.nl/~johan/

Type	Title	Author	Source	Year
	Windmolen-eiland	H. Lagerwey	NL1008318	1999
	Offshore Wind Power Plant	Detmier *et al*	DE19727330	1997
	Offshore Wind-wave energy converter	F. M. Erik	WO9600848	1996
	Wind Energy Converter in the Offshore Sector	Erno Raumfahrttecknik	DE3224976	1984
Other patents	AU2785995, AU3964000, DE19714512, DE19805667, DE19819929, DE19846796, DE19851735, DE19859628, DE19962453, DE2922715, DE3003873, DE3107252, DE3637831, DE4017684, EP0074938, EP1013925, EP1058787, GB1492427, GB2327970, JP58020814, JP6200516, US4495424, US4775340, US6100600, WO0039903, WO0056982, WO0058621, WO0068570, WO0134977, WO123253, WO9409272, WO9747516, WO9826177, WO9943956			
3.2.6 Miscellaneous				
Concept Paper	Knowledge Based Computational Model Assembling	Martin Th. van Hees	Private Communication 2001-10-23	2001
User Guide	Windows versie QUAESTOR[6]	Martin Th. van Hees	Rapport nr. 14523-1-CP 1	
Magazine Article	Enter the think tank	IMechE	Professional Engineering Magazine	15 Aug 2001
	Flowing Prospects[7]	IMechE	Professional Engineering Magazine	15 Aug 2001

[6] introduction to QUAESTOR
[7] about other offshore renewable energies

3.3 References

1 Bertacchi, P. Di Monaco, A., de Gerloni. M., Ferranti, G., (1994). Eolomar - a moored platform for wind turbines; *Wind Engineering* Vol. 18, No. 4, p189

2 CA-OWEE, (2001), Offshore Wind Energy – Ready to Power a Sustainable Europe, Concerted Action on Offshore Wind Energy in Europe, Final Report, TUDelft, www.offshorewindenergy.org, 2001

3 Cesari, F. and Gaudiosi, G., (1999). Wind turbine on floating platforms for desalination plants, *Proceedings of the European Wind Energy Conference*, Nice,

4 Halfpenny, A., (1998), Dynamic analysis of both on- and off-shore wind-turbines in the frequency domain; PhD Thesis, University College London,

5 Henderson, A. R., (2000). Analysis Tools for Large Floating Offshore Wind Farms, PhD Thesis, University College London.

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4 Terms of Reference

Contents

Introduction

For the feasibility study of and determination of the constraints for floating offshore wind energy an inventory of the economic, technical and legal aspects has to be made.

During the kick-off meeting it is decided that there is not sufficient knowledge within the group of participants to deal with the legal aspects. This is not found to be a major problem especially,

- because it will probably not differ too much with bottom mounted wind turbines in international waters and,
- because the technical/economic feasibility is the major subject of this study.

Within the *terms of reference* the following items will be listed:

- definitions,
- targets,
- design conditions for a floating off shore wind power plant,
- design constraints and
- assessment criteria

4.1 Definitions

c	capacity factor $c = \frac{E}{365 \cdot 24 \cdot P_{rated}}$
LPC	Levelized Production Cost, see section 4.4
Weibull distribution	Probability distribution used for wind speed $P\left(V \geq V_{hub}\right) = 1 - e^{-\left(\frac{V_h}{a_h}\right)^{w_k}}$
a	Weibull mean factor = 1.13 $\bar{v}_h$
A	Area
w_k	Weibull shape factor
η_{park}	Array efficiency = $\left(\frac{E_{farm}}{n * E_{turbine}(sol.)}\right)$
E	yearly energy yield
F_{ax}	Axial or Thrust Force $= C_{D_{ax}} \cdot \frac{1}{2} \rho V^2 A_{rotor}$
P	Power $= C_p \frac{1}{2} \rho V^3 A_{rotor}$
Wind shear	Vertical shear of the average wind speed determined using $v_h = v_r \left(\frac{\ln\left(\frac{z_h}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \right)$
n	number of wind turbine systems in the wind farm
R	rotor diameter
v	Wind speed
z	height or roughness
λ	Tip speed ratio $= \frac{\omega R}{V_{wind}}$
ω	rotor rotational speed

subscripts

0	ground level
h	hub height
park	wind farm or array
r	reference height
rated	nominal power
sol.	solitaire, or stand alone

4.2 REFERENCE design

4.2.1 General

The reference design will be a large, approximately 500 MW, offshore wind power plant.

Location		North Sea	
Water depth		more than 50 m, see figure 3 for positions in North Sea	
Distance to shore		between 50 km and 200 km see figure 2	
Total area useful for installation of turbines (taken from owecop database)		About 1 % of Netherlands continental shelf	
Weibull wind speed parameters @ 10 m height		V_{ave} = 9 m/s k = 1.8	
Wind shear profile		determined from a roughness height of 0.0001 m	
Turbulence (IEC description)	I_{15} a	0.12 3	Ref. 2
wind rose		see table 4.1	
Wind farm turbine spacing		Approx. 8 Diameters apart.	
Wind farm array efficiency		95%	
Turbine data	General	Rated Power	5 MW
		Diameter	115 m
		Hub Height	>80 m[1]
		# blades	3
	Electrical system	Direct Drive generator	
Floater/Submersible		single wind turbine	
		3-5 wind turbines	
yawing		nacelle, not the entire windturbine	
Water conditions		defined by Marin, i.e. wave spectrum, characteristic wave height and frequency etc.	
Soil conditions(for anchoring)		sand	
Economic parameters	Real Interest rate inflation rate economic lifetime	5 0 20	

[1] Minimum height determined by rotor radius, maximum wave height and splash

Table 4.2 Distribution of the wind speed direction: K13 station, (data obtained from KNMI).

Sector	% of time
N	6.54
NNE	6.23
NEE	5.87
E	6.75
SEE	5.39
SSE	5.32
S	8.13
SSW	13.31
SWW	13.89
W	11.93
NWW	8.59
NNW	8.07

4.2.2 Wind turbine

The wind turbine model is designed using the BLADOPT code, the code description, theory and user's manual can be down loaded at ftp://ftp.ecn.nl/pub/www/library/report/2001/c01011.pdf

The general wind turbine parameters are
Rated power 5MW
Rotor diameter 115
number of rotor blades 3
Power control variable speed Tip Speed ratio 8.0
full span pitch to vane
Losses in the drive train are assumed to be 3% of the nominal power + 7% of the actual aerodynamic power. The relative losses are shown in a figure 1.

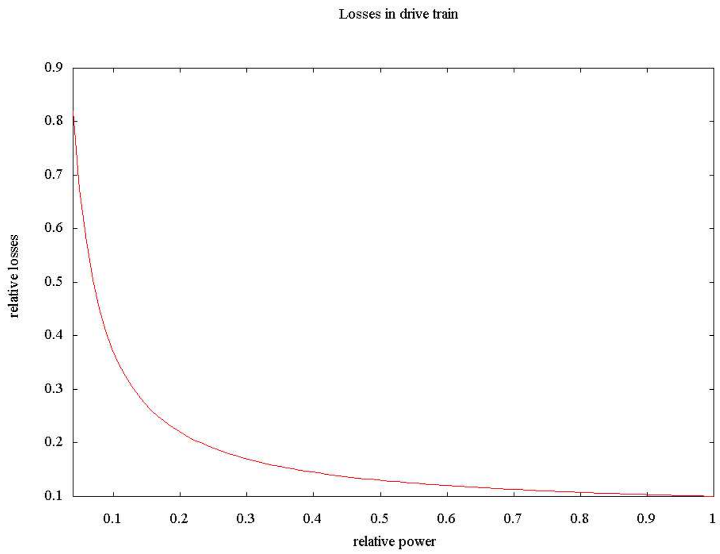

Figure 4.1 Relative losses in the drive train.

The overall rotor blade design is created with the BladOpt code taking only the blade and tower cost in the target function. The optimisation target was best price performance ratio. Taking the blade cost together with the tower cost in consideration results in a design with a balance between rotor yield and tower top axial force.

The remaining wind turbine parameters, which identify the turbine model, are the aerodynamic profile distribution:

Radius [%]	Profile name
	lsmod21
25	
	lsmod17
80	
	lsmod13

The resulting energy yield for the given wind speed distribution will be approximately 25 GWh/year assuming 100% availability and no array wake losses. The capacity factor is then approximately 59% which is realistic for an offshore wind turbine for the given wind conditions.
The power density of the rotor, P_{rated}/A_{rotor} = 480 W/m^2.

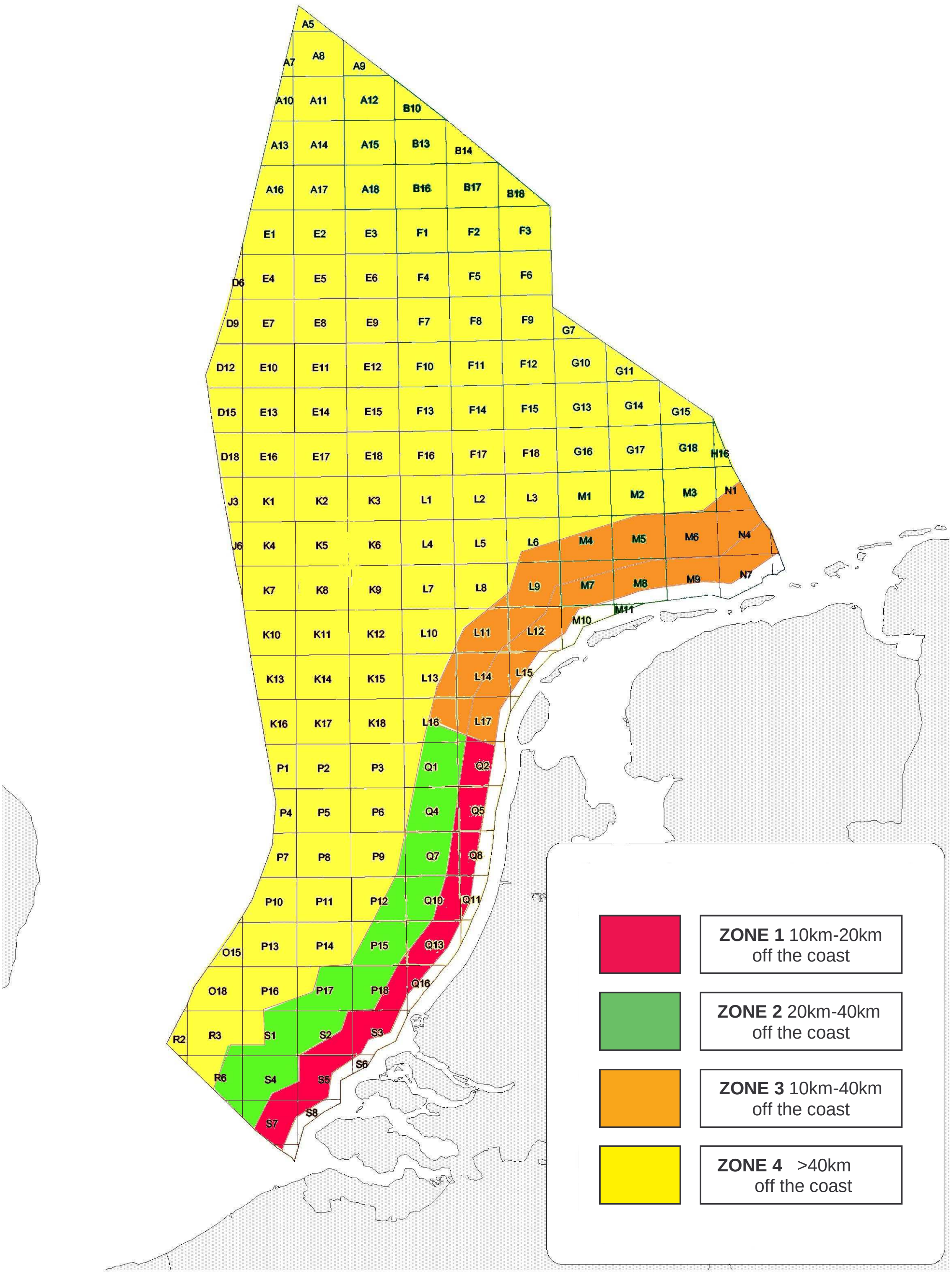

Figure 2 Distance to shore map of Netherlands continental shelf

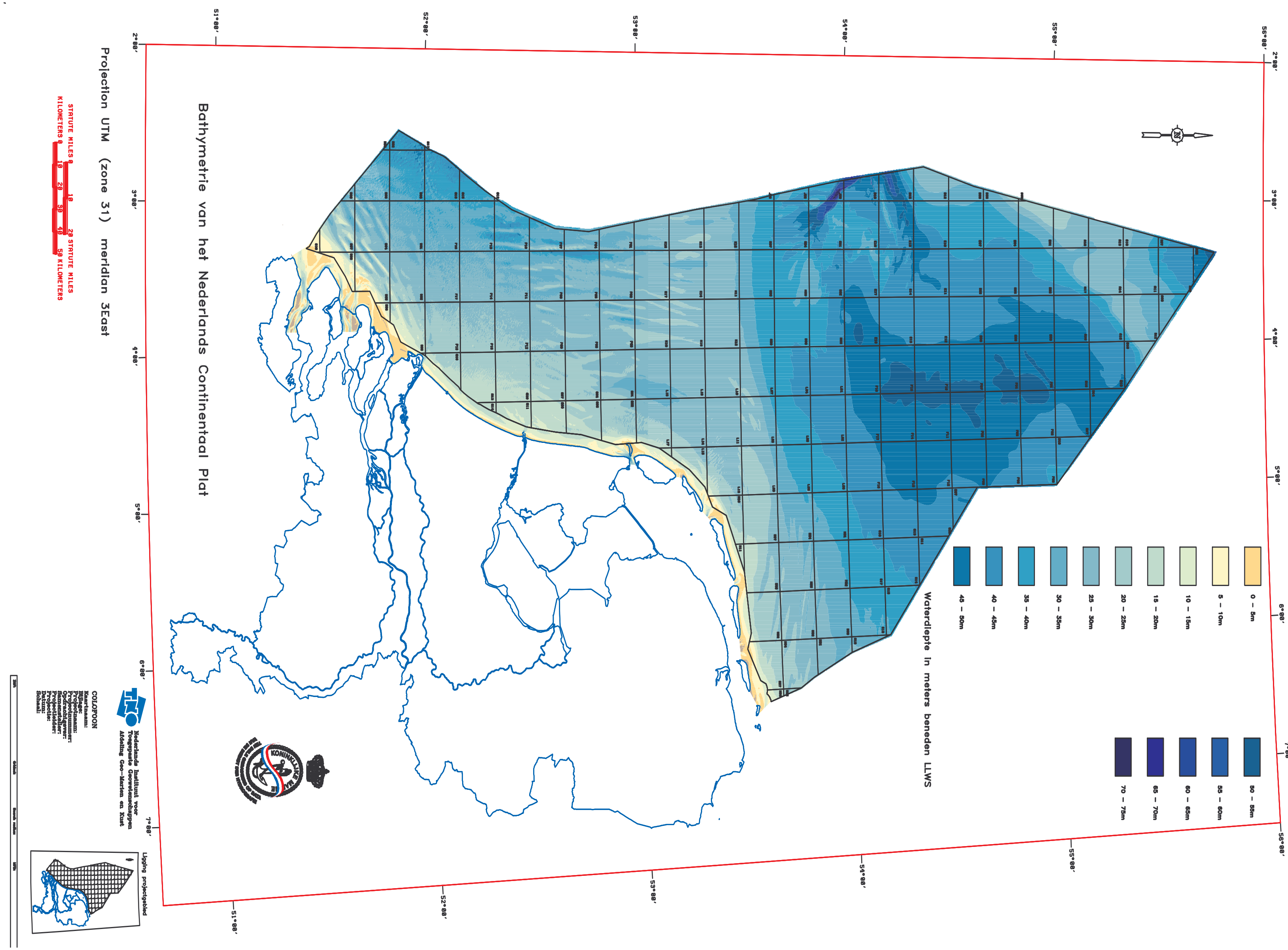

Figure 3 Bathymetric map of Netherlands continental shelf (Yellow=0-5 m, dark blue =70-75 m)

4.3 Requirements

The requirements are imposed by design codes and standards that are applicable for a floating (offshore) wind energy station. These requirements will change when the design codes and standards are updated.

The standards will deal with the
- integrity of the structure, see ref. 3 and ref. 4
- grid requirements, see ref. 8 and ref. 9

The wind turbine design will have to comply with the standard, in preparation, IEC 61400-3, WIND TURBINE GENERATOR SYSTEMS – PART 3: Safety requirements for offshore wind turbines, ref.4
The Dutch requirements for electricity producing plants are in grid code and system code, ref. 8, 9

Other design codes and regulations to be used for the design of off shore wind energy systems:

Lloyd's Register	Rules and Regulations for the Construction and Classification of a Floating Offshore Unit at a Fixed Location
	Rules and Regulations for the Classification of Mobile Offshore Units
	Rules and Regulations for the Classification of Fixed Offshore Installations
	Rules and Regulations for the Construction and Classification of Submersibles and Underwater Systems

4.4 Assesment Criteria

Assessment of the design will be based on cost and potential of reducing the cost.

The cost will be determined according to the Levelised Production Cost method defined in *"Recommended practices for wind turbine testing and evaluation # 2: ESTIMATION OF COST OF ENERGY FROM WIND ENERGY CONVERSIONSYSTEMS*, Ref. [7]. Levelised means that no variations in cost or energy yield are assumed during the lifetime of the project.

The simplified method will be used, which means that the following equation has to be evaluated

$$LPC = I/(a \cdot AUE) + TOM / AUE$$

In which

I Initial investment;

a annuity factor, depending on discount rate and economic lifetime ;

AUE Annual utilised energy;

TOM Total Levelised annual "downline cost", i.e. Operations and maintenance, insurance, retrofit cost, and salvage cost.

This results in a yearly capital cost and operating and maintenance cost divided by the net energy production minus electrical an aerodynamic losses within the wind farm. To determine the cost of energy it is necessary to determine the following quantities:

- Energy yield, determined on the basis of the power curve, wind conditions, wind turbine availability, wind farm losses, electricity losses in the wind farm and between wind farm and grid connection;
- Total investment cost, i.e. cost of the wind turbines , floaters, installation, electrical infrastructure in the wind farm and between wind farm and grid;
- Operating and maintenance cost, including insurance;
- Economic parameters like interest and depreciation period.

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5 Concepts generation with Quaestor

Contents

5.1 INTRODUCTION

The ‘DRIJFWIND’ project intends to study the feasibility of offshore floating wind farms at water depths of 50 m and above, i.e. at sea areas considered too deep for fixed structures. During the subsequent meetings held within the scope of this project., a variety of floating structures were presented and discussed of which some are, or will be described in separate documents or reports. The project was started with a literature survey which is presented in [Henderson, 2002].
One of the activities critical to the project is the development of a concept exploration model integrating aspects related to wind turbine design, floater construction, weight, stability, capital cost, wind farm architecture, electrical infrastructure, maintenance and operation in such way that these aspects can be studied in their coherence. The development of such models is a team effort in a sense that project participants have to represent and provide their knowledge of the above mentioned aspects in a format that allows implementation in some computer model.
A multi-disciplinary development effort as the DRIJFWIND project is largely a knowledge acquisition activity. Therefore, MARIN’s knowledge based system QUAESTOR [vHees, 1997, 1999] is used as the modelling environment. QUAESTOR is a declarative system capable to assemble executable computational models on the basis of a collection of numerical and nominal model fragments.
The DRIJFWIND knowledge base presented in this summary attempts to describe the concept of wind turbines on floating structures. Some basic floater concepts are parametrically described in terms of dimensions, mass, displacement and stability. The wind turbine design and analysis is dealt with in the ECN computer program BLADOPT [Bulder, 2001] that is interfaced with the DRIJFWIND knowledge base.
This report briefly describes the floater concepts and the properties included in the knowledge base as well as the aspects and properties still pending. A list of the parameters used in the knowledge base are presented in Appendix I. Appendix II presents an overview of the relations in the knowledge base. For the descriptions of calculation programs is referred to relevant manuals and papers.
The work reported here forms part of the Feasibility Study for Floating Offshore Wind energy (DRIJFWIND) project, which has received partial financial support from NOVEM under contract 224.721-0003 awarded under the TWIN-2 program and has been undertaken by Delft University of Technology, ECN, Lagerwey, MARIN and TNO under the co-ordination of TNO.

5.2 THE QUAESTOR KNOWLEDGE-BASED SYSTEM

5.2.1 History of computational modelling in design

Ever since the introduction of computers, application modules have been developed which allow certain calculations such as for resistance, weight, stability, strength, noise level, etc.

At first these applications were used as separate modules in the design or analys process where the designer was the bridge between these applications and disciplines. The designer went through an iterative process before he could make a satisfying (conceptual) design, often specified in terms of loading capacity, rate, type of ship, action radius etc.

As a rule the objectives to be obtained were and still are defined at the level of the executing party, viz. the ship owner translated the operational and financial aims in number, type and size of ships. These are then translated into installation, construction and necessary supplies by the shipyard. Traditionally, the exchange of thoughts on the interaction of this objective is only brief. Consequently, the concept is not always optimally attuned to the operational objectives of the ship owner.

During the following developments integrated design systems were built which, together with the application programs earlier mentioned, partly automated the interaction between the various applications and between the design process and the designer. As a rule these design systems are ready-made for the shipbuilding industry, have specifications such as loading capacity and speed for a starting point, and usually yield quite well detailed draft and engineering information. Mostly they contain no or only restricted mechanisms that makes use of experience and situations specifically relevant to the business.

In order to reach a quick estimation of optimate choices, Concept Exploration Models were introduced. These models generate a great number of alternative concepts and enable the user to select the most promising from these as a starting point for the more detailed design phase.

Four significant shortcomings of this method are apparent:

- It is common practice that the design concepts and analyses are not usually based on the end-user’s ultimate (mainly financial and operational) demands but demands derived from these as regards sizes, speeds and technical preconditions. This discourages the search of the ideal compromise between cost, results, risks and technical possibilities.
- The programs available comprise a somewhat closed process and are not flexible enough to allow a quick and efficient application of new views, preconditions, experiences, applications and problem defining.
- The programs available focus on a certain problem. Problem definition of another kind (e.g. economics, fishing or offshore) require the development or purchase of a new program, which in turn is often provided with other procedures and applications.
- The programs available are 'hard-wired', i.e. the user is not able to adjust the programs as they please to their own objectives and requirements.

Improvements on the programs can only be made by the suppliers and, therefore, take a long time to be put into effect and seldom lead to the flexibility required by users.

These shortcomings are a problem, especially during the conceptual phase when the creativity and the experience of the user are of vital importance and when designers are to accomplish the task of finding the one and only best solution in an abundance of possibilities within a short period of time.

5.2.2 Knowledge-based Computational Model Assembling

In order to overcome these shortcomings, in the late ’80s a start was made at MARIN with the development of a system that could control and apply (empirical) knowledge, mainly in numerical form. This development has led to the knowledge-based system QUAESTOR [vHees, 1997, 1999], a semi-automatic method for the assembling and execution or computational models.

Although initially meant for private use and restricted application, the basic principles and the developed prototype turned out to be very suitable for a more general use, especially in conceptual design applications and in feasibility studies. As early as 1993 the Royal Netherlands Navy introduced the application of the QUAESTOR prototype in her projects. By and by the program was used in various research and development projects. Among other things these projects comprise joint industry projects, a NATO project which resulted in a conceptual naval ship design system, a number of graduation studies from Technical Universities and Colleges, some PhD theses and an industrial propeller design and analysis system. These applications demonstrate QUAESTOR as an outstanding environment for industrial and scientific computational knowledge management without the shortcomings described above.

In the current languages and tools for solving computational problems little attention is paid to programming or assembling of computational models. As a rule these tools offer a number of numerical methods, as well as an instruction set for a manual description of the problem. In these tools, the assembling of computational models is considered as a programming activity. QUAESTOR overcomes this restriction because a number of time consuming activities required in the process of programming or assembling computational models are solved at a high level and, therefore, need not be carried out by the user any longer.

The first action is to select suitable model fragments and the second is to assemble these selected model fragments into an executable computational model, i.e. the actual coding of the model. Since QUAESTOR takes over the greater part of these tasks, all available time and energy can be spent on the actual core of the problem, i.e. the development, and improvement of the model parts or knowledge involved.

QUAESTOR makes it possible to develop and sustain a network or database containing computational knowledge elements and their characteristics. In a dialogue between the user and the inference engine or Modeller, the model assembling for arbitrary problem definitions is directed and then solved using the available model fragments in the database or knowledge base. This strategy enables the user to fully concentrate on actual knowledge content of the problems. The reasoning steps and the heuristic rules QUAESTOR applies when assembling computational models have been derived on the basis of many prototype applications.

The program is a combination of a knowledge-based system based on rules, computer algebra and constraint programming. When the system was put into practice a significant statement was made in that it appears to be an excellent support to the existing modes of operation and thought and that in fact other modes of operation need not be considered. This makes it possible to realise a smooth transfer from the design and analysis methods with ‘conventional’ tools to one with a knowledge-based system, among other reasons because the existing arithmetic programs can easily be used from the system.

5.2.3 Brief description of the computational domain

To a certain extent any system can be described by means of a collection of attribute/value pairs, such as numeric values (sizes, speed, volume) and nominal characteristics (colour, material, owner). There may be a relation between these attributes or *parameters* in any implicit or explicit form. Parameter values are DETERMINED or PENDING.

In the development of complex systems a great number of relations may play a role: empirical, physical and geometrical relations, but also legal or class requirements- and restrictions may be involved. Numerical and nominal expressions are indicated as *Relation*. A Relation is by definition an expression with in the left term a parameter, followed by an "=" sign and an arithmetic expression. A Relation is treated as an independent object or *frame* in which apart from the expression itself other information can be stored concerning origin, related data, if any, and information on their use in the form of *Properties*. A frame is a representation unit in which an expression or parameter can be stored together with a number of related data in *slots*. Slots are boxes in the frame, each containing a certain piece of information; e.g. a Reference, Data or the Properties as mentioned above.

It is important to know when a Relation or model fragment is applicable within a given context. Therefore, it is possible to connect Relations to one or more expressions that give information about its validity. These validities are represented in numerical or nominal form and may refer to either equalities or inequalities. These validity expressions are referred to as *Constraint*. Evaluating a Constraint yields a DETERMINED or PENDING FALSE or TRUE Boolean value. Constraints are also separate frames, though connected with the Relations to which they apply. The Relation can be applied in an assembled model provided that the connected Constraints are TRUE.

Each expression (Relation or Constraint) contains parameters. Parameters are also considered independent objects with related information, which are stored in separate frames.

5.2.4 QUAESTOR systems architecture

Any system able to work with the form of knowledge roughly described in the previous chapter basically consists of two main components, i.e. a knowledge management system and an inference engine. The knowledge management system allows inserting, adapting and searching knowledge (see fig. 1). In QUAESTOR the Knowledge Browser or simply browser gives access to the knowledge gathered in the databases. In fig. 1 the browser is the most significant component of the user interface. The browser offers all the necessary possibilities to adapt, search and even combine knowledge databases. Moreover, the browser provides tools, such as the Expression Editor, available to insert or adapt knowledge. In the Slots & Properties window, another part of the user interface, the properties of the parameters, Relations or Constraints can be viewed and adapted.
The other main part of knowledge-based systems is the inference engine for which in QUAESTOR the term Modeller is used. The Modeller uses the Workbase in order to save input and output and to communicate with the user. The knowledge base contains links with all kinds of (existing) specific software, referred to as satellite programs. The program can assemble the input required by these programs, have them executed and have the output transferred to other parts of the model.

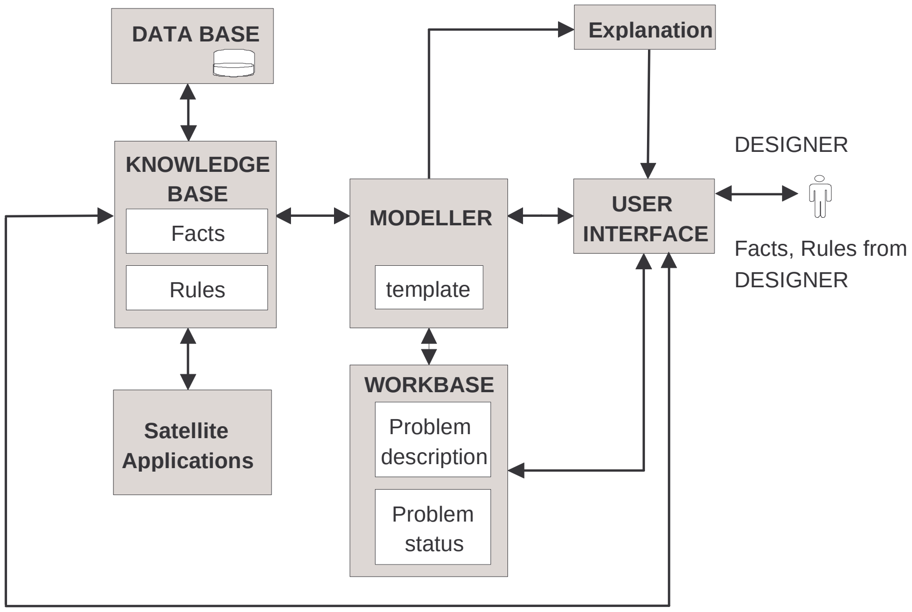


Fig. 1: QUAESTOR systems architecture

Knowledge-based systems can explain an achieved result (Explanation Facility). This implies that the system provides full insight into the model, what was calculated by what and why. The Frame Viewer in the user interface plays a significant part in this process of explanation but is also part of the browser. Beside a knowledge base the system disposed of a Database. In the Database among other things the input and output of computations can be saved.

5.3 DRIJFWIND: TURBINES and FLOATERS

5.3.1 Starting points

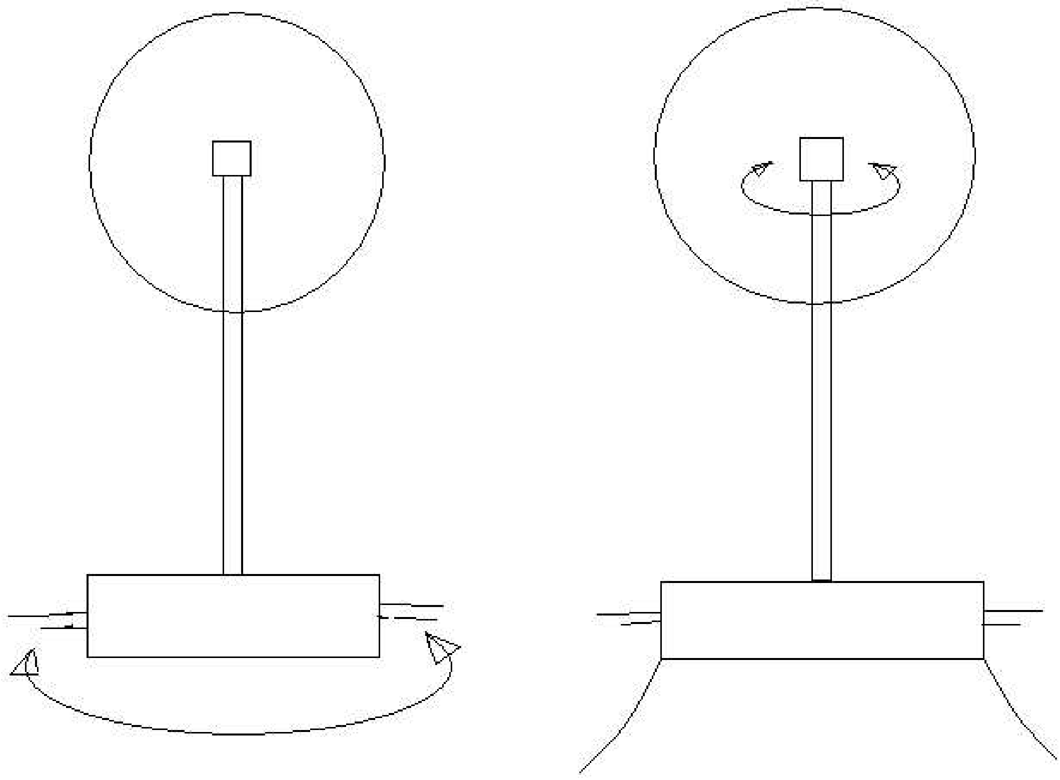
In the Terms of Reference [Bulder, 2001], a number of basic decisions are described such as:

- Wind farm size 500 MW
- Water depth >50 m
- Distance to shore >25 km
- Turbine diameter 115 m
- Turbine rated power 5 MW

Prior to performing any conceptual design of a floater-turbine combination, two important decisions were to be taken:

1) Weather-vaning or “fixed” floater ?

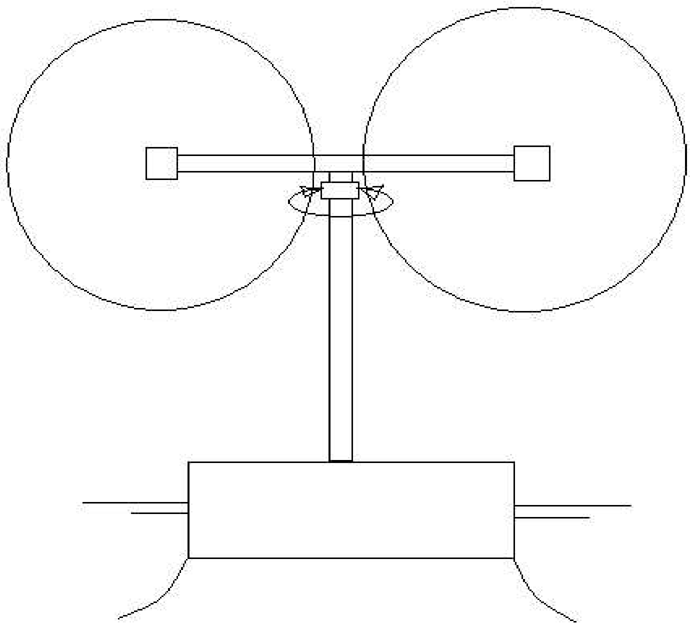
Will the turbine and floater be free to yaw and keep itself into the wind (“weather-vaning”) or will the floater not be allowed to yaw by e.g. a spread mooring? The latter implies the use of a yaw mechanism under the nacelle.



Weather-vaning **Yaw-mechanism**

A weather-vaning floater requires no yaw-mechanism, but in the arrangement of the concept should be taken into account that the forces by wind, waves and current are not necessarily in the same direction which means that the turbine may not always be properly directed towards the wind. Another problem with the weather-vaning concept is the delivery of generated power to the grid; a rotating- and most probably watertight connector is required. These connectors exist in the offshore industry but are complex and expensive equipment.
The vessel connected to a spread mooring will experience a mean yaw force due to the wind, waves and the current. This mean yaw force will be compensated by the yaw restoring of the mooring system. Therefore, the position quality with respect to the wind will be better enforced using a spread mooring system.
Base on these considerations, it was decided not to adopt the weather-vaning concept in this study.

1) One or more turbine per floater?
In view of overall reliability and from a maintenance perspective, it is attractive to apply the largest turbine, which can be constructed on the basis of currently available technology, or technology expected to be available in the near future. In the Terms of Reference [Bulder 2001], a 115 m turbine with a rated power of 5 MW was considered to be a feasible size. A 500 MW wind farm will consist of 100 units. A major conceptual decision is related to the number of turbines to be installed on a single floater. Taking the diameter of the turbine into account (115 m) it is not obvious to fit turbines above each other; this would imply a tower height of about 200 m, with a massive weight and equally massive stability moments which are already very large with the single turbine. Therefore, if more than one turbine is to be installed, it is probably confined to two machines in a T-shaped arrangement, as outlined in the sketch below.



Two turbines on one floater

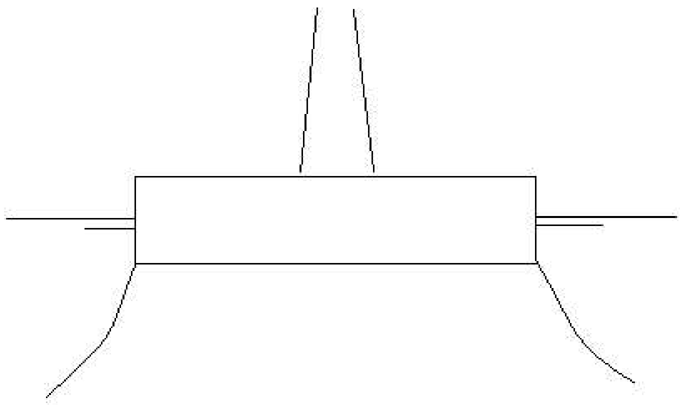
The tower top mass of the twin turbine will be about three times that of the single turbine due to the presence of the traverse. This requires a larger floater, simply to deal with the increased wind moment and vertical centre of gravity. The yaw mechanism should either be capable to deal with one machine shut down or both machines should be shut down in the event of a malfunction of one of the turbines, being the most probable solution. Tentative calculations on the single floater concept with one or two turbines indicate that a floater with two turbines contains about 170% of the steel of that of a floater with a single turbine.

For the purpose of the DRIJFWIND study, the single turbine solution will taken as the starting point since the twin turbine (“T”) arrangement can be designed and studied as a separate system and can in principle be fitted on each of the following floater concepts.

5.3.2 Floater concepts

The following parametric floater concepts are discussed during the consecutive meetings held within the scope of this project of which some are described in the DRIJFWIND knowledge base:

1) The single cylindrical floater ("pill-box") or buoy.
The floater is a simple vertical cylinder, held in position by a spread mooring. This concept was the starting point in the discussions.

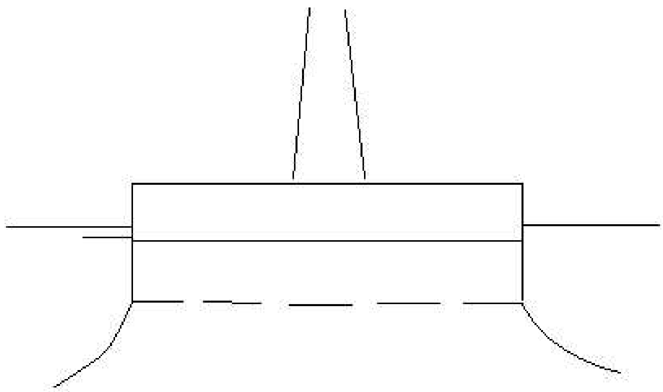


Single circular floater with water ballast

Tentative calculations were performed within the DRIJFWIND knowledge base to establish the basic dimensions of the "pill-box".

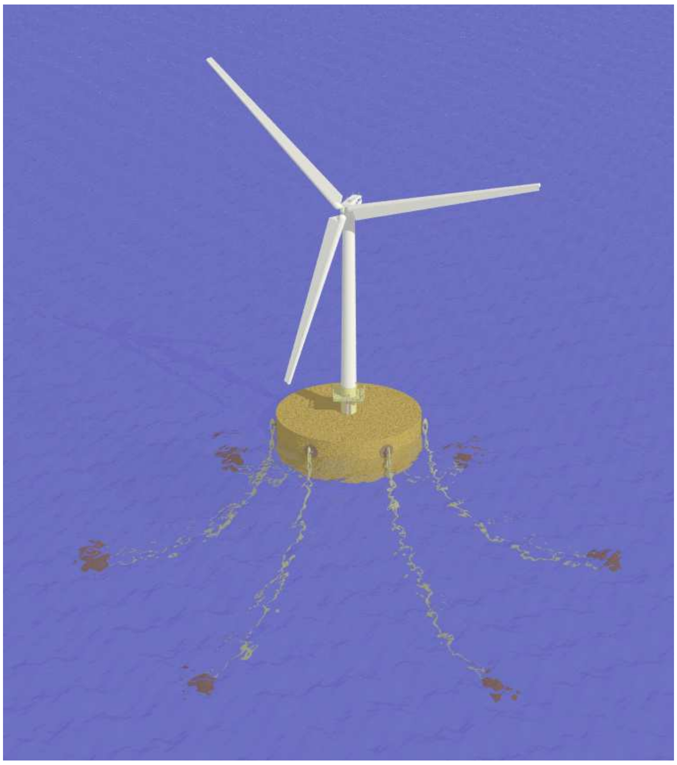
BM_Float	20.2	m
CVOL_Float	8203	m3
Draft_Float	4.27	m
D_Float	37.19	m
Freeb_Float	3.28	m
GM_Total	11.0	m
GZ_Max	1.97	m
H_Float	7.55	m
Ix	93783	m4
KB_Float	2.13	m
KG_Ballast	1.39	m
KG_Float	3.78	m
KG_Total	11.36	m
KM_Float	22.4	m
Kxx	22.53	m
Load_Fatig	1044	kN
M_Ballast	3098	t
M_Float	984	t
PhiMax	10	deg
Pretension	0.00	t
Steel_weight	1317	t
Tphi	13.62	s
Tz	8.17	s
VolMassConstr	0.12	t/m3
VOL_Floaters	4637	m3
WindArm	1.97	m

The stability range requires ballast water to achieve sufficient draft. Initial stability requires a diameter of at least 37 m. In the above results, about 3100 t of water ballast is used to achieve a draft of 4.27 m. This can either be stored in the pill box but this will require a lot of additional structure to prevent free surface stability loss. A more simple and effective solution is to introduce virtual ballast by constructing a buoy with a draft of about 1.4 m and circular skirts fitted underneath the bottom of about 3 m height.



Single circular floater with skirts

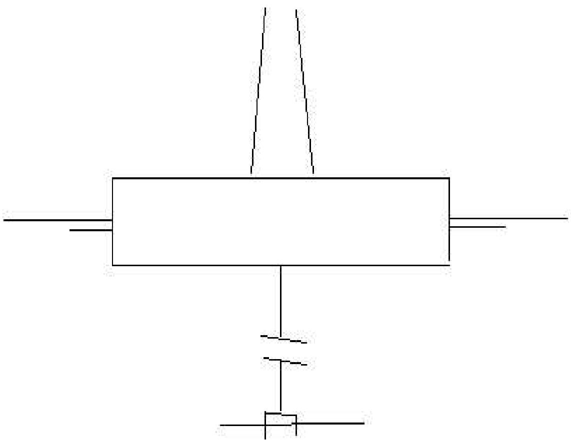
This circular skirt will confine about 3000 tons of seawater and can be considered as a ballast tank without bottom. From a stability perspective, a completely filled ballast tank can be regarded as flooded space vice versa. Although feasible from a stability perspective, this concept is not feasible from a motion perspective; in particular the heave period (Tz) of about 9 seconds is right within the high energy range of the wave spectrum as well as the roll period T_phi which is critical with about 13 seconds. Both roll and heave period should be about 16 seconds and there is no way to achieve that with the single circular floater, i.e. it is not possible to fulfil stability and motion requirements at the same time. Therefore, the "pill-box" concept was concluded to be technically infeasible.



Artist impression of "pill-box" floater

2) Similar to 1) but with a tension leg instead of a spread mooring

In order to fulfil stability requirements with a floater with a smaller diameter, it is an option to introduce pretension by means of a so-called *tension leg*. Next to this, the tension leg increases the vertical stiffness of the floating system, which reduces the heave period. In this way, the heave period can be moved out of the high-energy region of the spectrum. From a static stability point of view, this pretension can be considered as a point mass located at the connection point of the tension leg. In addition to the resulting downward shift of the virtual centre of gravity, the centre of buoyancy is also moved downward in *absolute* sense since additional buoyancy is required to compensate for the pretension.



Single floater with pretension

The introduction of pretension in restricted water is not attractive since only limited stability advantage can be achieved.

This can be understood by the following, simple equations:

```
GM = KB + BM – KG
```

in which:
- `GM` is the metacentric heigh and the primary indicator of static initial stability
- `KB` is the COG of the displaced volume above the base line
- `KG` is the centre of gravity of the floating object above of the base line

and

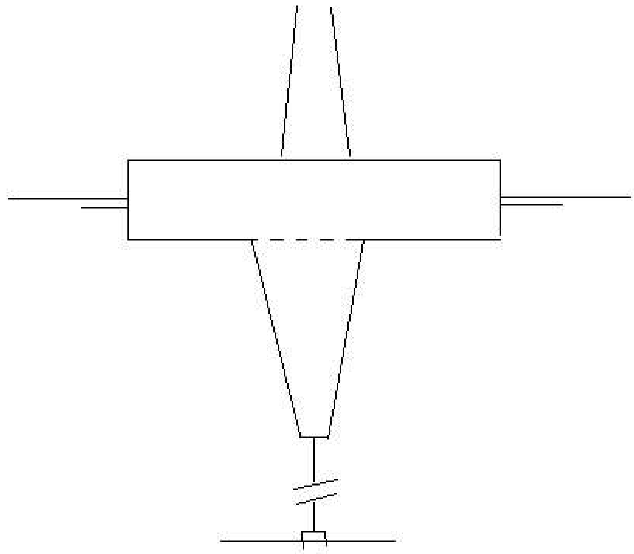
```
BM = Ixx/VOL
```

in which:
- `Ixx` is the (smallest) transverse moment of inertia of the waterplane of the floating object
- `VOL` is the displaced volume or `Mass/RhoSeawater`

`Ixx` is a property of the waterplane of the floating object and for a circular waterplane equivalent to:

```
Ixx = 0.049*D_Floater^4
```

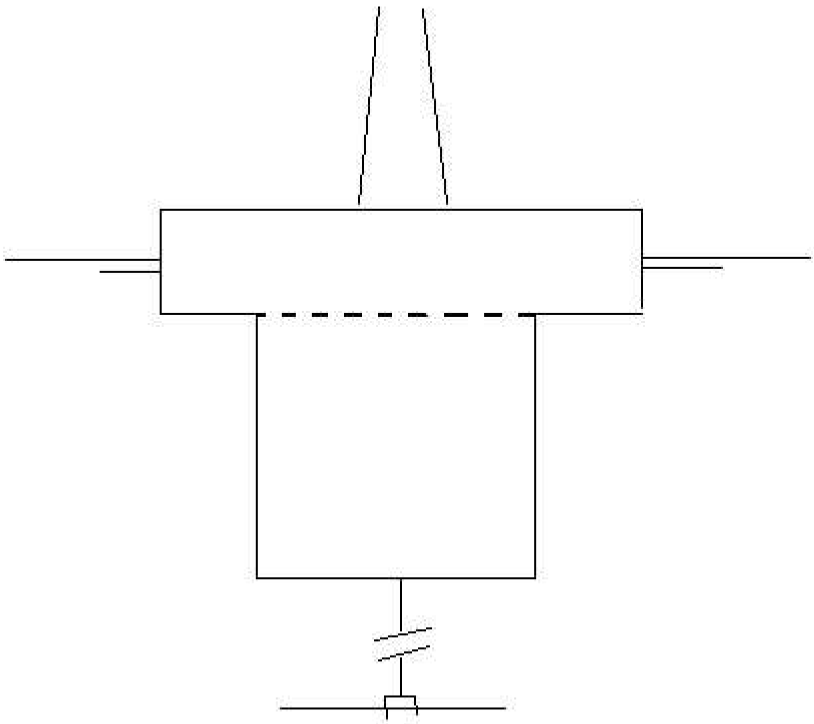
These relations show that BM is reduced if pretension is applied, the KG of the floater becomes larger with constant diameter since more draft is required to accommodate the additional volume required to compensate the pretension. KB becomes larger too, for a simple cylinder it is equivalent to the draft/2. The virtual KG is reduced by the pretension, and it is in particular affected by the vertical position of the tension leg connection point. If the connection point is located on a deeply submerged rod, the virtual KG can reduce; if it is simply connected to the bottom of the floater, the effect on KG is limited, which will be the case in restricted water depths. Summarising, the tension leg concept is not suitable for the water depths considered in this study since not enough stability advantage is achieved by the pretension. For this concept, the only reason to introduce pretension is the reduction of the heave period, which is making the single floater into an infeasible concept.



Single floater with low connection of tension leg

In consultation with R. H. M. Huijsmans from MARIN, a number of calculations were made on a combination of tension leg and spar buoy with water ballast. The best results are obtained with a “inverted” spar buoy; two cylinders on top of each other, largest diameter protruding the water surface (H/3), smallest diameter below (2*H/3) and a tension leg connecting the small cylinder with the sea bed.

The initial calculations for the single floater as presented above, showed that a diameter of approximately 37 m was required to fulfil the basic stability requirements. Smaller diameters are only possible with a tension leg and not as spar buoy, since stability is hardly affected by the amount of ballast water in the buoy.



Inverted spar buoy with pretension

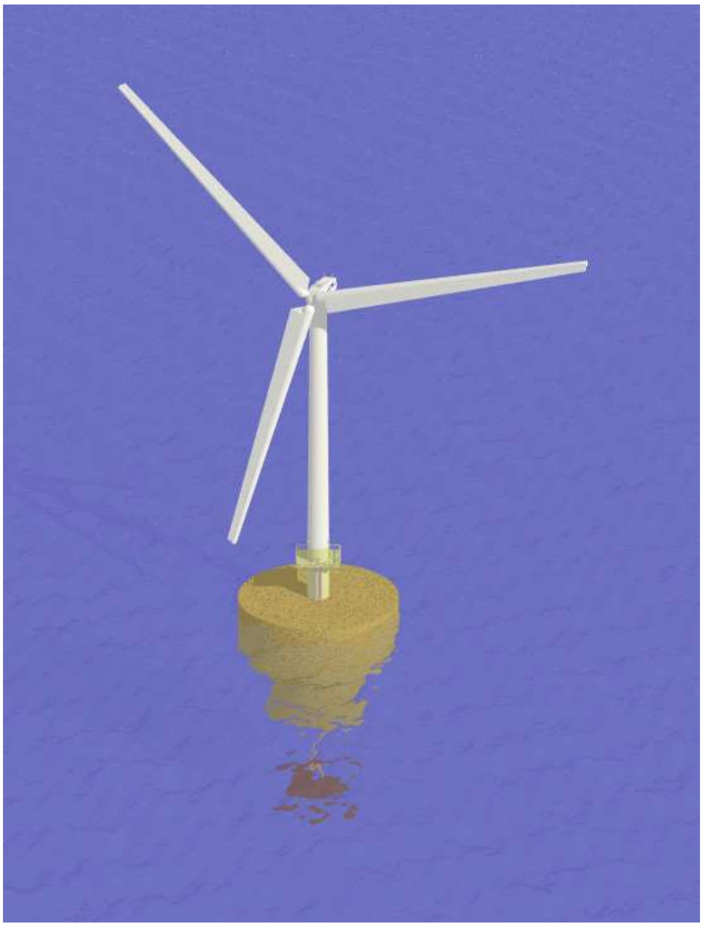
The amount of pretension required to counterbalance the wind moment is computed for a range of floater diameters assuming a maximum angle of inclination of 10 degrees:

M_ballast 3000.00 [t]

Nr	Draft_Float	D_Disc	D_Float	H_Disc	H_Float	Pretension	Steel_weight	VOL_Float
	[m]	[m]	[m]	[m]	[m]	[t]	[t]	[m3]
1	43.53	12.00	20.00	29.04	51.80	2662	2002	7838
2	37.70	13.20	22.00	25.15	45.25	2943	2106	8213
3	32.87	14.40	24.00	21.92	39.72	3175	2191	8522
4	28.70	15.60	26.00	19.15	34.83	3333	2250	8734
5	24.95	16.80	28.00	16.64	30.32	3387	2270	8806
6	21.42	18.00	30.00	14.29	25.97	3291	2235	8679
7	17.92	19.20	32.00	11.95	21.53	2977	2118	8258
8	14.17	20.40	34.00	9.45	16.66	2315	1873	7373
9	12.05	21.00	35.00	8.04	13.85	1770	1672	6645
10	10.87	21.30	35.50	7.25	12.27	1413	1540	6168
11	9.57	21.60	36.00	6.38	10.50	973	1377	5580
12	8.05	21.90	36.50	5.37	8.43	410	1169	4827

The pretension should also be sufficient to avoid the tension leg from becoming slack in extreme wave conditions, which can only be determined with some real accuracy by means of thorough motion analyses.

The above results show that large pretensions (Pretension) are required, in the order of 3000 ton, about 3000 ton water ballast (M_ballast) and about 2200 tons of steel (Steel_Weight), resulting in a total displacement about 8500 tons. The large (upper) cylinder diameter is in the range of 26-30 m (D_Float), the small diameter lower cylinder about 16 m (D_Disc), being 60 per cent of the floater diameter. Total floater heights (H_Float) are about 30 m, drafts (Draft_Float) in the order 25 m. These values can hardly be considered as a feasible solution in terms of investment cost and complexity for supporting a single 115 m turbine in waters up to 50 m deep.



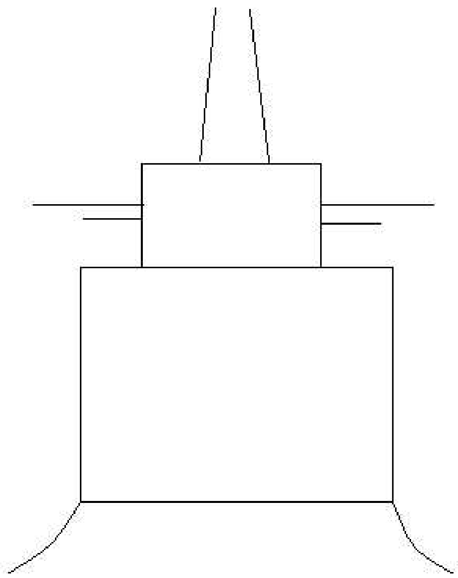
Artist impression of "inverted spar" with pretension

3) Similar to 1) but with a box-shaped floater, i.e. a square or rectangular barge.
Although included as concept in the "Drijfwind" knowledge base, it has not been separately evaluated since the results are expected to be very similar to the circular single floater.

4) 'Catamaran' type of floater with truces connecting the floaters
The floaters are prismatic and the truces are cylindrical, a spread mooring is applied. Although included as concept in the "Drijfwind" knowledge base, it has not been separately evaluated.

5) 'Spar' floater

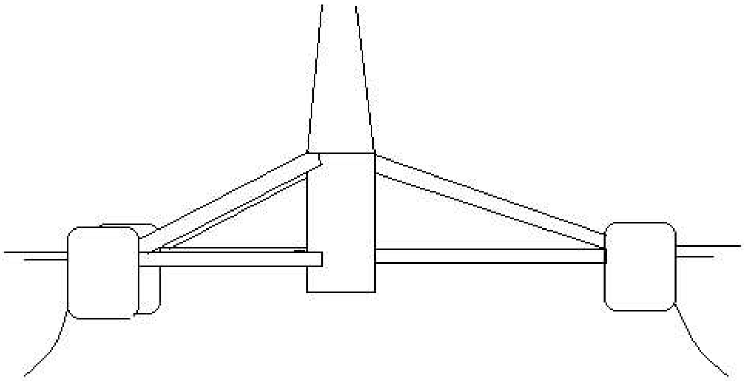
This floater is a so-called 'spar' buoy with a large lower vertical cylinder referred to in the knowledge base as 'disc' and a smaller upper cylinder protruding the water surface on which a single pole is located. A spread mooring holds the buoy in position.



Spar buoy with spread moorings

This concept can- and has been evaluated with the DRIJFWIND knowledge base. In terms of initial stability, the Spar as outlined in the above sketch is not feasible in water depths around 50 m due to its enormous size, necessary to achieve sufficient static stability.

6) *Triple floater concept with truces connecting the floaters and a single turbine located in the centre between the floaters.*



Triple floater with tubular truces

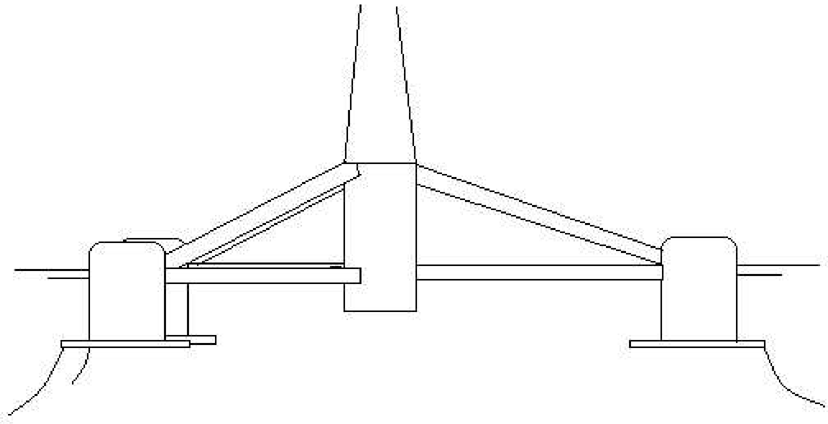
In order to improve the vertical motion response and to reduce overall construction volume, the triple floater concept was proposed. The floater consists basically of a centre column carrying the wind turbine, which is connected with cylindrical floaters by means of tubes or truces. Tentative relations were derived for the hydrostatic properties, stability and weight on the basis of a limited number of describing parameters and were included in the DRIJFWIND knowledge base (see Appendix III).

A concept variation was performed for a range of floater distances. Floater dimensions are established on the basis of stability requirements, as was done for the “pill-box” concept. Stability requires particular values of GM, which can only be fulfilled by a particular minimum diameter of the floater bodies. The primary results are presented in the table below:

D_Truces 3.01 m

DistFloat	Draft_Float	D_Float	Freeb_Float	H_Float	M_Ballast	Steel_weight	Total_Mass	Tphi	Tz	WindArm
[m]	[m]	[m]	[m]	[m]	[t]	[t]	[t]	[s]	[s]	[m]
36.00	5.67	13.45	4.36	10.04	1465	873	2707	13.49	6.27	3.55
40.00	5.99	12.25	4.61	10.60	1270	815	2455	13.26	6.22	3.93
44.00	6.34	11.23	4.87	11.21	1138	773	2280	13.06	6.18	4.25
48.00	6.70	10.36	5.15	11.85	1042	741	2152	12.90	6.18	4.53
52.00	7.07	9.62	5.44	12.51	983	717	2070	12.81	6.19	4.73
56.00	7.46	8.99	5.74	13.19	962	701	2033	12.82	6.22	4.85
60.00	7.85	8.40	6.04	13.88	831	672	1873	12.44	6.30	5.28
64.00	8.25	7.90	6.35	14.60	777	655	1802	12.29	6.37	5.51
68.00	8.66	7.47	6.66	15.32	775	647	1792	12.35	6.43	5.57
72.00	9.08	7.13	6.98	16.06	931	663	1964	13.12	6.48	5.14

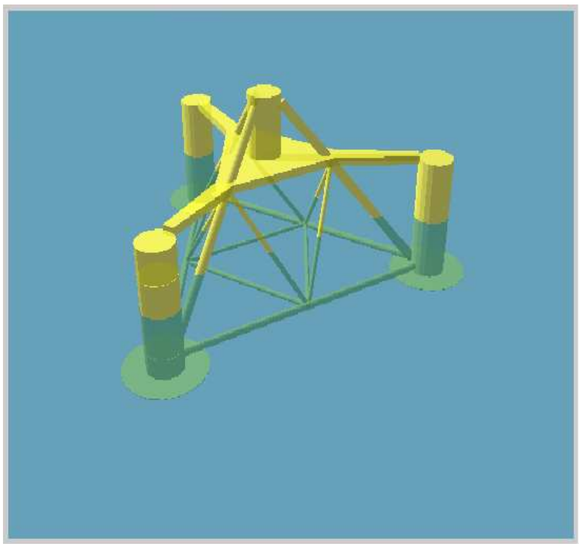
The above results indicate that the triple floater concept requires less steel than the single floater/spar floater concepts. However, the vertical motion response is still within a critical region and should be shifted either to higher frequencies (only possible by introducing pretension) or to lower frequencies in the order of 15-16 seconds. This can be done e.g. by fitting large circular plates or cylinders underneath the floaters, increasing the (hydrodynamic) mass of the floater as indicated in the sketch below.



Triple floater with damping plates

This concept was selected for the calculation of the motion responses by Huijsmans of MARIN [Huijsmans, 2002] and served as starting point for the more detailed construction design by MSC [MSC, 2002] as shown in 7)

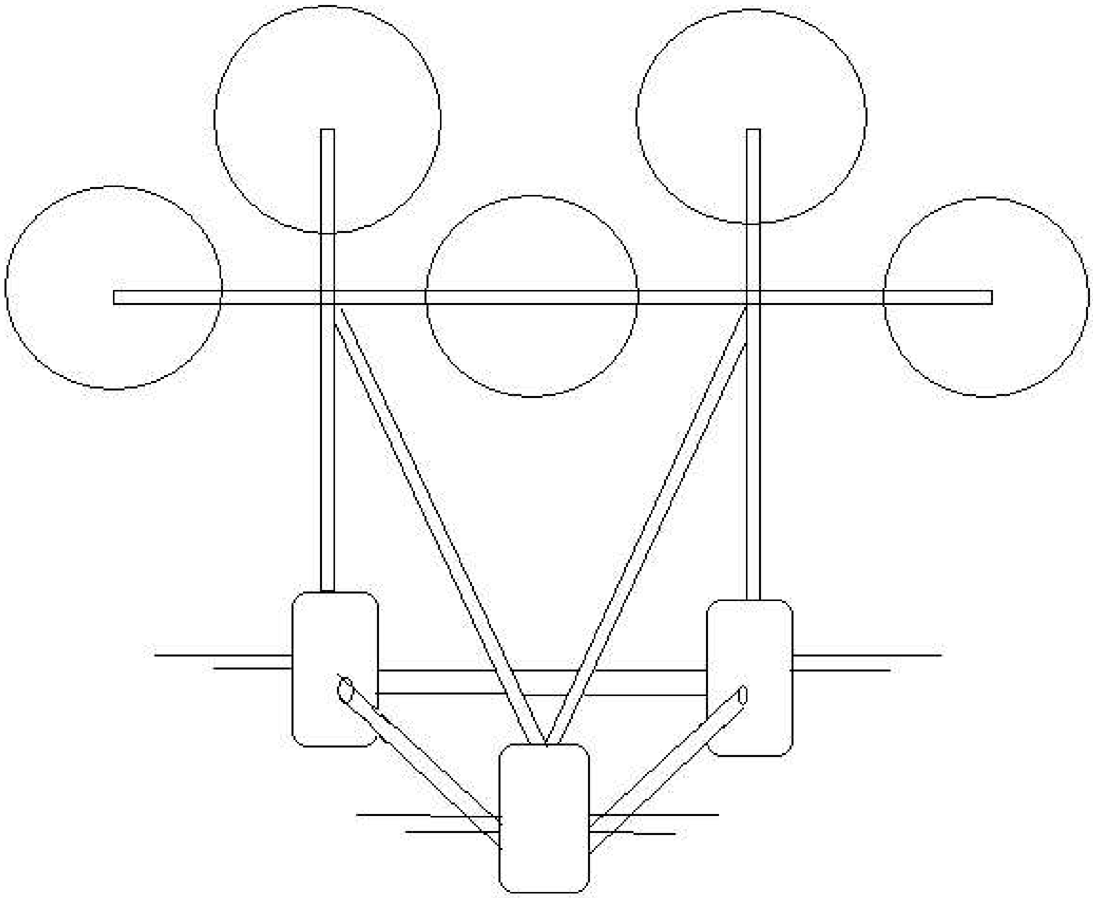
7) Equal to 1) but with a single turbine located on one of the floaters
This concept was proposed and presented by MSC on the basis of the initial calculations performed under 6). Re-assessment of this concept showed that a lighter construction could be achieved by returning to option 6) since it allows lighter truces connecting the three floaters.



Triple floater arrangement proposed by MSC [MSC, 2002]

8) Triple floater with 5 turbines of 71 m.
This concept was developed by Lagerwey and Heerema and included the preliminary construction design. Therefore, the weight figures should be reasonably accurate and suitable to verify the relations in the DRIJFWIND knowledge base. The subsequently performed calculations with DRIJFWIND indicated that the weight of the floaters (1300 t) is too high if compared to average values of volume

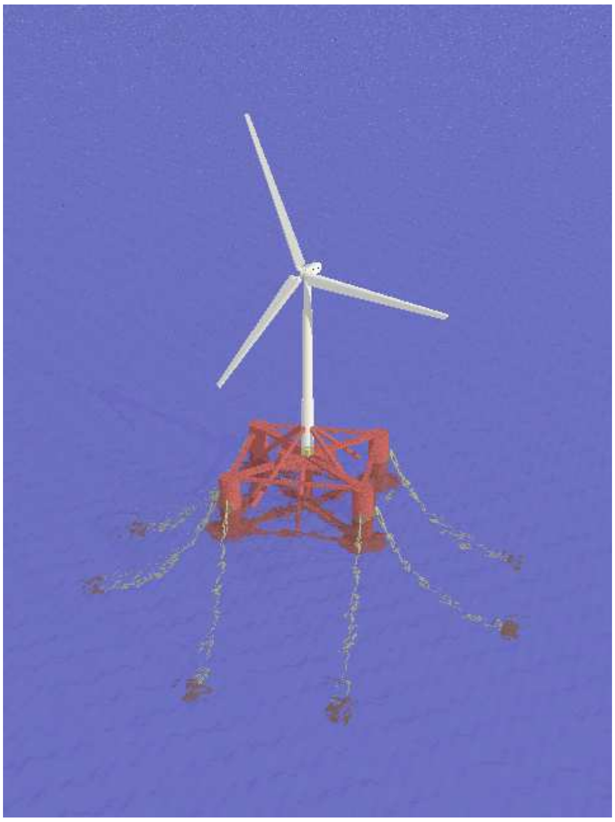
weight of such structures (0.12-0.16 t/m3). Apparently, water ballast is included in this figure of which the amount could not be traced. The weight of the superstructure (800 t) and of the five turbines (500 t) correspond quite well with the DRIJFWIND relations. This concept was supposed to be moored by means of a single steel pile in the centre of the triangle formed by the three floaters. The floater should be weather-vaning; i.e. the floater should keep the turbines in the wind due to the resulting turning moment of the wind force. An obvious disadvantage of this concept is its inherent vulnerability; if one out of five turbines needs to be shut down for maintenance or due to a malfunction, the weather-vaning capability is lost which implies that the other four have to be shut down too. The concept is presented in the sketch below.



Lagerweij/Heerema triple floater concept

9) Quadruple floater concept with truces connecting the floaters

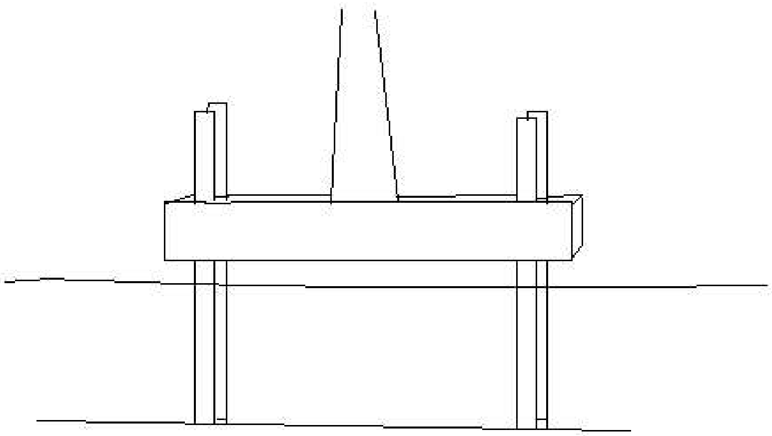
The floaters are cylindrical as well as the truces, a spread mooring is applied. This concept is very similar to the triple floater concept. With equal floater dimensions, the distance between the floaters can be somewhat smaller. The steel weight of the quadruple floater is expected to be higher due to the larger amount of connecting structure between the four floaters, as is obvious from the comparison of the artist impressions from the triple and the quadruple floaters.



Artist impression of the quadruple floater

10) The jackup platform on three or four legs

The jack-up concept was proposed as an option to allow simple installation and convenient transportation to and from the wind farm. A jack-up concept eliminates wave-induced motions of the turbine and forms a stable foundation of a single or multiple turbine system. However, the jack-up concept has a major drawback: its cost. According to data provided by MSC, a jackup suitable to carry a single 115 m turbine will cost about € 12,000,000.= which makes it totally impossible to apply the jackup as a platform for wind turbines.



Four-leg jackup with single turbine

5.4 the DRIJFWIND Knowledge base

5.4.1 Properties described in the knowledge base

The following properties are described in the DRIJFWIND knowledge base:

1) Wind turbine and pole dimensions, weight + COG, energy yield, cost etc., based on the ECN BLADOPT program which are applicable to *on shore* turbines.
2) Main dimensions of the single floater, number of floaters in a platform.
3) Floater displacement and gross structural volume based on weight, weight in its term based on simple volume weight, freeboard is taken in to account in the determination of the structural volume.
4) The initial stability is based on wind arm (forces from BLADOPT) and stability index based on an agreed operational heel of 10 degrees.
5) The investment cost based on BLADOPT data for wind turbines and rough estimate of floater and multi turbine support structure cost on the basis of Euros/kG. The point design by MSC is used to correct these figures in the knowledge base
6) Average KWh cost on the basis of BLADOPT energy yield and the above estimates, interest rate, depreciation period and scrap value
7) Cost of shore connection [Pierik, 2002] as a function of distance to shore.
8) Maintenance cost offshore or tow to harbour and onshore maintenance on the basis of ProjectData.xls [Wijnants, 2002]

5.4.2 Current limitations of DRIJFWIND knowledge base

The following aspects and properties are either dealt with in a very simple way, included as rough estimates or are not included at all in the knowledge base:

1) Steel weight of floaters is treated as a simple weight per m3 construction volume. The applied value of 0.12 ton/m3 is verified with the three floater point design by MSC and found to be too low since it indicates values around 0.16 t/m3.
2) The initial stability is modelled in a correct manner but the stability requirements for unmanned wind turbine carrying platform should be clarified by relevant classification societies.
3) The relation between weight, structure, strength and loads are not described. The relation between weight and stability is obvious and introduces conceptual uncertainties. A number of buoy/barge designs should be made or existing designs should be further analysed.
4) The buoy structural strength is not included in the knowledge base and is difficult to implement since it requires full integration of motion and strength calculations. A number of point designs are required to derive general data on structure size, strength and weight.
5) Structural description of the single pole may be correct in BLADOPT for on shore turbines, a number of multiple turbine structures should be designed or rather, the strength assessment of multiple turbine structures should be included

in the knowledge base, introducing the motion induced terms in the structural loads.

6) Motions of single and multiple floater concepts are described with simple formulae for heave and roll. The hydrodynamic mass is determined on the basis of geometric considerations. Future extension of the DRIJFWIND knowledge base with an interface to a sea keeping code should enhance the conceptual evaluations since motions are mainly determining the technical feasibility of a floater concept.
7) Mooring properties, current and wave drift forces as well as the effect of mooring forces on stability are not modelled in the knowledge base and introduce conceptual uncertainty.
8) Cost of floater structure on the basis of simple cost/kg, uncertainty of weight equals uncertainty of floater cost, cost is also a function of the building location.
9) Installation cost on the wind farm site is not modelled but can be derived from the data presented in ProjectData.xls [Wijnants, 2002].
10) Cost of onshore turbine based on BLADOPT, extra cost of maritime turbine is not modelled.

5.5 CONCLUSIONS

Some initial calculations performed within the DRIJFWIND knowledge base show that the single “pill-box” buoy concept without pretension is not feasible as free floating buoy and requires buoy diameters as much as 37 m for a 115 m turbine. Smaller buoy sizes are only possible when a tension leg concept is applied. This implies to some extend that the single buoy/single turbine concept is not feasible at all since a tension leg concept does not allow the buoy + turbine to be towed to a harbour facility for maintenance. From a perspective of motions, the “pill-box” floater is not feasible since in particular the vertical motion response is within the high-energy region of the wave spectrum.

The multi-floater i.e. triple-floater concept is feasible in terms of stability and its structural weight is smaller if compared to a single floater. However, the size of the structure becomes quickly too large for a single turbine. The requirement of a movable platform implies a requirement for stability afloat, say during the passage from shore to the wind farm. A hybrid solution could be a jackup, which is a fixed structure when on location and a floating one related to transport and maintenance. The jackup, however, is not feasible due to its high construction cost.

The course approximations in the DRIJFWIND knowledge base allowed to rapidly focusing on the technically feasible concepts. In order to select/optimise the presented concepts in terms of both economical and technical aspects, it is absolutely necessary to fill in the white spots discussed in section 4.2. Based on the concept variations performed in DRIJFWIND, the triple floater concept was selected as basis of a point design, performed by MSC [MSC, 2002].

The DRIJFWIND knowledge base in QUAESTOR proved to be a useful tool to establish the focus of research performed within this project. The DRIJFWIND knowledge base forms an extendable and easy to maintain body of knowledge on floating wind farms and is open to extensions and enhancements that results from future research.

Appendix I: References

[Bulder, 2001] – Bulder, B.H. et al.Theory and user manual BLADOPT, ECN Report ECN-C—01-011

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[vHees, 1997] - Van Hees, M.Th.: “QUAESTOR: Expert Governed Parametric Model Assembling”, Doctors thesis, Technical University Delft, 1997, ISBN: 90-75757-04-2

[vHees, 1999] - Van Hees, M.Th.: “Windows Version QUAESTOR”, MARIN Report No. 14532-1-CP

[Henderson, 2002] - Henderson, A.R., Feasibility Study for Floating Offshore Windenergy (DRIJFWIND), Literature Review, Delft University of Technology, Section Wind Energy, report SW-0218x

[Huijsmans, 2002] – Huijsmans, R.H.M., Motion response calculations of a floating wind turbine, Marin Report 16602-1-RD

[Pierik, 2002] – Pierik, J.T.G., ‘DRIJFWIND electrical system, conceptual design and cost, ECN report ECN-CX- -02-025

[MSC, 2002] - COncept design floating wind turbine, MSC ref P 10499-3940

[Wijnants, 2002] - Wijnants, G.H., Integral maintenance cost estimate for Remote Offshore Platforms, TNO Building and Construction Research, 22 July 2002

Appendix II: Review of 'DRIJFWIND' parameters

```
Class: Top Goals/Undefined

Land_Enery_Cost
          Energy cost of wind turbines statio .[EUROCT/kWh]
Sea_Enery_Cost
          Drijfwind cost/kWh ..................[EUROCT/kWh]


Class: Options

Turbs_Floater
          Number of turbines per floater ...............[#]
Web_or_Singleline
          Mooring system ..............................[ID]
Floater_Concept
          1 <EQ> circular floater .....................[ID]


Class: Cost

Cost_Unit Cost per unit ..........................[EUR/kWh]
Blades_Cost
          Cost of blades ..............................[EUR]
Hub_Cost  Cost of turbine hub .........................[EUR]
Drive_Train_Cost
          Cost of drive train .........................[EUR]
Elec_Syst_Cost
          Cost of electric system .....................[EUR]
Nacelle_Cost
          Cost of generator housing ...................[EUR]
Yaw_Mech_Cost
          Cost of yaw mechanism .......................[EUR]
Saf_Contr_Cost
          Safety and control system cost .............[EUR]
Tower_Cost
          Cost of tower ...............................[EUR]
Assembly_Cost
          Cost of assembling ..........................[EUR]
Wind_Farm_Cost
          Total wind farm cost per turbine ...........[EUR]
Extra_Cost_Land
          Extra cost not accounted for in land opera .[EUR]
Total_Investment
          Total investment cost of wind turbine + fl .[EUR]
Energy_Yield
          Produced kWh's per year .................[kWh/yr]
CostPerKgFloat
          Construction cost of floater per Kg .....[EUR/kg]
Floater_Cost
          Cost of floater .............................[EUR]
CostPerKgTower
          Cost per Kg tower construction ..........[EUR/kg]
Constr_Cost
          Steel construction cost of tower+floater ...[EUR]
Depreciation
          Depreciation of floater+turbines ........[EUR/yr]
```

```
Deprec_Period
          Depreciation period, e.g. 20 years ..........[yr]
ScrapValuePerc
          Percentage scrap value after depreciation= ...[%]
Interest  Yearly interest rate ....................[EUR/yr]
IntRate   Yearly interest rate .........................[%]
Capital_Cost
          Yearly capital cost .....................[EUR/yr]
Year_Cost Total system cost/year ..................[EUR/yr]
Maint_CostPercSea
          Yearly maintenance cost percentage of tot .[%/yr]
Maintenance_KWh
          Maintenance cost per kWh ............[EUROCT/kWh]
Maint_CostPercLand
          Yearly maintenance cost percentage of total  .[%]
SeaFarmCF Multiplication factor windfarm cost land->se .[-]
Extra_Cost_Sea
          Extra cost not accounted for in sea operat .[EUR]
```

Class: Climate

```
Water_Depth
          Sea water depth ..............................[m]
Wind_Clim Wind climate type ...........................[ID]
Wind_V    Wind speed .................................[m/s]
Wind_Dir  Wind direction .............................[deg]
Wave_Spectrum
          Wave spectrum type ..........................[ID]
R_Windspeed
          Rated windspeed of windturbine .............[m/s]
W_current Current velocity ...........................[m/s]
```

Class: Turbine

```
NP_Turbine
          Nominal power per turbine ...................[kW]
Turbine_Type
          Type of turbine .............................[ID]
Nr_Blades Number of turbine blades .....................[#]
Rotor_Diam
          Rotor diameter ...............................[m]
X_Shaft   X position of turbine shaft ..................[m]
Y_Shaft   Y position of turbine shaft ..................[m]
Z_Shaft   Z position of turbine shaft ..................[m]
M_Turbine Mass of turbine ..............................[t]
P_Turbine Power per turbine ...........................[kW]
Ch_R15    Blade chord length on 15% radius .............[m]
Ch_R25    Blade chord length on 25% radius .............[m]
Ch_R100   Blade chord length on 100% radius ............[m]
C_Loss_Drive
          constant loss of energy in drive train (typi .[-]
V_Loss_Drive
          Speed dependent loss of energy in drive train
Nr_Main_Towers
          Number of main towers per floater ............[#]
RatedRPM  Rated rotation rate of turbine ...........[1/min]
AimPow    Target power of single turbine ..............[kW]
```

```
TipSpeed  Maximum tip speed of rotor .................[m/s]
PowerDensity
          Power density of rotor disk .............[kW/m^2]
TipHeight Vertical distance between rotor tip and wate .[m]
```

Class: Tower

```
Tower_Height
          Tower height .................................[m]
Tower_F_Th
          Foot wall thickness of tower ................[mm]
Tower_T_Th
          {\rtf1\ansi\ansicpg1252\deff0\deftab720{\fo .[mm]
Tower_F_D Foot diameter of tower .......................[m]
Tower_T_D Top diameter of tower ........................[m]
Tower_Eigenfr
          Tower eigen frequency .......................[Hz]
TowFloD_Ratio
          Floater diameter/Tower foot diameter .......[m/m]
```

Class: Electric

```
AC_DC     AC or DC ...................................[ID]
Voltage   Operational voltage ........................[kV]
E_Current Electric current .............................[A]
```

Class: Floater

```
VOL_Floaters
          Displacement (submerged) volume of floater .[m^3]
RAO_Floater
          Responce amplitude operator ................[m/m]
D_Floaters
          Outside diameter of floater topside ..........[m]
H_Floaters
          Height of floater ............................[m]
Freeb_Floaters
          Freeboard of floater .........................[m]
H_Disc    Height of disc (lower part of buoy) ..........[m]
0
D_Disc    Diameter of lower part of floater (disc) .....[m]
0
DiscFloatRatio
          Ratio of disc height/floater height ..........[-]
TowFloDiscD_Ratio
          Floater disc diameter/Tower foot diameter ....[-]
DistFloat Distance between floaters (triple or quadrup .[m]
CVOL_Floaters
          Total construction volume of floaters + tr .[m^3]
Nr_Floaters
          Number of floaters per island ................[#]
Draft_Floaters
          Draft of floaters ............................[m]
D_Truces  Diameter of connection pipes between floater .[m]
VOL_Truces
          Total volume of connection pipes between f .[m^3]
```

```
L_Floaters
          Length of floater(s) .........................[m]
g         Gravitational accelleration ..............[m/s^2]
Pretension
          Pretension ...................................[t]
```

Class: Weights

```
M_Floaters
          Steel weight of floater ......................[t]
Total_Mass
          Total mass of turbine, tower, floater and (w .[t]
Tower_Top_Mass
          Mass of generator + turbine ..................[t]
Tower_Mass
          Mass of tower ................................[t]
Blade_Mass
          Mass of one turbine blade ....................[t]
M_Ballast (Water) ballast amount or pretension  ........[t]
VolMassConstr
          Construction mass per m3 of the floater  .[t/m^3]
Steel_weight
          Total steel weight, i.e. towers + floaters ...[t]
```

Class: Stability

```
KG_Floaters
          Centre of gravity of floater above BL ........[m]
KB_Floaters
          Centre of buoyancy of floater above BL .......[m]
GM_Total  Metacentric height of floater + turbine ......[m]
Load_Storm
          Storm load on turbine ......................[kN]
Load_Extreme
          Extreme load on turbine ....................[kN]
Load_Fatig
          Fatigue load on turbine ....................[kN]
VCG_Tower Vertical centre of gravity of tower ..........[m]
BM_Floaters
          Metacentre above centre of buoyancy ..........[m]
KM_Floaters
          Metacenter height above keel of floater(s) ...[m]
KG_Total  Vertical centre of gravity of turbine, tower .[m]
KG_Ballast
          Vertical COG of ballast or ...................[m]
GZ_Max    Maximum arm of static stability ..............[m]
WindArm   Required wind arm at Phi_Max .................[m]
MomMaxStab
          Maximum stability momen ..................[kN*m]
PhiMax    Maximum allowable heel of tower ............[deg]
StabIndex Stability moment/wind moment at Phi_Max ......[-]
Ix        Moment of inertia of water plane area ......[m^4]
Ballast_Factor
          Percentage ballast space used ................[%]
```

Class: Mooring

```
Nr_moorings
          Number of mooring cables .....................[#]
```

Class: Motions

```
ma        Added mass for heave .........................[t]
Tz        Natural period of heave ......................[s]
Rho       Sea water density ........................[t/m^3]
Tphi      Natural period of roll and pitch .............[s]
Kxx       Radius of gyration for roll and pitch ........[m]
Kzz       Radius of gyration for yaw ...................[m]
```

Class: Farm

```
D_Shore   Distance of farm to shore ...................[km]
FL_Farm   Number of islands per farm ...................[#]
Total_Power
          Total electric power of wind farm............[kW]
```

Class: Input, Objects & Reports

```
REPORT$   Output DESIGN.REP of BLADOPT.EXE ...........[Str]
COST$     Parsed results from BLADOPT output .........[Str]
BLADOPTINPUT$
          Input of BLADOPT.EXE GEODAT.N ..............[Str]
DB$       Database of clustered solutions ............[Str]
DEFINS$   Engineering cost functions .................[Str]
DEFINE$   Parametric cost functions ..................[Str]
DESIGNDATA
          Design data ................................[Obj]
ENGDAT$   Engineering data as additional input for B .[Str]
```

Appendix III: Review of 'DRIJFWIND' relations

<u>Class: Top Goals/Undefined</u>

```
Energy cost of wind turbines stationed on land

Land_Enery_Cost = SELECT(COST$, 1, "Land_Enery_Cost",
1)*DIM("EUR/kWh")/2.20371*100
--------------------------------------------------
Drijfwind cost/kWh

Sea_Enery_Cost = Year_Cost/Energy_Yield*100
--------------------------------------------------
```

<u>Class: Cost</u>

```
Total cost of wind turbine (excl. floater)

Total_Investment = Blades_Cost + Hub_Cost + Drive_Train_Cost
+ Elec_Syst_Cost + Nacelle_Cost +
                   Yaw_Mech_Cost + Saf_Contr_Cost +
Assembly_Cost + Extra_Cost_Sea + Constr_Cost +
                   Turbs_Floater*Wind_Farm_Cost*SeaFarmCF
--------------------------------------------------
Cost of blades

Blades_Cost = Turbs_Floater*SELECT(COST$, 1, "Blades_Cost",
1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of assembling

Assembly_Cost = Turbs_Floater*SELECT(COST$, 1,
"Assembly_Cost", 1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of drive train

Drive_Train_Cost = Turbs_Floater*SELECT(COST$, 1,
"Drive_Train_Cost", 1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of electric system

Elec_Syst_Cost = Turbs_Floater*SELECT(COST$, 1,
"Elec_Syst_Cost", 1)*DIM("EUR")/2.20371
--------------------------------------------------
Total cost of wind farm

Wind_Farm_Cost = SELECT(COST$, 1, "Wind_Farm_Cost",
1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of yaw mechanism

Yaw_Mech_Cost = Turbs_Floater*SELECT(COST$, 1,
"Yaw_Mech_Cost", 1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of turbine hub
```

```
Hub_Cost = Turbs_Floater*SELECT(COST$, 1, "Hub_Cost",
1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of generator housing

Nacelle_Cost = Turbs_Floater*SELECT(COST$, 1, "Nacelle_Cost",
1)*DIM("EUR")/2.20371
--------------------------------------------------
Cost of tower

Tower_Cost = SELECT(COST$, 1, "Tower_Cost",
1)*DIM("EUR")/2.20371
--------------------------------------------------
Safety and control system cost

Saf_Contr_Cost = Turbs_Floater*SELECT(COST$, 1,
"Saf_Contr_Cost", 1)*DIM("EUR")/2.20371
--------------------------------------------------
Total cost of wind turbine (excl. floater)

Total_Investment = LININT(DB$,3, "Rotor_Diam",
"Tower_Height", "Tower_Cost",

Rotor_Diam,Tower_Height,1)*DIM("EUR") + Floater_Cost
--------------------------------------------------
Cost per unit

Cost_Unit = Turbs_Floater*SELECT(COST$, 1, "Cost_Unit",
1)*DIM("EUR/kWh")/2.20371
--------------------------------------------------
Produced kWh's per year

Energy_Yield = Turbs_Floater*SELECT(COST$, 1, "Energy_Yield",
1)*DIM("kWh")/1000
--------------------------------------------------
Cost of floater

Floater_Cost = M_Floaters*CostPerKgFloat*1000
--------------------------------------------------
Cost of tower

Tower_Cost = Tower_Mass*CostPerKgTower*1000
--------------------------------------------------
Steel construction cost of tower+floater

Constr_Cost = Tower_Cost + Floater_Cost
--------------------------------------------------
Depreciation of floater+turbines

Depreciation = 1.0/Deprec_Period*Total_Investment*(1.0-
ScrapValuePerc/100)
--------------------------------------------------
Yearly interest rate

Interest = IntRate*Total_Investment/100
--------------------------------------------------
Yearly capital cost

Capital_Cost = Interest + Depreciation
```

```
--------------------------------------------------
Total system cost/year

Year_Cost = Capital_Cost +
Total_Investment*Maint_CostPercSea/100
--------------------------------------------------
```

Class: Turbine

```
Power per turbine

P_Turbine = DIM("kW")*INCASE(Wind_V,LT,3,THEN,
                     0,
                  ELSEIF,Wind_V,GT,R_Windspeed,THEN,
                    NP_Turbine,
                  ELSE,
                    (Wind_V-3)^2*NP_Turbine/(R_Windspeed-3)^2
                 )
--------------------------------------------------
Blade chord length on 15% radius

Ch_R15 = 0.053*Rotor_Diam
--------------------------------------------------
Blade chord length on 25% radius

Ch_R25 = 0.046*Rotor_Diam
--------------------------------------------------
Blade chord length on 100% radius

Ch_R100 = 0.014*Rotor_Diam
--------------------------------------------------
Rated rotation rate of turbine

TipSpeed = RatedRPM*Rotor_Diam*Pi/60
--------------------------------------------------
Target power of single turbine

AimPow = PowerDensity*Pi/4*Rotor_Diam^2
--------------------------------------------------
```

Class: Tower

```
Foot wall thickness of tower

Tower_F_Th = SELECT(COST$, 1, "Tower_F_Th", 1)*DIM("m")*1000
--------------------------------------------------
Foot wall thickness of tower

Tower_T_Th = SELECT(COST$, 1, "Tower_T_Th", 1)*DIM("m")*1000
--------------------------------------------------
Foot diameter of tower

Tower_F_D = SELECT(COST$, 1, "Tower_F_D", 1)*DIM("m")
--------------------------------------------------
Top diameter of tower

Tower_T_D = SELECT(COST$, 1, "Tower_T_D", 1)*DIM("m")
```

```
--------------------------------------------------
Tower eigen frequency

Tower_Eigenfr = SELECT(COST$, 1, "Tower_Eigenfr",
1)*DIM("Hz")
--------------------------------------------------
Tower height

Tower_Height = Rotor_Diam + TipHeight
--------------------------------------------------
```

Class: Electric

```
Electric current

E_Current = Total_Power/Voltage
--------------------------------------------------
```

Class: Floater

```
Displacement volume of floater

VOL_Floaters = (Total_Mass + Pretension)/Rho
--------------------------------------------------
Displacement volume of floater

VOL_Floaters =
Nr_Floaters*0.25*Pi*(D_Floaters^2*(Draft_Floaters - H_Disc) +
                               D_Disc^2*H_Disc) + VOL_Truces
--------------------------------------------------
Outside diameter of floater

D_Floaters = TowFloD_Ratio*Tower_F_D
--------------------------------------------------
Height of disc (lower part of buoy)

H_Disc = H_Floaters*DiscFloatRatio
--------------------------------------------------
Diameter of lower part of floater (disc)

D_Disc = TowFloDiscD_Ratio*Tower_F_D
--------------------------------------------------
Total construction volume of floaters

CVOL_Floaters = VOL_Floaters +
0.25*Pi*D_Floaters^2*Nr_Floaters*Freeb_Floaters
--------------------------------------------------
Draft of floaters

Draft_Floaters = H_Floaters - Freeb_Floaters
--------------------------------------------------
Total volume of connection pipes between floaters for 3
floater concept only

VOL_Truces =
Nr_Floaters*0.25*Pi*D_Truces^2*(0.333*SQRT(3)*DistFloat-
(D_Floaters+Tower_F_D)/2)
```

```
--------------------------------------------------
Draft of floaters

Draft_Floaters = Freeb_Floaters*1.3
--------------------------------------------------
```

Class: Weights

```
Total mass of turbine, pole and floater

Total_Mass = Steel_weight + Tower_Top_Mass + M_Ballast
--------------------------------------------------
Mass of generator + turbine

Tower_Top_Mass = Turbs_Floater*SELECT(COST$, 1,
"Tower_Top_Mass", 1)*DIM("kg")/1000
--------------------------------------------------
Mass of tower

Tower_Mass = Nr_Main_Towers*SELECT(COST$, 1, "Tower_Mass",
1)/1000 +
             (Turbs_Floater-
Nr_Main_Towers)*Rotor_Diam^1.5/8.4
--------------------------------------------------
Mass of one turbine blade

Blade_Mass = Nr_Blades*Turbs_Floater*SELECT(COST$, 1,
"Blade_Mass", 1)*DIM("kg")/1000
--------------------------------------------------
Mass of floater

M_Floaters = CVOL_Floaters*VolMassConstr
--------------------------------------------------
Total steel weight, i.e. towers + floaters

Steel_weight = M_Floaters + Tower_Mass
--------------------------------------------------
```

Class: Stability

```
Extreme load on turbine

Load_Extreme = Turbs_Floater*SELECT(COST$, 1, "Load_Extreme",
1)*DIM("kN")/1000
--------------------------------------------------
Fatigue load on turbine

Load_Fatig = Turbs_Floater*SELECT(COST$, 1, "Load_Fatig",
1)*DIM("N")/1000
--------------------------------------------------
Storm load on turbine

Load_Storm = Turbs_Floater*SELECT(COST$, 1, "Load_Storm",
1)*DIM("N")/1000
--------------------------------------------------
Vertical centre of gravity of tower
based on linear thickness and diameter
```

```
distribution

VCG_Tower = ((Tower_F_D*Tower_F_Th -
Tower_T_D*Tower_T_Th)*Tower_Height/2*Tower_Height/3 +
           Tower_T_D*Tower_T_Th*Tower_Height*Tower_Height/2)/
           ((Tower_F_D*Tower_F_Th +
Tower_T_D*Tower_T_Th)*Tower_Height/2)
--------------------------------------------------
Metacentre above centre of buoyancy

BM_Floaters = Ix/VOL_Floaters
--------------------------------------------------
Metacenter height above keel of floater

KM_Floaters = KB_Floaters + BM_Floaters
--------------------------------------------------
Centre of buoyancy of floater above BL

KB_Floaters = (Nr_Floaters*0.125*Pi*
                 (D_Floaters^2*(Draft_Floaters-
H_Disc)*(Draft_Floaters + H_Disc) + D_Disc^2*H_Disc^2) +
0.5*VOL_Truces*Draft_Floaters)/VOL_Floaters
--------------------------------------------------
Centre of gravity of floater above BL

KG_Floaters = H_Floaters/2
--------------------------------------------------
Vertical centre of gravity of turbine, tower and floater
above keel of floater

KG_Total = (KG_Floaters*M_Floaters +
            (VCG_Tower + H_Floaters)*Tower_Mass +
            (Tower_Height + H_Floaters)*Tower_Top_Mass +
            M_Ballast*KG_Ballast +

1.4*VOL_Truces*VolMassConstr*1/6*SQRT(3)*D_Floaters)/Total_Ma
ss
--------------------------------------------------
Metacentric height of floater

GM_Total = KM_Floaters - KG_Total
--------------------------------------------------
Distance of sunction anchor connection point below keel of
floater

KG_Ballast =
M_Ballast/(2*Rho*Nr_Floaters*0.25*Pi*D_Floaters^2)
--------------------------------------------------
Maximum arm of static stability

GZ_Max = GM_Total*SIN(PhiMax*Pi/180) +
BM_Floaters*TAN(PhiMax*Pi/180)^2/2*SIN(PhiMax*Pi/180)
--------------------------------------------------
Heel angle at which the deck enters the water
(determines the freeboard)

PhiMax = ATAN(Freeb_Floaters/(0.5*D_Floaters +
0.5*DistFloat))*180/Pi
--------------------------------------------------
```

```
Maximum stability momen

MomMaxStab = GZ_Max*Total_Mass*g
--------------------------------------------------
Required wind arm at Phi_Max

WindArm = Load_Fatig*(H_Floaters + Tower_Height-
KB_Floaters)/(Total_Mass*g)
--------------------------------------------------
Stability moment/wind moment at Phi_Max
Value should be > 1

StabIndex = GZ_Max/WindArm
--------------------------------------------------
Moment of inertia of water plane area

Ix = INCASE(Floater_Concept,EQ,1,THEN,
          0.049*D_Floaters^4,
       ELSEIF,Floater_Concept,EQ,2,THEN,
          1/2*0.25*Pi*D_Floaters^2*DistFloat^2 +
3*0.049*D_Floaters^4,
        ELSEIF,Floater_Concept,EQ,3,THEN,
          0.25*Pi*D_Floaters^2*DistFloat^2 +
4*0.049*D_Floaters^4,
       ELSEIF,Floater_Concept,EQ,4,THEN,
          1/12*D_Floaters^3*L_Floaters,
       ELSE,
          1/6*D_Floaters^3*L_Floaters +
0.5*DistFloat^2*D_Floaters*L_Floaters)*DIM("m^4")
--------------------------------------------------
```

Class: Motions

```
Eigen fequency of heave motion

Tz = 2*Pi*SQRT((1 + ma/Total_Mass)*Draft_Floaters/g)
--------------------------------------------------
Hydrodynamic mass as half sphere under cylinder

ma = Nr_Floaters*Pi/12*D_Floaters^3*Rho
--------------------------------------------------
Natural period of roll and pitch

Tphi = 2*Pi*Kxx/SQRT(GM_Total*g)
--------------------------------------------------
Radius of gyration

Kxx = SQRT((2*M_Ballast/Nr_Floaters*(DistFloat/2)^2 +
      M_Ballast*KG_Ballast^2+
      Tower_Mass*(VCG_Tower^2 +
0.0625*(Tower_Height+Draft_Floaters)^2) +

2*CVOL_Floaters*VolMassConstr/Nr_Floaters*(DistFloat/2)^2 +
      CVOL_Floaters*VolMassConstr*(H_Floaters/2)^2 +
      Tower_Top_Mass*Tower_Height^2-
      Total_Mass*KG_Total^2)/Total_Mass)
--------------------------------------------------
Radius of gyration for yaw
```

```
Kzz = SQRT((M_Ballast*(0.333*SQRT(3)*DistFloat)^2 +

VOL_Floaters*VolMassConstr*(0.333*SQRT(3)*DistFloat)^2)/Total
_Mass)
--------------------------------------------------
```

Class: Farm

```
Total electric power of wind farm

Total_Power = FL_Farm*Turbs_Floater*P_Turbine
--------------------------------------------------
```

Class: Input, Objects & Reports

```
Output DESIGN.REP of BLADOPT.EXE

REPORT$ = GET$("DESIGN.REP", "BLADOPT", PUT$("GEODAT.N",
BLADOPTINPUT$),
                                        PUT$("DEFINS.DEF",
DEFINS$),
                                        PUT$("DEFINE.DEF",
DEFINE$),
                                        PUT$("ENGDAT.I",
ENGDAT$))
--------------------------------------------------
Parsed results from BLADOPT output

COST$ = PARSE$(REPORT$)
--------------------------------------------------
Input of BLADOPT.EXE GEODAT.N

BLADOPTINPUT$ = TEMPLATE$(QKB$("BLADOPTINPUT$", "DATA"), 1,
Nr_Blades, Ch_R15, Ch_R25, Ch_R100,
                 Tower_Height, C_Loss_Drive, V_Loss_Drive,
IntRate, Deprec_Period,
                 Maint_CostPercLand, Extra_Cost_Land,
RatedRPM, AimPow)
--------------------------------------------------
Database of clustered solutions

DB$ = UNFOLD#(CLUSTER#("Solution"), "Blade_Mass", 0,
"BLADOPTINPUT$", "REPORT$")
--------------------------------------------------
```

Appendix IV: Concise user manual of QUAESTOR1.

1 Introduction

The knowledge base representing the knowledge of the user (designer, analyst) contains a random collection of Relations, basic conditions and rules. These Relations are expressed in formulas such as in spreadsheet-programs. Therefore, the formulas contain numeric (and nominal) expressions, logical operators, functions and relational operators. Moreover, complete computer programs (satellite programs) can be applied to the knowledge base as a Relation, which guarantees the re-use of procedures already available.

All Relations in de knowledge base establish connections between the various parameters, each defined by among other things a unique name and corresponding dimensions, explanation and if necessary, an initial value for iterative applications. In theory the user can select any variable in the knowledge base as a desired final outcome; the program will then automatically find the required path to determine the value of that parameter. This implies that a great many different phrasings are possible that essentially use the same model fragments, such as:

given the propeller characteristics and resistance of the ship, calculate the required capacity needed for a definite speed power

given the speed, power resistance, calculate the propeller characteristics

given the propeller characteristics, power and speed, what is the corresponding resistance of the ship

etc, etc.

QUAESTOR is especially suitable for this kind of *What If*-scenarios since the program can be asked to solve any questions fitting within the knowledge base, like: "How does an increase of 20% cargo effect the fuel consumption and what if a certain speed has to be kept up? Does that require a more powerful engine?" These simple cases demonstrate one of the major advantages of QUAESTOR: the possibility to present random questions on the basis of a constant (or extending) collection of submodels or Relations. A software developer is not needed; the program asks the very questions that stimulate the user to provide exactly that piece of information needed to find the correct answer. The program disposes of a powerful numerical solver hardly requiring anything from the format of the Relations in the knowledge base. Moreover, the program enables the user to add new Relations at any given moment when they can immediately be used for problem solving. Thus new insights and experiences can immediately be put into effect or the consequences of new demands from customers or suppliers can immediately be specified.

2. System requirements

The program requires Windows 95 or later (proper functioning under Windows Millenium Edition is not guaranteed), installed printer drivers (the printer itself is not necessary) and preferably a 17” monitor or larger.

3. Installation

Put the CD in the drive and start the file Setup.exe. If the program is installed from a network, copy the files Quaestor.cab, Setup.lst and Setup.exe to your C:\TEMP directory and start the file Setup.exe. Follow the instructions on the screen to state where you wish to install QUAESTOR and where you wish to store your data. You are advised to refer to the installled default directory \Program Files. It is advisable to read the Readme.txt file, before you first use QUAESTOR, so that you are informed on the latest updates.

4. Screen view

When you open the main window of QUAESTOR for the first time you are to decide first which windows you wish to make use of. You could in fact open all windows, but this will make your work sheet rather unorganised. In fig. 6 of this report a useful layout is given as an example. In this example the Knowledge Browser, Frame Viewer, Workbase and Workbase Graph have been opened.

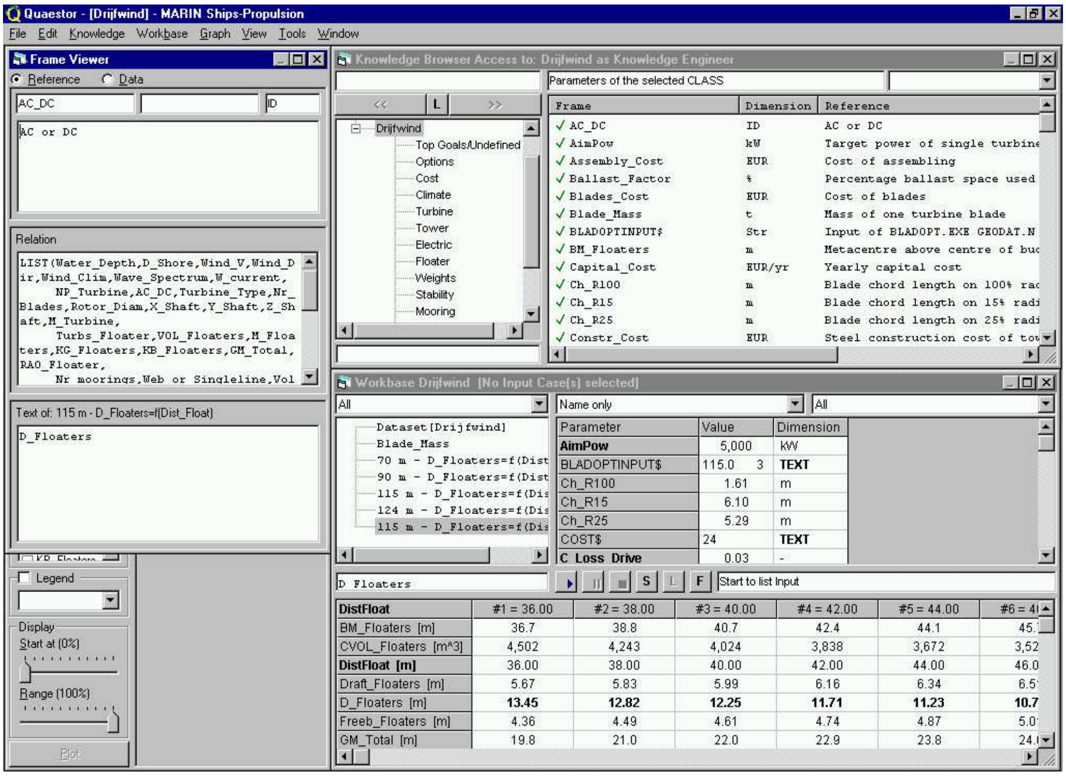


Fig. 2: Recommended lay-out of QUAESTOR tools

5. Open an existing knowledge base

Start QUAESTOR, open the pull-down menu, select **File**, **Open**. Select the directory containing the file with the required data and open it. If you cannot find the right file, look for it in another directory or on another hard disk.

6. Save a knowledge base

You can save the adjusted file by selecting **File** and then **Save KB**; the file is now saved under the same name. The option **Save KB As** enables you to save the file under a new name. After inserting the new name, click Save.

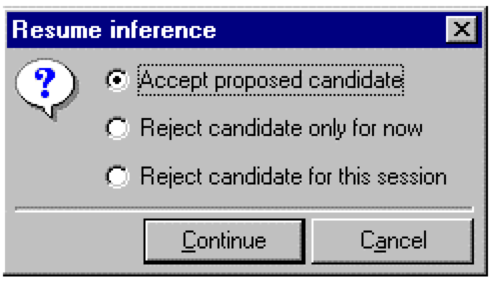
7. Create a new knowledge base

To get an empty work sheet click **File**, **New** in the menu. Now click the right mouse button in he Knowledge Browser under *Parameters of the selected CLASS* and select **New Relation** (if you right-click in another field, you get other, context-related options). You will now see the Expression Editor entitled *New Relation in top section, data in bottom section*; here you can insert a Relation c.q. formula. After you have inserted a Relation, click the Save button. Now you see that the Relation and its parameters have been inserted into the Knowledge Browser. Furthermore, in the window Slots & Properties (can be opened as option in the main menu *Tools*) you are to state for each variable what properties they will have. These properties determine whether the system or the user is to provide the data, the number of decimal places, the output, the format of the output and if a variable has to be restricted by a minimum and a maximum value. A red cross before a variable means that the properties or Dimension of this variable are still to be defined or corrected. When this has been done, the red cross is replaced by a green check mark. New Relations can also be inserted through the main menu option **Knowledge** and **New Relation**.

When you have finished defining the Relations in your knowledgebase, save the data by clicking **File, Save KB As**. Select the right directory and insert the new name for your knowledge database. The file will automatically be saved under the new name with the extension .QKB (QUAESTOR Knowledge Base).

8. Create a new solution

Double click the left mouse button on the parameter in the Knowledge Browser you wish to calculate. The green check mark now changes into a question mark. If the variable is not visible, click on the Knowledge base main node in the Knowledge Browser (by alternatively clicking and double clicking you switch between showing either variables or Relations in function format). The parameters are now shown. Select the required parameter. Click in the Workbase on the Play button (the tooltip wizard refers to this button as the (Re)Start Modeller). You are now asked to insert a number of variables. Confirm each value by pressing the Enter button. You will now see a new menu entitled 'Resume Interference':



Now click the option ‘Accept proposed candidate’ and the required value is calculated and shown on the screen in bold letters. If you wish to make the same calculation with different values, again click (the play button) and provide values by clicking in the field of a parameter and by typing the new value. If you do not provide a value, the system itself will try to calculate the missing values with the help of other Relations. Of course these Relations must be present and valid. When you have finished your calculations and do not wish to save the data, this Solution can be removed from the Workbase by clicking on it with your right mouse button and selecting **Solution Delete** or simply by pressing the DEL key. The option **Empty Workbase** will clear the Workbase of all Solutions. All procedures of all calculations made for the Solution(s) are then removed from the memory. If you finished your calculation You are ready for another calculation. Within a selected Solution a new question can always be asked by double clicking in the Knowledge Browser on a parameter not yet calculated and after the start answering 'no' to the question **Add new Solution?.** If the answer to this question is 'yes', a new Solution is created within the Workbase.

9. Make a range

Basically the procedure is the same as described in 3.8: double click on the variable you wish to calculate, press  and provide values of any parameter you know. Instead of a singular value, a range can be provided by a minimum value, a step size and a maximum value, e.g., a minimum value of 100, a step of 10 and 200 as the maximum value. The syntax is then as follows: 100(10)200 – after you have input and confirmed all remaining values by pressing Enter, and click: ‘Accept proposed candidate’ with ‘Continue’, the results (top goals and sub goals) are shown in the Workbase table printed in bold. You can also input the required steps directly: the syntax is then 100,110,120,190,200. If a large number of steps have to be defined the latter option is not very practical.

10. Create a graph

The results of any multi-case solution can be plotted as a graph. Activate the Workbase Graph by clicking in it. Activate the variable for the Y-axis by clicking the variable. A black check mark will appear before the variable. Click *Plot* and the diagram is generated. If you wish to insert another variable on the Y-axis, click the black arrow of Independent Axis, select the required variable. The required variable now appears behind the checkmark box. Activate it and click *Plot*. You can export the diagram to a word processor by copy/paste or by saving it as a bitmap (extension BMP) and insert it into a text as a file. Right click the Workbase Graph, select **Save As** and insert a name and click the Save button.

11. Generate a report

After a problem has been defined and calculated through, from these data a report can be generated. Click **Workbase** and select **Make Report**. Now you can select the data you wish to export and their destination. You can have your data printed on paper by clicking the option **Printer**. However, a better way is to select the option **Screen**. This will give you the Report Window in which the data have been processed into a report and in which it is possible to make adaptions and completions. From this window it is possible to send the text to a printer or save it. Please note that you had best use a non-proportional letter (such as Courier New) when you copy the tekst from this window e.g. to Word by means of the clipboard, otherwise the text may not be properly lined out.

6 Motion response analysis of a floating wind turbine

Contents

REVIEW OF TABLES, FIGURES AND RESULTS

Tables:

Figures:

6.1 Summary

In September 2001, Novem has awarded a consortium, consisting of TNO, ECN, TU-Delft, Lagerwey, and MARIN, to investigate the possibility of a floating wind farm alternative in non-shallow water conditions.
Various concepts were selected for review using the QUAESTOR programme. The most promising concept, a tri--floater, was further investigated with respect to its motion behaviour in waves. The motion characteristics in regular waves were established using a linearised potential flow panel programme called DIFFRAC.
The wave conditions that were selected for this study were taken from near shore locations like meetpost Noordwijk ,K13 and data from the European Centre of Medium Weather Forecast (ECMWF) in Reading UK.
Due to the nature of the wave climate near shore also wave climates were generated using wind-wave generation models (SWAN).
Based on the motion characteristics and the wave climate an estimate can be determined of the most probable extremes of the motions in 10 years time.
For the floating wind farm limiting conditions of maximum 10 degrees rolling or pitching were assumed.
From the statistical analysis it is observed that for the various wave conditions studied the rolling and pitching criteria were not exceeded.
From the motion behaviour one may conclude that the tri-floater concept is a viable alternative for a floating wind farm.

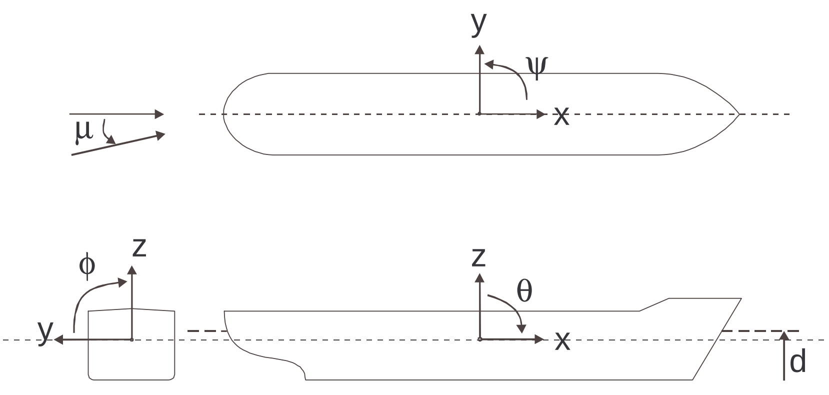
6.2 Description of computational procedure

6.2.1 Definition of motions and wave headings

The figures below show the definition of the vessel motions and the direction of the incoming waves. The following definitions hold:

- Surge is positive when the vessel is moving forward.
- Sway is positive when the vessel is moving to port.
- Heave is positive when the vessel is going up.
- Roll is positive starboard side down.
- Pitch is positive bow down.
- Yaw is positive when the vessel rotates counter clockwise (seen from above).

A 180 degrees wave heading corresponds to head waves. A 0 degrees wave heading corresponds to stern waves. A 90 degrees wave heading corresponds to waves from starboard side. Because of the symmetry of the vessel, the motion behaviour is the same for waves coming in from starboard side and from port side. Therefore, only the wave headings between 0 and 180 degrees are considered.



Motions:

x = surge
y = sway
z = heave
ϕ = roll
θ = pitch
ψ = yaw

μ = wave direction
d = water depth

6.2.2 Computational procedure

In order to compute the motions of the Sea Horizon due to wave excitation, the underwater shape of the vessel needs to be modelled. For that purpose, a facet distribution of the vessel was made. This is shown in Figure 2. On each of these facets the fluctuating water pressure in regular waves is computed. With these pressures, the total force on the vessel can be computed, and the resulting motions.

The following regular wave is considered:

$$\zeta = \zeta_0 \cos(kx\cos\mu + ky\sin\mu - \omega t)$$

where:

ζ	=	wave elevation	[m]
ζ_0	=	wave amplitude	[m]
k	=	wave number	[m^{-1}]
μ	=	wave direction	[rad]
ω	=	wave frequency	[rad/s]

The wave frequency, wave number and water depth (h) are related by means of the following dispersion relation:

$$\omega^2 = gk\tanh(kh)$$

The following steps are taken to compute the motions of the tri-floater:

1) Compute the hydrostatic restoring forces for the heave, roll and pitch motions (when the vessel is pushed downwards, the increased buoyancy results in an upward force).
2) Compute the added mass and damping forces. These forces relate the motions of the vessel with the waves that are radiated by these motions in otherwise calm water (no incoming waves). The added mass force gives the part of the force that is in phase with the motions. The damping force gives the part of the force that is out of phase with the motion.
3) Compute the force on the vessel when it is fixed (no motions) in a regular wave.
4) Solve the equation of motion. The response of the vessel is at the same frequency as the wave frequency.

This approach is valid for small vessel motions. For large motions, non-linear effects play a role. The equation of motion that has to be solved is linearised for small vessel motions and given below:

$$(M + A)\ddot{X} + B\dot{X} + CX = F$$

where:

M	=	6×6 mass matrix with masses and moments of inertia
A	=	6×6 added mass matrix
X	=	6×1 vector with the vessel motions at the centre of gravity
B	=	6×6 matrix with the wave making damping
C	=	6×6 matrix with hydrostatic springs
F	=	6×1 vector with wave forces

The diffraction analysis is based on non-viscous flow (potential flow). Therefore, the roll and pitch damping is underestimated and additional viscous damping is added to the equation of motion.

The solution to the equation of motion is as follows:

$$X_k = A_k \cos(\omega t + \varepsilon_k) \quad k=1..6$$

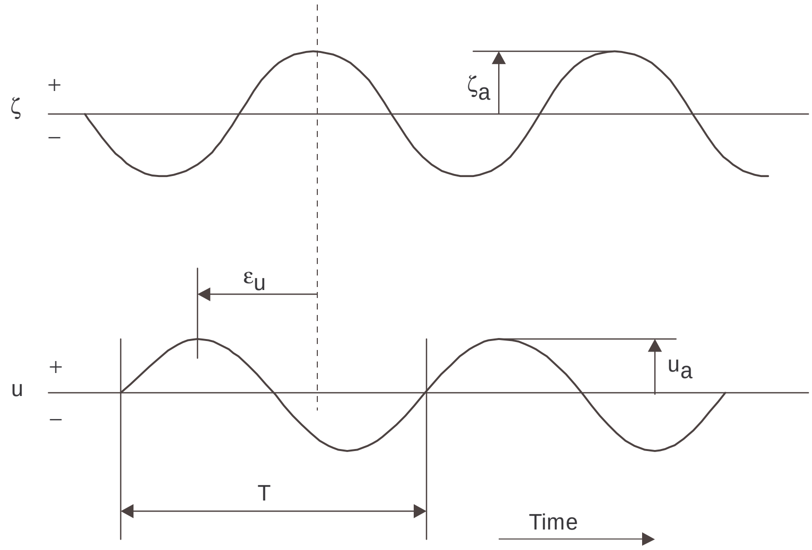
where:

X_k = k-th element of motion vector
A_k = motion amplitude of k-th motion
ε_k = phase difference between k-th motion and wave elevation in the centre of gravity

The meaning of the phase difference is shown below:

Wave elevation in centre of gravity G

Vessel motion



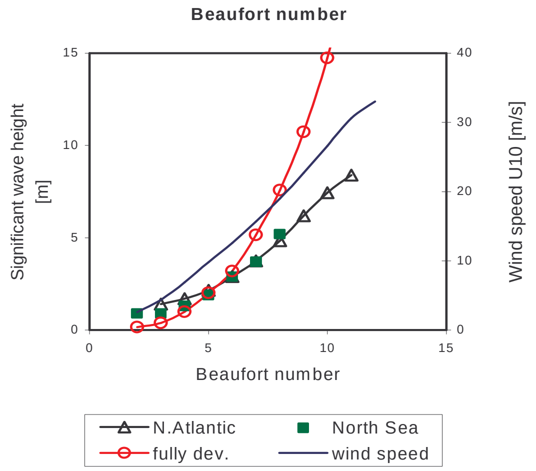
The motion response is made non-dimensional by dividing the motion amplitude by the amplitude of the incoming wave. This is called the Response Amplitude Operator (RAO):

$$RAO_k = \frac{A_k}{\varsigma_0}$$

The response amplitude operator therefore represents the response (motion) of the vessel is regular waves with an amplitude of 1 metres.

6.2.3 Wave statistics

The oldest and simplest way to characterise an offshore environment is to characterise the wind climate, for instance in terms of the frequency of occurrence of various Beaufort numbers. These wind classes are related to area dependent "average" wave conditions. The appendix III summarises some commonly used relations.



Although often used in ship operations this approach fails to recognise the fact that one wind speed can come with a wide range of wave heights and periods, strongly depending on the fetch and duration (or more general the history) of the wind. Since wind speed and direction are highly variable it means that in practice the waves are never in equilibrium with the wind.

The statistics of the waves are described by a scatter diagram, In which for each each significant wave height and period combination a probability is attached.

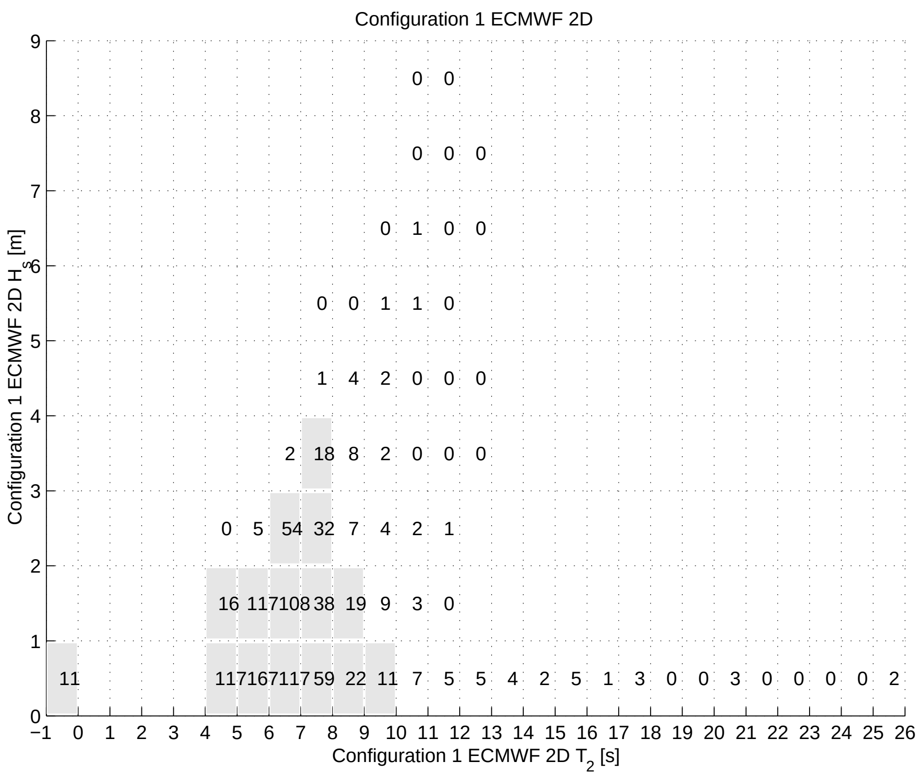


Figure 1 Example of Wave scatter diagram taken from ECMWF data for Southern North Sea

However for arbitrary locations in the North Sea often no wave scatter diagrams are available. Even nearby locations with known wave statistics may not be used due to e.g. the different bottom topography of the selected location. In these circumstances use is made of a wind—wave generation model based on long term wind statistics. These wind statistics are not too sensitive with respect to the location. The wind—wave generation model that is used is based on SWAN.

6.2.4 Determination of probability of exceedance

From the wave data and the responses characteristics (RAO's) of the floating wind turbine the motion response spectrum in irregular waves can be determined from:

$$S_x(\omega) = \left|H_x(\omega)\right|^2 * S_\varsigma(\omega)$$

Here x represents the 6 modes of motion. $H_x(\omega)$ is the motion response function in regular waves as calculated using the diffraction program. $S_\zeta(\omega)$ represents the irregular wave spectrum. From the response spectra, the root mean square (RMS) and significant double amplitudes (SDA) are determined.
The SDA value is equal to 4 times the RMS value. Because the wave information (in the form of spectra) is given statistically, as a time serie, the basic result from the simulation is also statistical in nature. The RMS is the standard deviation of the motion during a time step of 1 hour. This means that –given a certain maximum allowed criterion for a motion- the distribution of the motion during 1 hour must be known in order to calculate the maximum motion during a time step.

A Rayleigh distribution was assumed to establish the most probable maximum value from the RMS value σ_x :

$$\mathrm{MprMax}(SDA, T) = \sigma\sqrt{2 \ln N_{osc}}$$

$$N_{osc} = \frac{3600}{T}$$

$$\sigma = \frac{SDA}{4}$$

In which:

σ	RMS of motion
N_{osc}	Number of oscillations during 1 hour
T	Period of motion

The downtime is defined as the number of time steps at which the MprMax of a motion exceeds the criterion value, divided by the total number of time steps. Once the probability of exceedance per oscillation is determined the total probability of exceedance can be calculated.

$$P_{exc}^{(i)}\Big|_{oscillation}(x \geq x_a) = e^{-\frac{x_a^2}{\sigma_i^2}}$$

Number of oscillations N_{osc} is 3600 divided by the mean period in that hour

The total probability of exceeding the criterium during N years follows from:

$$P_{\Pi} = 1 - \prod_{i=1}^{N} (1 - P_{exc}^{(i)}\Big|_{oscillation})^{N_{osc}^{i}}$$

The mean probability on exceedance per oscillation follows from:

$$P_{\Sigma} = \frac{\sum_{i=1}^{N} N_{osc}^{i} * P_{exc}^{(i)}\Big|_{oscillation}}{\sum_{i=1}^{N} N_{osc}^{i}}$$

This expression allows translating the mean probability of exceedance per oscillation to the full service life of the vessel. For example a probability of exceedance of 10^-8 per oscillation leads to a failure rate of say once per 20 to 25 years (assuming a mean period of roughly 7-8 seconds).
The probability of exceedance is calculated for the roll or pitch motions for varying most probable maxima.

The wave statistics from the scatter diagram can be used to estimate the most probable extreme. The procedure is highlighted in appendix II.

6.3 Overview of results

Table 1 shows an overview of the stability data of the tri floater as computed from the quaestor programme as reported in 16602-2-RD.

The Response Amplitude Operators are shown in Results section A.
In the following figure the panelization of the tri-floater (distance between columns is 68m) for the diffraction computations is presented

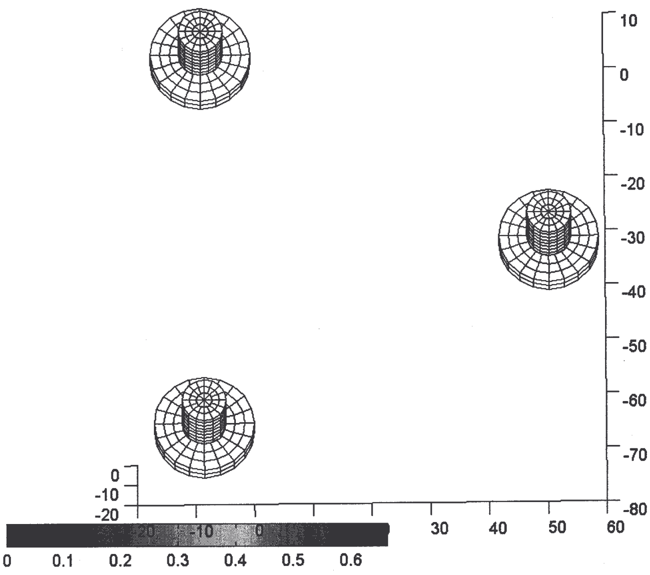


Figure 2 Panelization of the Tri-Floater Wind Turbine

The tri-floater consists of three identical cylindrical type of elements. Each element consists of two cylindrical shaped structures. The top structure intersecting the water surface has a diameter of 8.0 m and a draft of 12.m The second cylinder has a diameter of 17.5 m and a draft of 4.0 m.
The geometry of the elements follows from observation as reported by J.Hooft.[1]. Basically one tries to design the platform such that the natural heave periods are close to the wave cancellation effects on the semi submersible This design leads to low natural periods away from the wave regime. The distance between the floater is 64.m respectively 56.m designated as case 7 and case 7b.

Typical motion response of the tri—floater in 90 degrees waves are shown below.

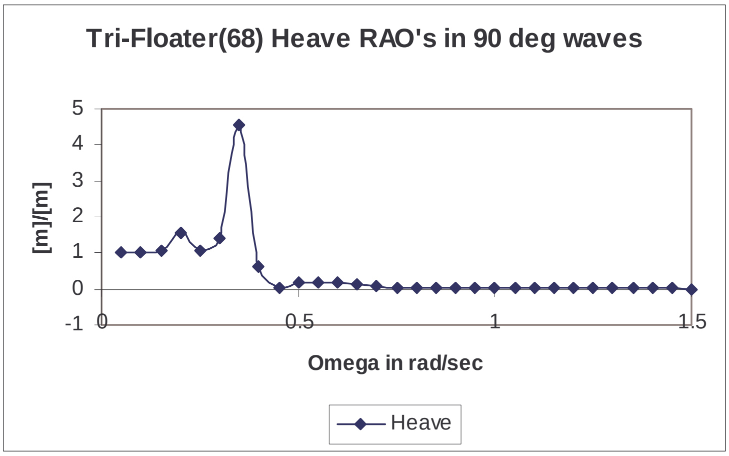


Figure 3 Calculated Heave Rao in regular waves

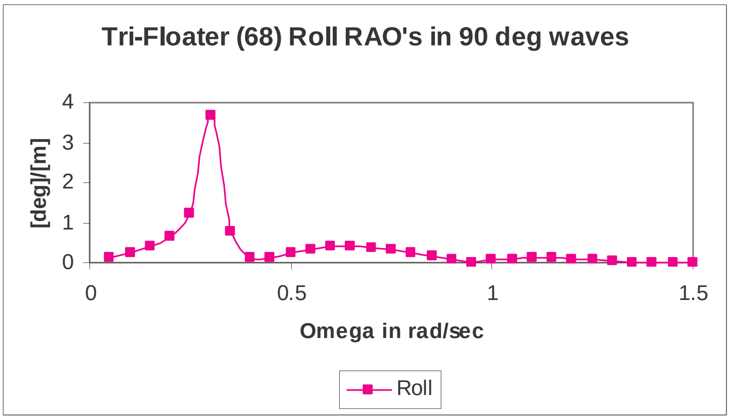


Figure 4 Calculated Roll RAO in regular waves

[1] J.Hooft: Hydrodynamical aspects of semi-submersible platforms. PhD thesis Delft 1970.

6.3.1 Sensitivity of floater design to Wave Data

In order to review the sensitivity of the floater design to the wave data, use is made of different wave databases. The wave data have been obtained using three different sources:

1. ECMWF data from Reading (UK) (5 years)
2. Meetpost Noordwijk (RIKZ) (20 years)
3. SWAN analysis (5 year generated)

The data from the ECMWF organisation originated from buoy measurements in the southern north sea similar to the K13 location.
The wave data from meetpost Noordwijk were obtained from a fixed platform wave measurements over a long period of time, however at a waterdepth of +- 15 m and also located near the shore.
The wave data from the SWAN analysis were taken from computed wave generation using statistical wind field data for the north sea. This has the advantage that at other possible locations of the floating wind turbine, were no wave buoy are available, one can generate wave data also taking into account the local bottom topography.
From the three possible wave databases also wave scatter diagrams were generated, in order to asses the distribution of the wave energy over the mean wave periods.
In chapter 9 all the probability of exceedance for the three wave climates are presented. Since the wave data did not have the same duration, the probablility of exceedance were calculated (extrapolated) for a 10 years period.

6.4 Discussion and Conclusions

In appendix II an example is give on the procedure how to use the calculated motion response operators for irregular wave calculations using single wave spectra.
One observes a noticeable difference between the three wave climates for the probability of exceedance (PoE) for roll and pitch. The SWAN data allows for much larger PoE than the ECMWF or RIKZ data. This effect is caused by the wind generated waves near the shore, leading to a fetch limited wave growth and shorter wave periods than in the ECMWF. Therefore excitation near the roll, heave or pitch natural periods (around 20 seconds) is limited.
From the statistical analysis one also observes that a larger floater distance (ref. case 7 and case 7b) leads to reduction of the PoE for roll, heave and pitch. However looking at a once every 10 years exceedance, the 10 degrees roll or pitch angle is never exceeded. Therefore the smaller floater distance 0f 56.0 m is sufficient from a motion point of view.

6.5 APPENDIX I

DESCRIPTION OF THE DIFFRACTION THEORY

First order wave loads and motions

The ship is considered as a rigid body, oscillating sinusoidal about a state of rest, in response to excitation by a long-crested regular wave. The amplitudes of the motions of the ship as well as of the wave are supposed to be small, while the fluid is assumed to be ideal and irrotational. A right-handed, fixed system of coordinates $O\text{-}X_1\text{-}X_2\text{-}X_3$ is defined with the origin in the waterline and the $O\text{-}X_3$ axis vertically upwards.

The oscillating motion of the ship in the j-th mode is given by:

$$x_j = \zeta_j \, e^{-i\omega t} \qquad j = 1,\ldots,6 \tag{1}$$

in which ζ_j is the amplitude of the motion in the j-th mode and ω the circular frequency. The motion variables x_1, x_2 and x_3 stand for the translations surge, sway and heave, while x_4, x_5 and x_6 denote rotations around $O\text{-}X_1$, $O\text{-}X_2$ and $O\text{-}X_3$ axis respectively.

The free surface at great distance from the ship is defined by:

$$\zeta = \zeta_0 \, e^{ik(x_1 \cos\alpha + x_2 \sin\alpha) - i\omega t} \tag{2}$$

where:

ζ_0 = amplitude of the wave
k = wave number = $2\pi/\lambda$, where λ is the wave length
α = angle of incidence.

The flow field can be characterized by a first order velocity potential:

$$\Phi(x_1, x_2, x_3, t) = \phi(x_1, x_2, x_3) e^{-i\omega t} \tag{3}$$

The potential function ϕ can be separated into contributions from all modes of motion and from the incident and diffracted wave fields:

$$\phi = -\, i\omega \zeta_0 (\phi_0 + \phi_7) - i\omega \sum_{j=1}^{6} \phi_j \zeta_j \tag{4}$$

The incident wave potential is given by:

$$\phi_0 = \frac{1}{\nu} \frac{\cosh k(x_3 + d)}{\cosh k.d} e^{ik(x_1 \cos\alpha + x_2 \sin\alpha)} \tag{5}$$

in which:
ν = ω^2/g
d = water depth
α = angle of incidence of the waves.

The cases j = 1,....,6 correspond to the potentials due to the motion of the ship in the j-th mode, while ϕ_7 is the potential of the diffracted waves. The individual potentials are all solutions of the Laplace equation, which satisfy the linearized free surface condition and the boundary conditions on the sea floor, on the body's surface and at infinity.

The potential function ϕ_j can be represented by a continuous distribution of single sources on the boundary surface S_0:

$$\phi_j(x_1,x_2,x_3) \; \frac{1}{4\pi} \iint_{S_0} \sigma_j(a_1,a_2,a_3) \cdot \gamma_j(x_1,x_2,x_3,a_1,a_2,a_3)\, dS \qquad (6)$$

for j = 1,2,....,7

where:
$\gamma_j(x_1,x_2,x_3,a_1,a_2,a_3)$ = the Green's function of a source, singular in a_1, a_2, a_3
a_1, a_2, a_3 = the vector describing S_0
$\sigma_j(a_1, a_2, a_3)$ = the complex source strength.

For the Green's function a function is chosen which satisfies the Laplace equation and the boundary conditions on the sea bottom, in the free surface and at infinity. This function is given by (see Wehausen and Laitone [1]):

$$\gamma = \frac{1}{r} + \frac{1}{r_1} +$$

$$+ PV\int_0^\infty \frac{2(\xi+\nu)e^{-\xi d} \cdot \cosh\xi(a_3+d) \cdot \cosh\xi(x_3+d)}{\xi \sinh\xi d - \nu \cosh\xi d} J_0(\xi R)d\xi + \qquad (7)$$

$$+ i\frac{2\pi(k^2-\nu^2) \cdot \cosh k(a_3+d) \cdot \cosh k(x_3+d)}{k^2 d - \nu^2\; d + \nu} J_0(kR)$$

in which:

$$\left.\begin{aligned} r &= \sqrt{(x_1-a_1)^2+(x_2-a_2)^2+(x_3-a_3)^2} \\ r_1 &= \sqrt{(x_1-a_1)^2+(x_2-a_2)^2+(x_3+2d+a_3)^2} \\ R &= \sqrt{(x_1-a_1)^2+(x_2-a_2)^2} \end{aligned}\right] \qquad (8)$$

John [2] has derived the following series for γ, which is the analogue of (7):

$$\gamma = 2\pi \frac{\nu^2 - k^2}{k^2 d - \nu^2 d + \nu} \cosh k(a_3 + d) \cdot \cosh k(x_3 + d) \cdot \{Y_0(kR) - iJ_0(kR)\} + \\ + \sum_{i=1}^{\infty} \frac{4(\mu_i^2 + \nu^2)}{d\mu_i^2 + d\nu^2 - \nu} \cos \mu_i (x_3 + d) \cdot \cos \mu_i (a_3 + d) \cdot K_0(\mu_i R) \quad (9)$$

where μ_i is the positive solution of:

$$\mu_i \tan(\mu_i d) + \nu = 0 \quad (10)$$

Although these two representations are equivalent, one of the two may have preference for numerical computations depending on the values of the variables. In general, equation (9) is the most convenient representation for calculations. When R = 0 the value of K_0 becomes infinite; therefore equation (7) must be used when R is small or zero.

The unknown source strength function σ must be determined in such a way that the boundary condition on the body's surface S is fulfilled. Due to the linearization this boundary condition is applied to the surface in its equilibrium position S_0.

$$n_j = \tfrac{1}{2}\sigma_j(x_1, x_2, x_3) + \\ + \frac{1}{4\pi} \iint_{S_0} \sigma_j(a_1, a_2, a_3) \cdot \frac{\partial}{\partial n} \gamma(x_1, x_2, x_3, a_1, a_2, a_3) \; dS \quad \text{for } j = 1, \ldots 6 \quad (11)$$

$$n_j = -\frac{\partial \phi_0}{\partial n} \quad \text{for } j = 7$$

n_1 through n_6 are the generalized direction cosines on S_0, defined by:

$$\left.\begin{aligned} n_1 &= \cos(n, x_1) \\ n_2 &= \cos(n, x_2) \\ n_3 &= \cos(n, x_3) \\ n_4 &= x_2 n_3 - x_3 n_2 \\ n_5 &= x_3 n_1 - x_1 n_3 \\ n_6 &= x_1 n_2 - x_2 n_1 \end{aligned}\right] \quad (12)$$

To solve equation (6) numerically the surface S is subdivided into a number of finite, plane elements on which the source strength is constant. The boundary condition is applied in one control point on each element, being the centre of the element. The integral equation (6) then reduces to a set of algebraic equations in the unknown source strengths. In general, the Green's function γ may be computed with sufficient accuracy as if the source strength is concentrated in the centre (control point) of each element. When, however, the influence of an element on its own control point is evaluated, γ has a singularity of the type 1/r, which can be removed by spreading the source uniformly over the element. When the influence of an element on a control point, which is at a close distance of this element and not lying in the same plane, is considered the source is spread uniformly and integrated numerically to obtain its contribution to ϕ or $\partial\phi/\partial n$.

After solving the equations for the source strengths, the first order potential function is known. The pressure on the surface S can then be found from Bernoulli's theorem. The linearized pressure is given by:

$$\begin{aligned} p(x_1,x_2,x_3,t) &= -\rho \frac{\partial \Phi}{\partial t} \\ &= \{\rho\,\omega^2\,\zeta_0(\phi_0+\phi_7)+\rho\,\omega^2 \sum_{j=1}^{6} \phi_j\,\zeta_j\}\,e^{-i\omega t} \end{aligned} \tag{13}$$

Subsequently, the first order wave exciting forces and moments can be found from:

$$X_k = -\rho\,\omega^2 \zeta_0\, e^{-i\omega t} \iint_{S_0} (\phi_0+\phi_7)\, n_k\, dS \tag{14}$$

The oscillating hydrodynamic forces (k = 1,2,3) and moments (k = 4,5,6) in the k-th direction are:

$$F_k = -\rho\,\omega^2 \sum_{j=1}^{6} \zeta_j\, e^{-i\omega t} \iint_{S_0} \phi_j\, n_k\, dS \tag{15}$$

According to common practice the hydrodynamic forces are represented by means of added mass and damping coefficients:

$$a_{kj} = -\rho\, \mathrm{Re}\, \{\iint_{S_0} \phi_j\, n_k\, dS\} \tag{16}$$

$$b_{kj} = -\rho\,\omega^2 \mathrm{Im}\, \{\iint_{S_0} \phi_j\, n_k\, dS\} \tag{17}$$

where:
a_{kj} = the added mass coefficient in the k-th mode due to motion in the j-th mode
b_{kj} = the damping coefficient in the k-th mode due to motion in the j-th mode.

Finally, the motion response to first order excitation is computed by means of the well known equations of motion in the frequency domain:

$$\begin{aligned} &\sum_{j=1}^{6} \{-\omega^2 (M_{kj}+a_{kj})\cdot\cos(\omega t+\varepsilon_j) - b_{kj}\cdot\omega\cdot\sin(\omega t+\varepsilon_j) + C_{kj}\cdot\cos(\omega t+\varepsilon_j)\}\zeta_j \\ &= X_k\cdot\cos(\omega t+\delta_k) \qquad \text{for } k=1,\ldots,6 \end{aligned} \tag{18}$$

in which:
X_k = wave excited force in the k-th mode
ε_j, δ_k = phase angles.

M_{kj} is an inertia matrix:

$$M_{kj} = \begin{vmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_6 \end{vmatrix} \qquad (19)$$

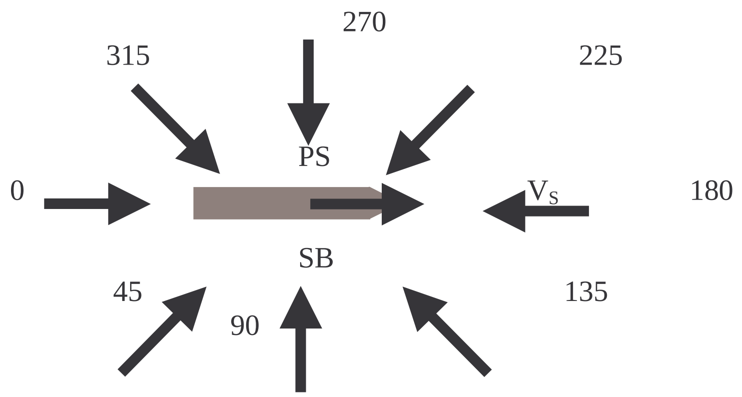
where:
m = mass of the ship
I_k = moment of inertia in the k-th mode.

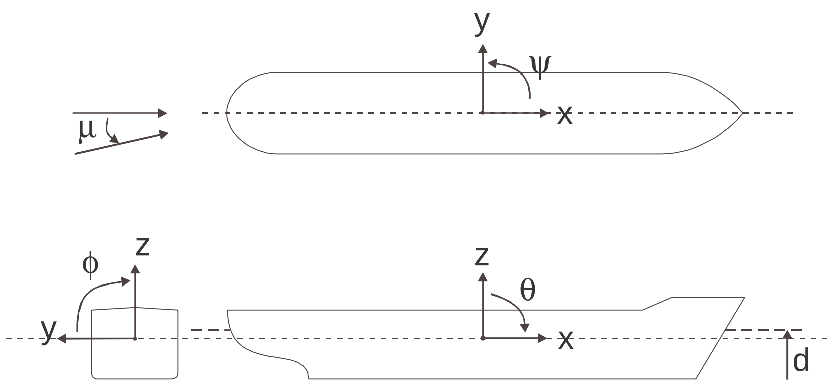
DEFINITION OF WAVE DIRECTION, MOTIONS AND RESPONSE FUNCTIONS

Wave direction and motions

The following sign convention for the heading applies:

Ship heading convention	
180 deg	Head seas
135 deg	Bow quartering seas over starboard
90 deg	Beam seas over starboard
45 deg	Stern quartering seas over starboard
0 deg	Following seas



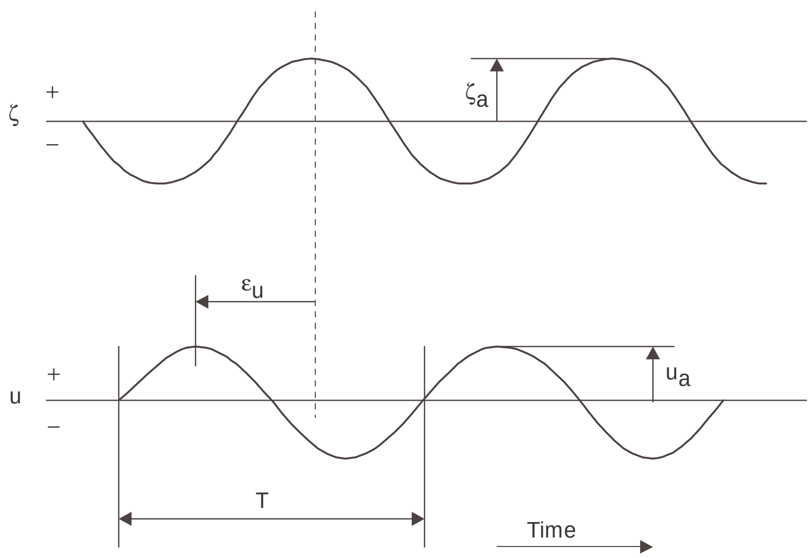


Motions:
x = surge
y = sway
z = heave
φ = roll
θ = pitch
ψ = yaw

μ = wave direction
d = water depth

Wave elevation
in centre of
gravity G

Particular



Phase $\varepsilon_{u\zeta} = (S/T) \times 360°$	:	$u(t)$	=	$u_a \cos(\omega t + \varepsilon_{u\zeta})$
In phase component	:	u_i	=	$u_a \cos \varepsilon_{u\zeta}$
Out of phase component	:	u_u	=	$-u_a \sin \varepsilon_{u\zeta}$
Amplitude	:	u_a	=	$\sqrt{(u_i^2 + u_u^2}$
Phase	:	$\varepsilon_{u\zeta}$	=	$\arctan(-u_u/u_i)$

6.6 References

1. Wehausen, J.V. and Laitone, E.V.; “Handbuch der Physik”, Vol. 9, Springer Verlag, Berlin, 1960.

2. John, F.; “On the motions of floating bodies”, Comm. on Pure and Applied Mathematics, Part I: 2, pp. 13-57, 1949 and Part III: 3, pp. 45-100, 1950.

6.7 APPENDIX II

Motion Response in Irregular Waves of Floating Wind Farm

Motion Characteristics

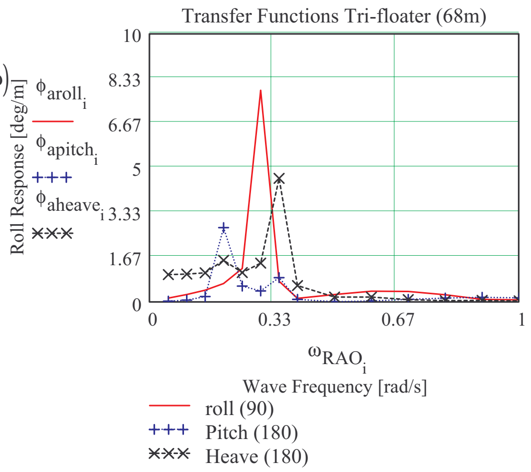
The motion characteristics are defined in terms of transfer functions ("response amplitude operators RAO) which is, in the case of a linear system, the response in a wave of unit amplitude.
The three transfer functions for the roll , the pitch and heave are defined for 14 input frequencies ω_{RAO} according:

The input data are generalized in terms of a function which interpolates linearly between the data points.

$$\phi_{roll}(\omega) := \text{linterp}(\omega_{RAO}, \phi_{aroll}, \omega)$$

$$\phi_{pitch}(\omega) := \text{linterp}(\omega_{RAO}, \phi_{apitch}, \omega)$$

$$\phi_{heave}(\omega) := \text{linterp}(\omega_{RAO}, \phi_{aheave}, \omega)$$



Wave Spectrum

The response in irregular waves can be calculated if the distribution of the wave energy over the wave frequencies, which is defined in terms of the "wave spectrum" S is known.

In the following we will use the well-known JONSWAP formulation.

The wave spectrum is a function of the significant wave height H_s and the average zero-upcrossing period T_2 as well as the peak enhancement factor γ. A value of $\gamma = 1$ returns the well known Pierson Moskowitz spectrum. The actual formulation is based on the peak period which is approximated by:

$$T_p(T_2, \gamma) := T_2 \cdot \left[1.221 + 0.0176 \cdot (6 - \gamma) + 0.00408 \cdot (6 - \gamma)^2\right]$$

The peak frequency becomes:

$$\omega_p(T_2, \gamma) := \frac{2 \cdot \pi}{T_p(T_2, \gamma)}$$

The wave spectrum contains a frequency dependent enhancement according:

$$\sigma_a := 0.07 \qquad \sigma_b := 0.09 \qquad \sigma(\omega,\omega_p) := \text{if}(\omega < \omega_p, \sigma_a, \sigma_b) \qquad \alpha(\omega,\omega_p) := e^{-\frac{\left(\frac{\omega}{\omega_p}-1\right)^2}{2\cdot\sigma(\omega,\omega_p)^2}}$$

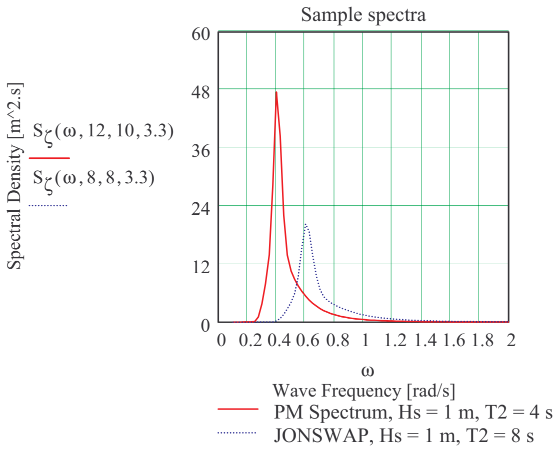
and a normalising constant C according:

$$C(\gamma,T_p) := \frac{5}{\frac{16}{T_p}\cdot\left(1.15 + 0.168\cdot\gamma - \frac{0.925}{1.909+\gamma}\right)\cdot 2\cdot\pi}$$

The spectrum follows from:

$$S_\zeta(\omega,T_2,H_s,\gamma) := \frac{C(\gamma,T_p(T_2,\gamma))\cdot H_s^{\,2}\cdot\gamma^{\alpha(\omega,\omega_p(T_2,\gamma))}}{\left(\frac{\omega}{\omega_p(T_2,\gamma)}\right)^5}\cdot e^{-\frac{1.25}{\left(\frac{\omega}{\omega_p(T_2,\gamma)}\right)^4}}$$

$\omega := 0.1, 0.125 .. 2$



e adjacent figure shows two amples of calculated wave ectra as a function of the wave quency ω (which ranges from to 2 rad/s).

e significant wave height in h cases is 1 m, the o-upcrossing periods are 4 d 8 s.

Motion Response in Irregular Waves

Multiplication of the square of the response function with the wave spectrum yields the response spectrum Sϕ. The three response spectra are given by the adjacent functions:

$$S_{\phi roll}(T_2,H_s,\gamma,\omega) := \phi_{roll}(\omega)^2\cdot S_\zeta(\omega,T_2,H_s,\gamma)$$
$$S_{\phi pitch}(T_2,H_s,\gamma,\omega) := \phi_{pitch}(\omega)^2\cdot S_\zeta(\omega,T_2,H_s,\gamma)$$
$$S_{\phi heave}(T_2,H_s,\gamma,\omega) := \phi_{heave}(\omega)^2\cdot S_\zeta(\omega,T_2,H_s,\gamma)$$

The variance of the roll,pitch angles and heave is given by the area below the response spectra . The rms values follow by taking the square root:

$$rms_{\phi roll}(T_2, H_s, \gamma) := \sqrt{\int_{0.10}^{2.0} S_{\phi roll}(T_2, H_s, \gamma, \omega)\, d\omega}$$

$$rms_{\phi pitch}(T_2, H_s, \gamma) := \sqrt{\int_{0.10}^{2.0} S_{\phi pitch}(T_2, H_s, \gamma, \omega)\, d\omega}$$

$$rms_{\phi heave}(T_2, H_s, \gamma) := \sqrt{\int_{0.10}^{2.0} S_{\phi heave}(T_2, H_s, \gamma, \omega)\, d\omega}$$

The significant values of the roll,pitch and heave becomes:

Roll : $sgf_{\phi roll}(T_2, H_s, \gamma) := 4 \cdot rms_{\phi roll}(T_2, H_s, \gamma)$

Pitch : $sgf_{\phi pitch}(T_2, H_s, \gamma) := 4 \cdot rms_{\phi pitch}(T_2, H_s, \gamma)$

Heave : $sgf_{\phi heave}(T_2, H_s, \gamma) := 4 \cdot rms_{\phi heave}(T_2, H_s, \gamma)$

Results

Adopting a wave condition given by:

Peak enhancement factor γ: $\gamma := 3.3$

Significant Wave Height H_s: $H_s := 10.$ m

Average Zero-Upcrossing Period T_2: $T_2 := 12$ s

The rms of the roll,pitch and heave becomes:

Roll 90: $rms_{\phi roll}(T_2, H_s, \gamma) = 3.16$ deg

Pitch 180: $rms_{\phi pitch}(T_2, H_s, \gamma) = 0.7$ deg

Heave 90: $rms_{\phi heave}(T_2, H_s, \gamma) = 3.8$ m

The significant values of the roll,pitch and heave becomes:

Roll 90: $sgf_{\phi roll}(T_2, H_s, \gamma) = 12.649$ deg

Pitch 180: $sgf_{\phi pitch}(T_2, H_s, \gamma) = 2.9$ deg

Heave 90: $sgf_{\phi heave}(T_2, H_s, \gamma) = 15.1$ m

Assuming a one hour time duration of the storm

$$T_{storm} := 3600 \quad sec$$

number of oscillations $N_{osc} := T_{storm} \cdot \frac{1.}{T_2}$ $N_{osc} = 300$

Most probable extreme in one hour of survival storm

Roll : $MPM_{roll} := 1. \sqrt{2 \cdot \ln(N_{osc})} \, rms_{\phi roll}(T_2, H_s, \gamma)$ $MPM_{roll} = 10.68$

Pitch : $MPM_{pitch} := 1. \sqrt{2 \cdot \ln(N_{osc})} \, rms_{\phi pitch}(T_2, H_s, \gamma)$ $MPM_{pitch} = 2.489$

Heave : $MPM_{heave} := 1. \sqrt{2 \cdot \ln(N_{osc})} \, rms_{\phi heave}(T_2, H_s, \gamma)$ $MPM_{heave} = 12.784$

6.8 APPENDIX III Beaufort number, wind speed and wave height

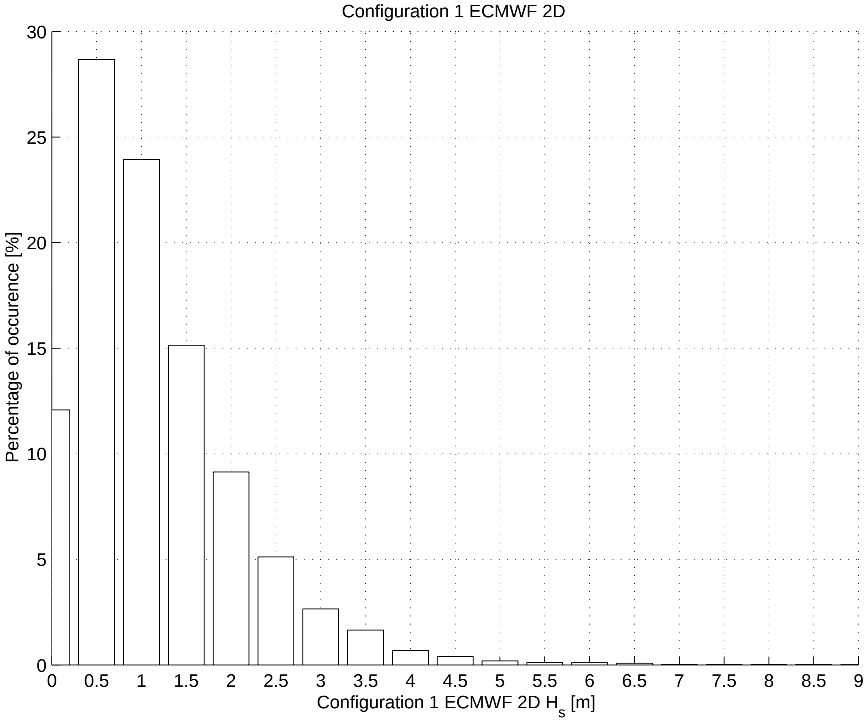
Average relations

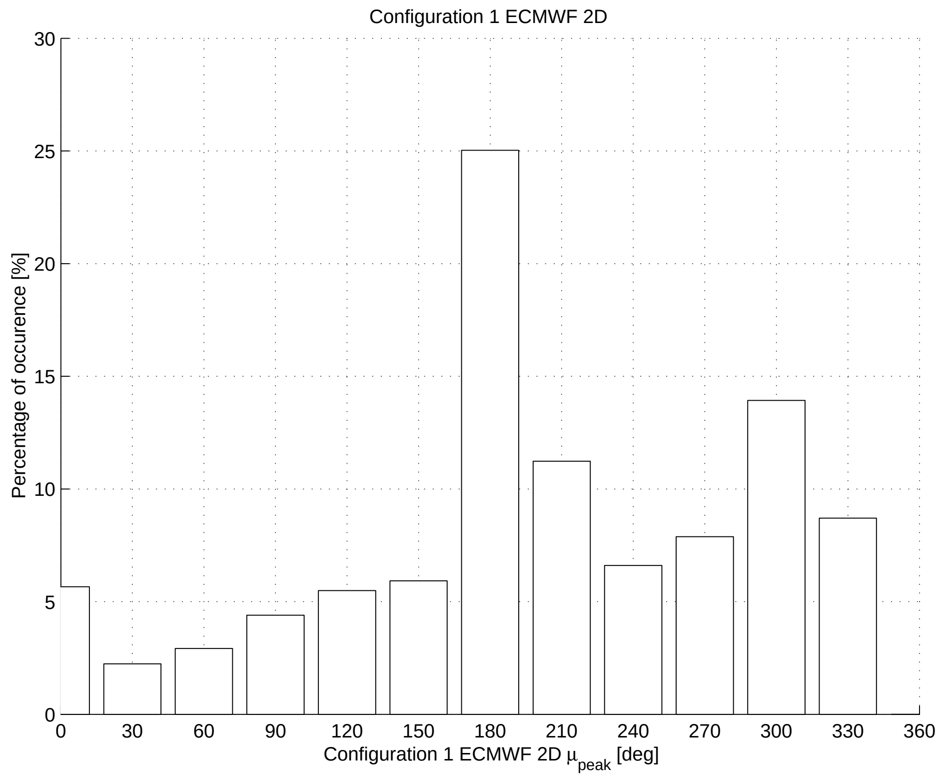
Beaufort Number	Wind velocity	Significant wave height		
		North Atlantic Ocean	North Sea	Fully arisen sea (theoretical)
		Roll [1953][2]	Petri [1958][3]	Bhattacharyya [1978][4]
	V_W [m/s]	$H_{1/3}$ [m]	$H_{1/3}$ [m]	$H_{1/3}$ [m]
2	2.6		0.9	0.15
3	4.4	1.4	0.9	0.40
4	6.9	1.7	1.3	1.00
5	9.8	2.15	1.9	2.01
6	12.6	2.90	2.9	3.20
7	15.7	3.75	3.7	5.15
8	19.0	4.85	5.2	7.58
9	22.7	6.20		10.73
10	26.6	7.45		14.73
11	30.6	8.40		19.63
12	>33.0			

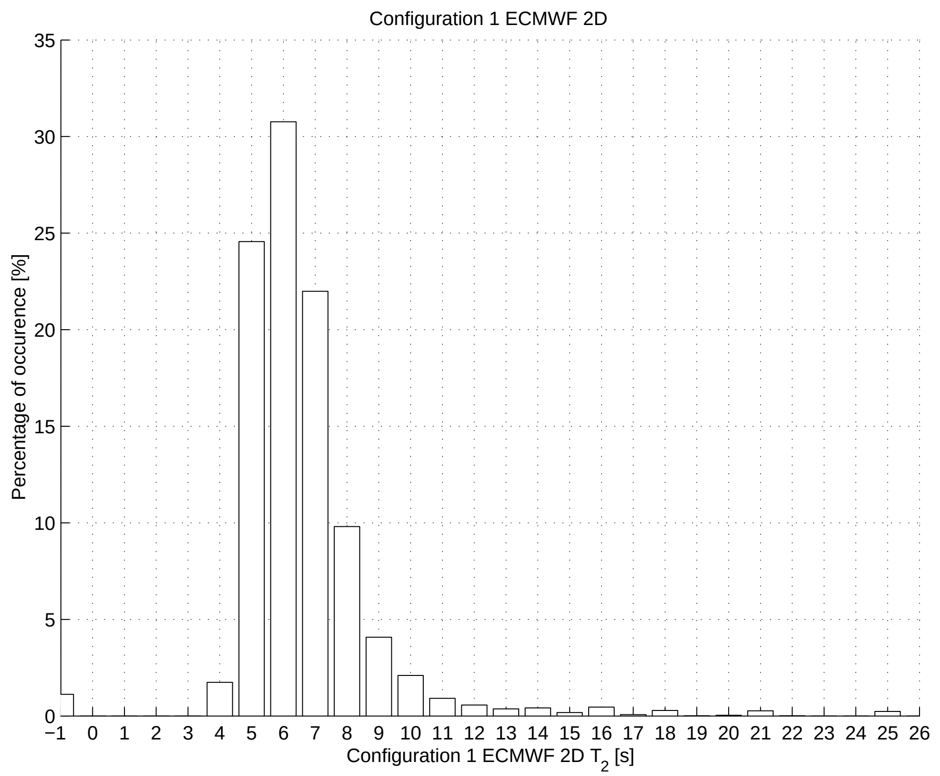
[2] Roll, H.U.; "Höhe, Länge und Steilheit der Meereswellen im Nordatlantik", Deutscher Wetterdienst, Seewetteramt, Einzelveröffentlichungen Nr. 1, Hamburg, 1953.
[3] Petri, O.; "Statistik der Meereswellen in der Nordsee", Deutscher Wetterdienst, Seewetteramt, Einzelveröffentlichungen Nr. 17, Hamburg, 1958.
[4] Bhattacharyya R.; "Dynamics of Marine Vehicles", ISBN 0-471-07206-0, 1978.

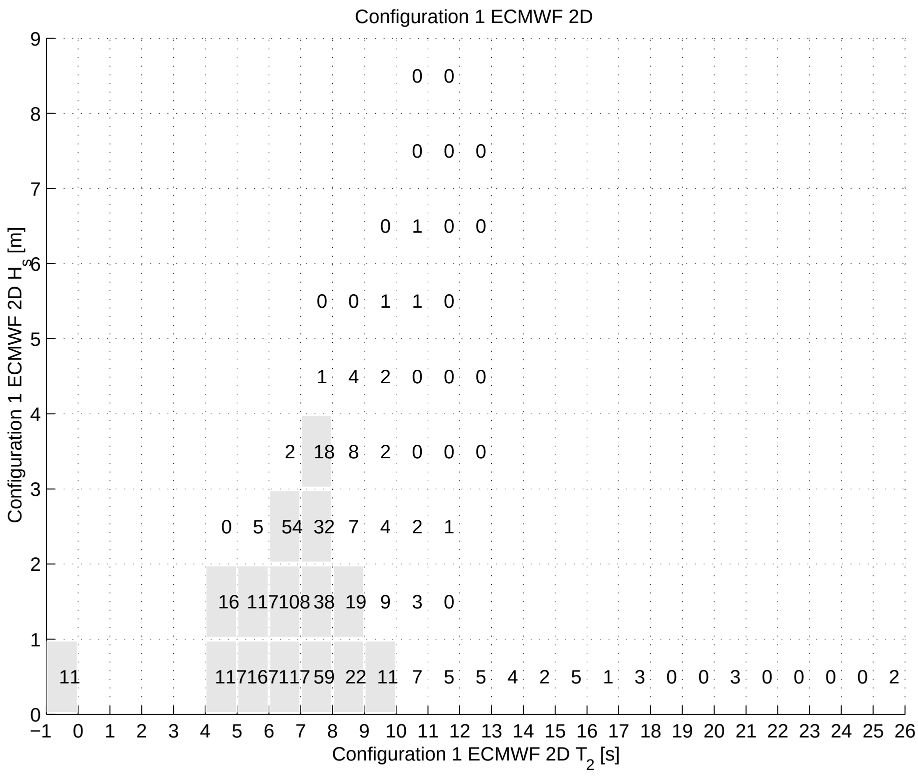
6.9 Wave scatter diagrams and Probability of exceedance

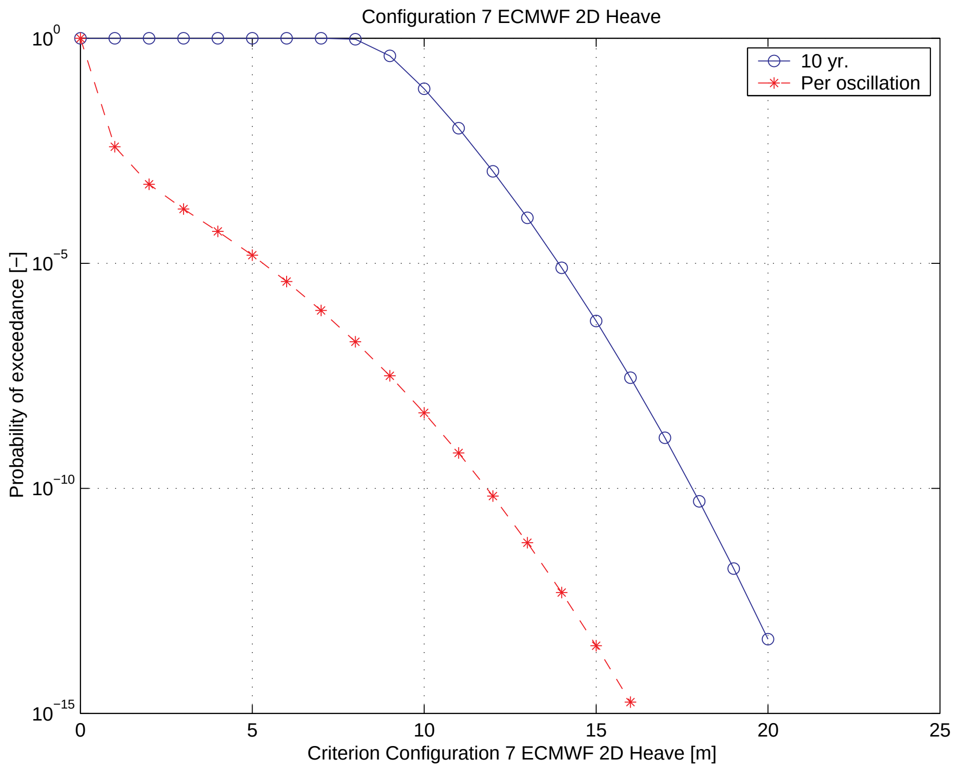
6.9.1 ECMWF DATA

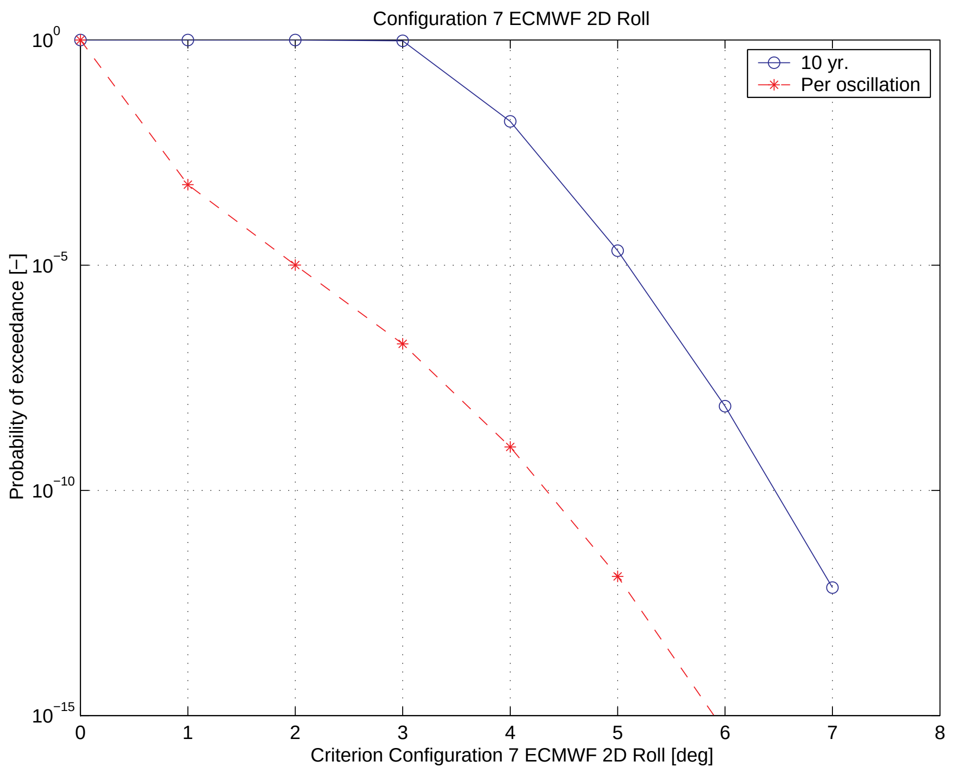


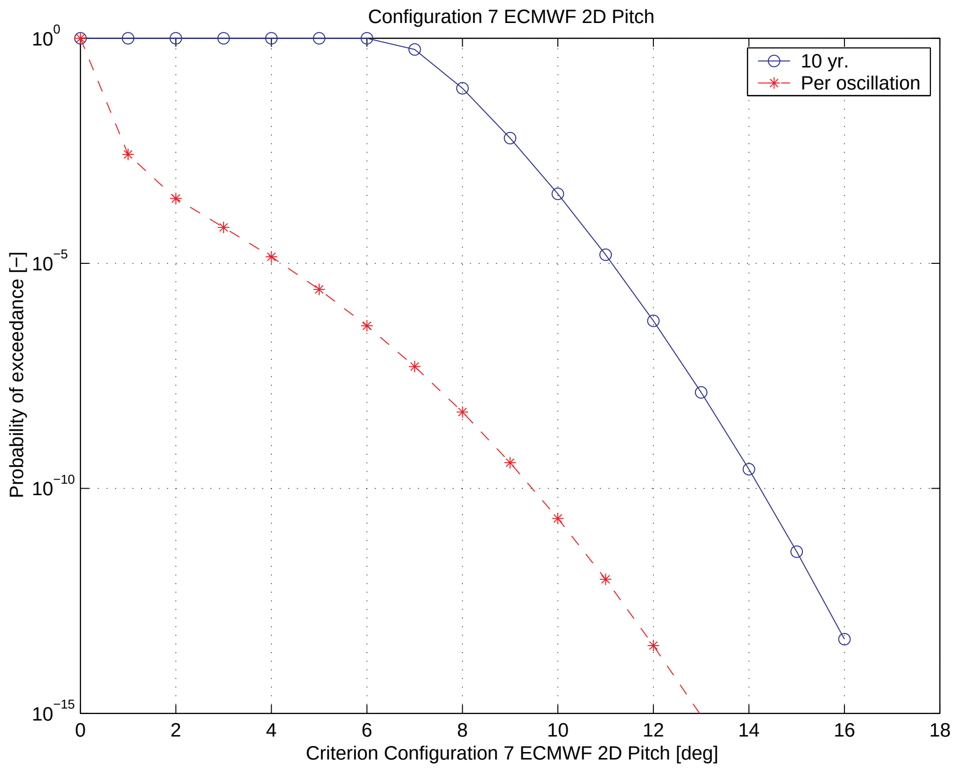

Configuration 1 ECMWF 2D
Percentage of occurence [%]
0
5
10
15
20
25
30
0 30 60 90 120 150 180 210 240 270 300 330 360
Configuration 1 ECMWF 2D μpeak [deg]

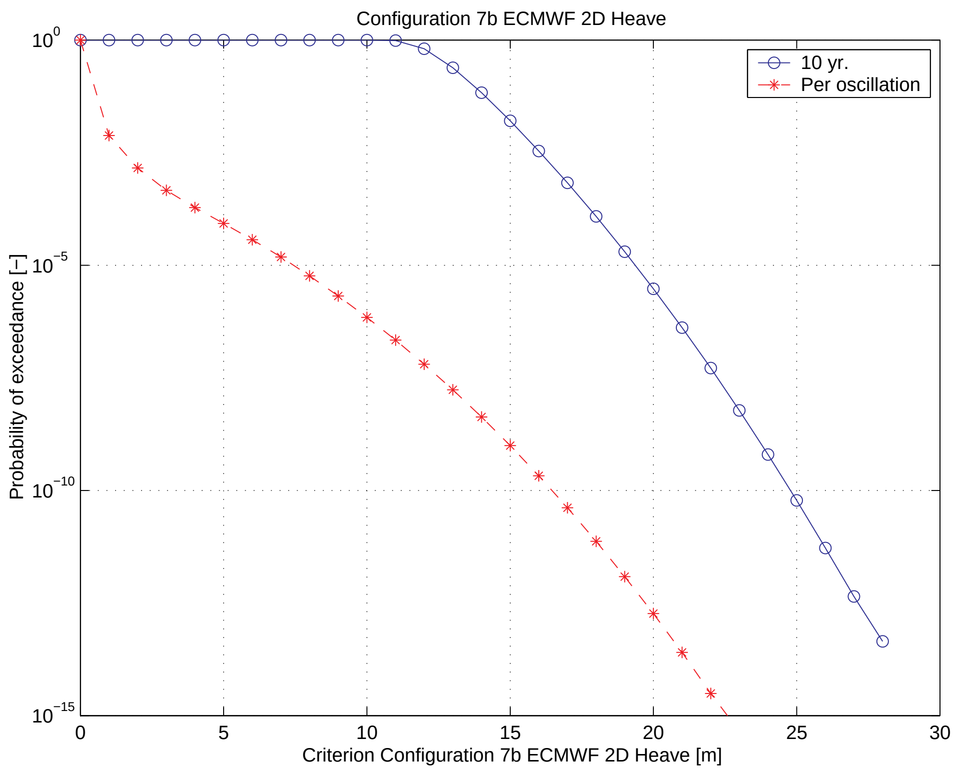

Configuration 1 ECMWF 2D
Percentage of occurence [%]
0
5
10
15
20
25
30
35
−1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Configuration 1 ECMWF 2D T2 [s]

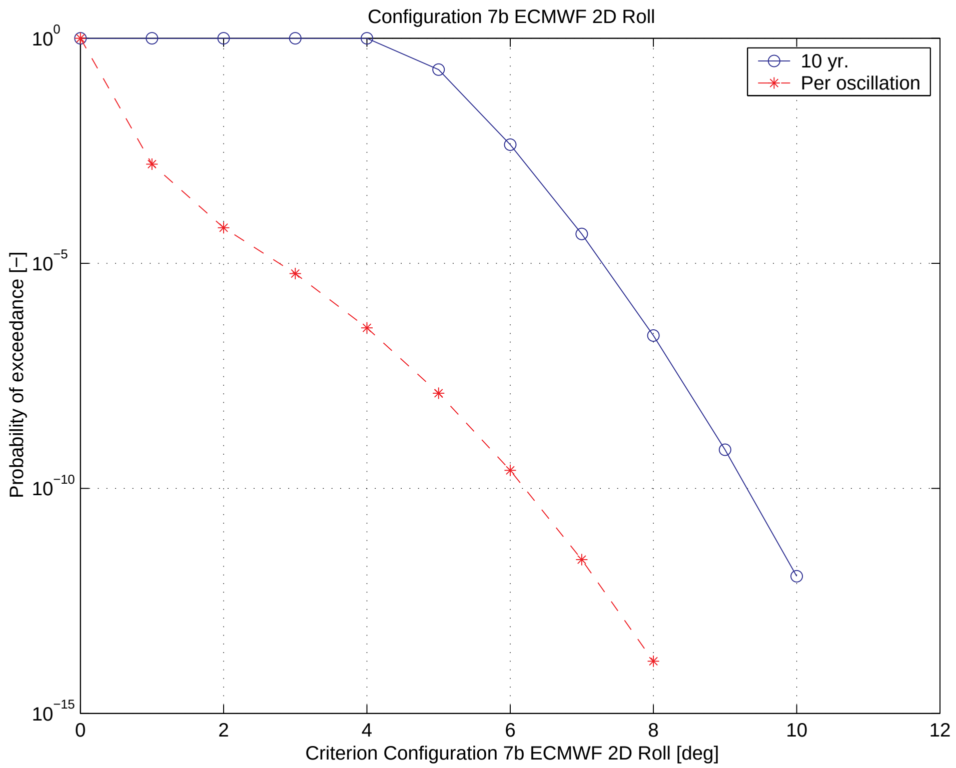

Configuration 1 ECMWF 2D
Configuration 1 ECMWF 2D H_s [m]
Configuration 1 ECMWF 2D T_2 [s]

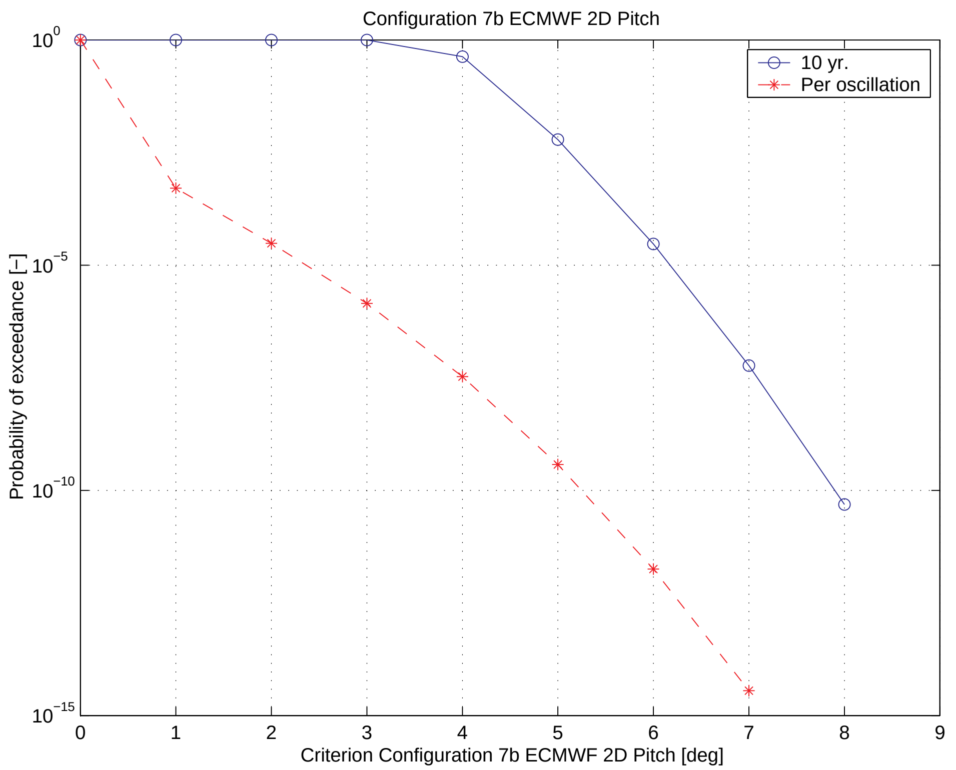

Configuration 7 ECMWF 2D Heave
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 ECMWF 2D Heave [m]


Configuration 7 ECMWF 2D Roll
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 ECMWF 2D Roll [deg]

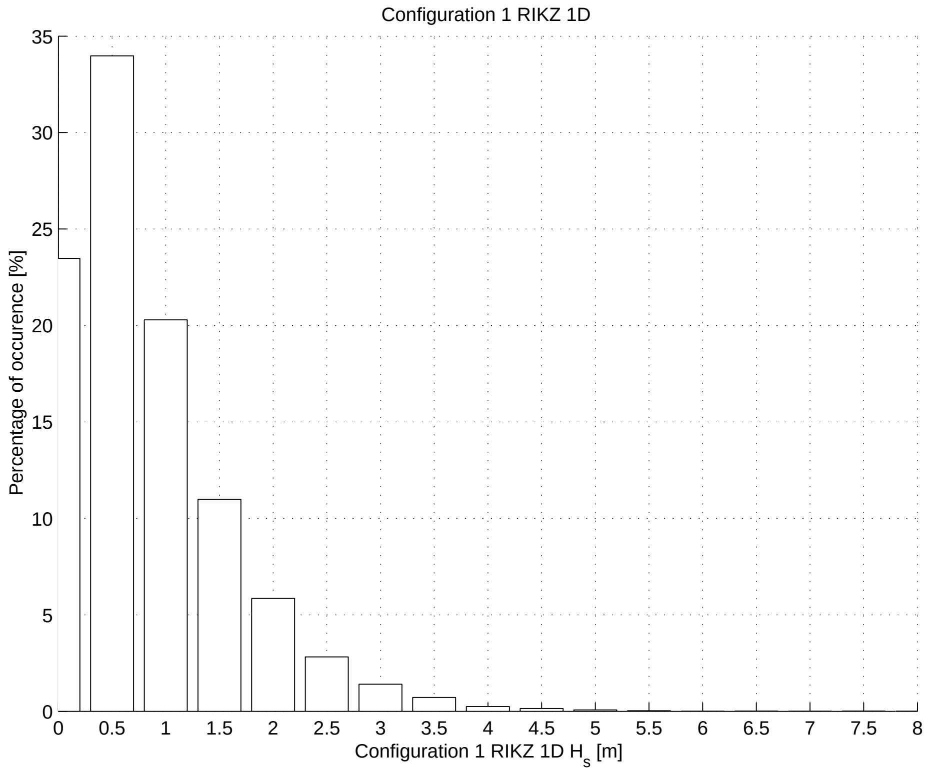

Configuration 7 ECMWF 2D Pitch
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 ECMWF 2D Pitch [deg]

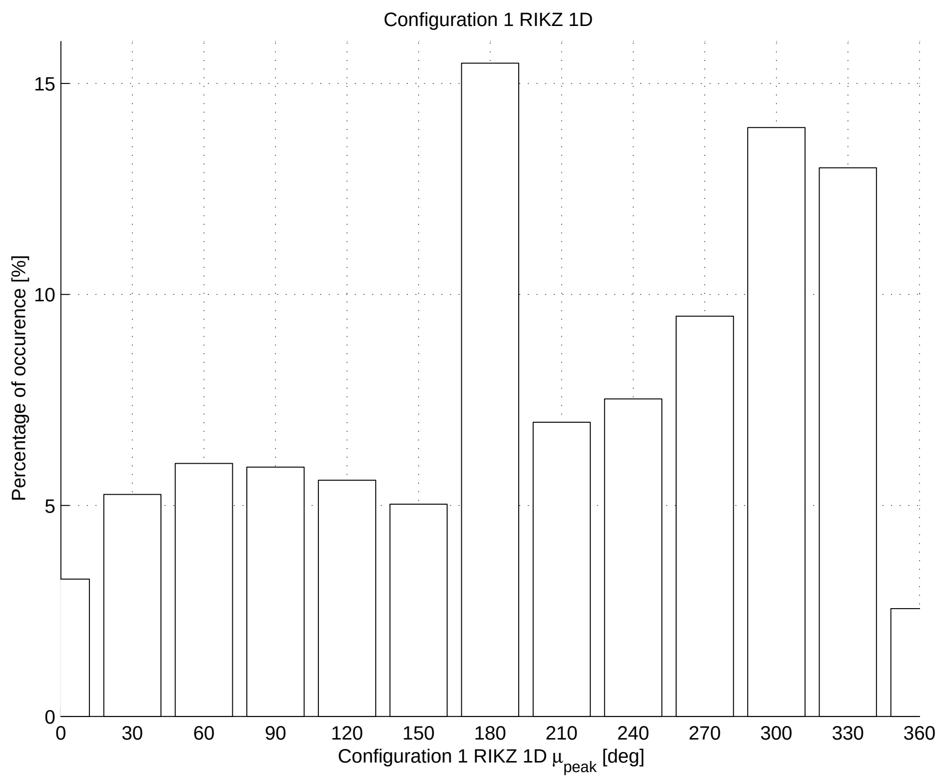

Configuration 7b ECMWF 2D Heave
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7b ECMWF 2D Heave [m]

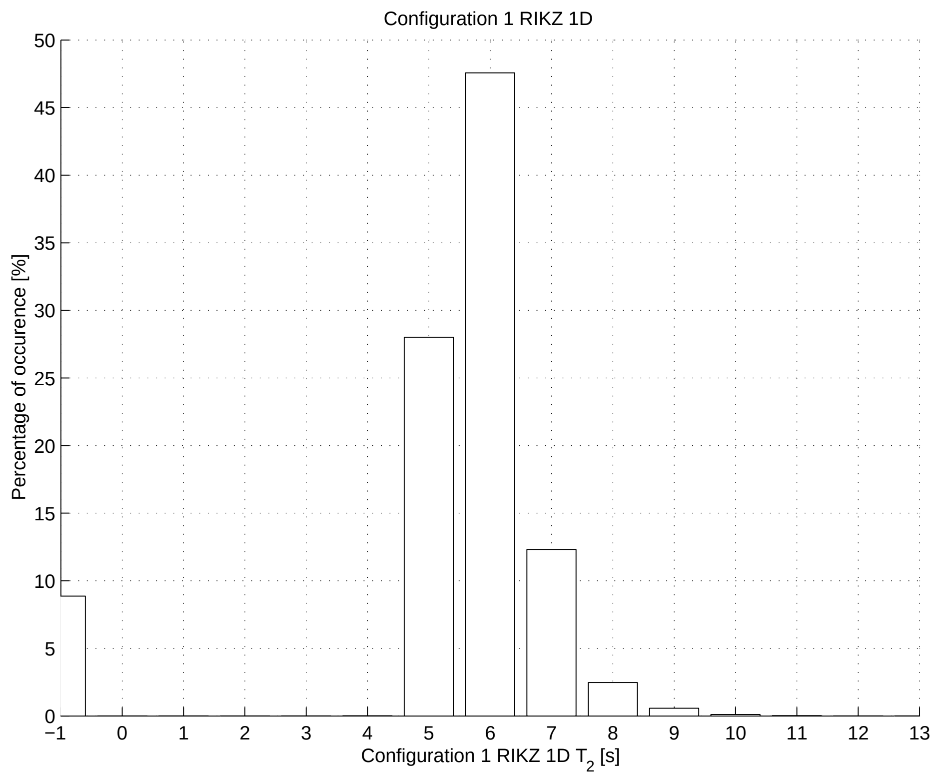

Configuration 7b ECMWF 2D Roll
10 yr.
Per oscillation
Probability of exceedance [-]
10^0
10^-5
10^-10
10^-15
0
2
4
6
8
10
12
Criterion Configuration 7b ECMWF 2D Roll [deg]

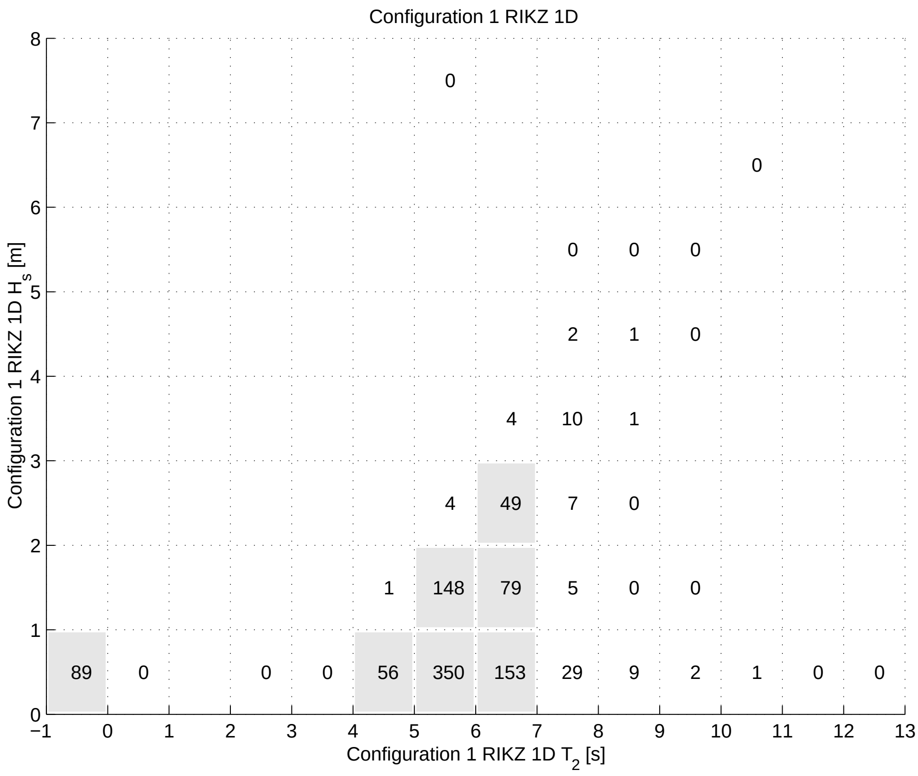

Configuration 7b ECMWF 2D Pitch
10 yr.
Per oscillation
Probability of exceedance [-]
10^0
10^-5
10^-10
10^-15
0
1
2
3
4
5
6
7
8
9
Criterion Configuration 7b ECMWF 2D Pitch [deg]

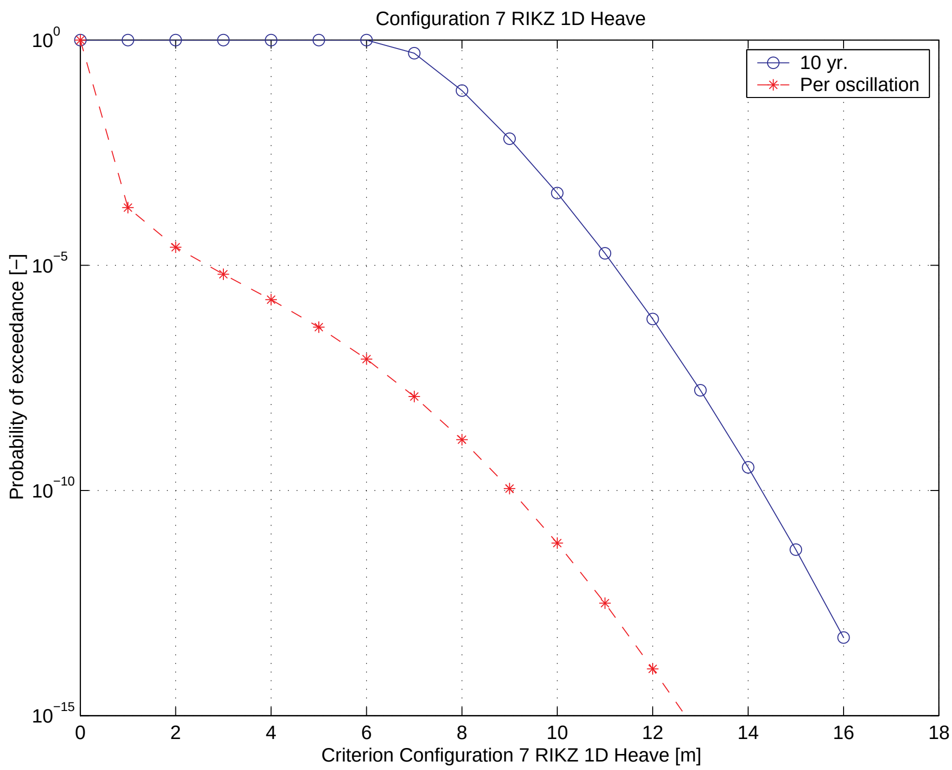
6.9.2 RIKZ DATA

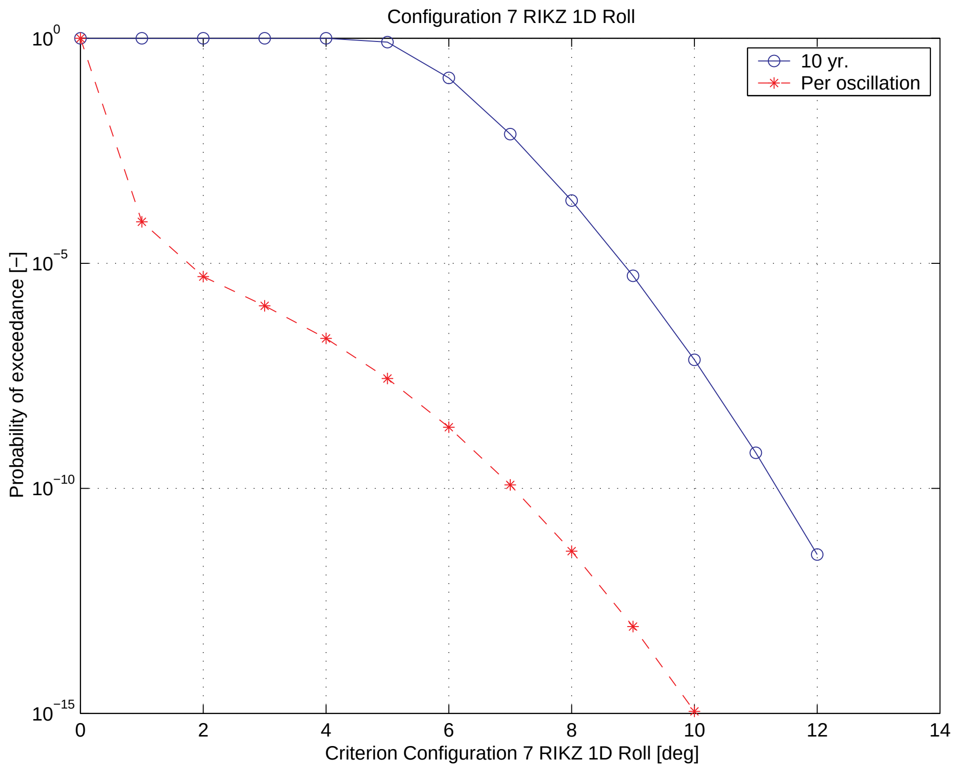


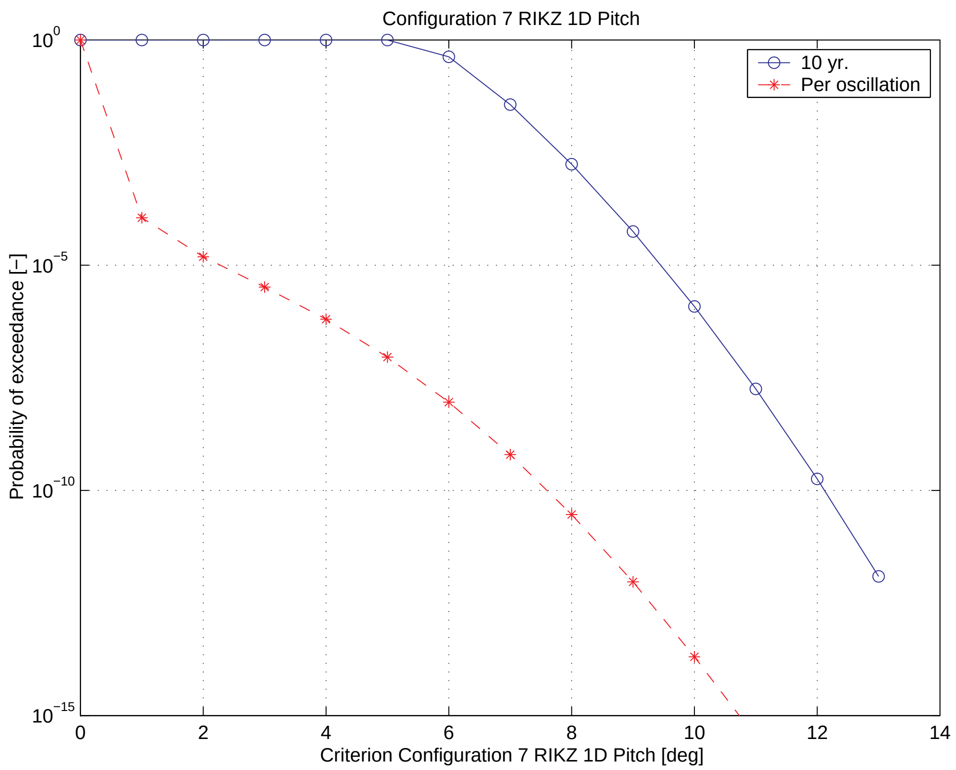

Configuration 1 RIKZ 1D
Percentage of occurence [%]
0
5
10
15
0 30 60 90 120 150 180 210 240 270 300 330 360
Configuration 1 RIKZ 1D μ_{peak} [deg]

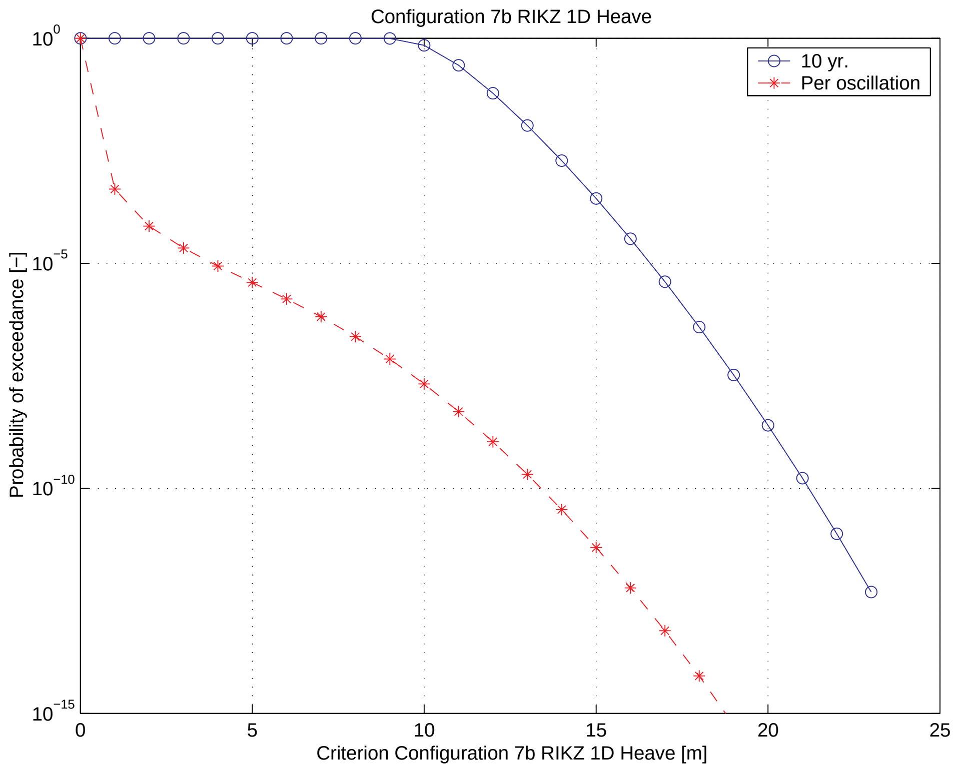

Configuration 1 RIKZ 1D
Percentage of occurence [%]
0 5 10 15 20 25 30 35 40 45 50
−1 0 1 2 3 4 5 6 7 8 9 10 11 12 13
Configuration 1 RIKZ 1D T_2 [s]

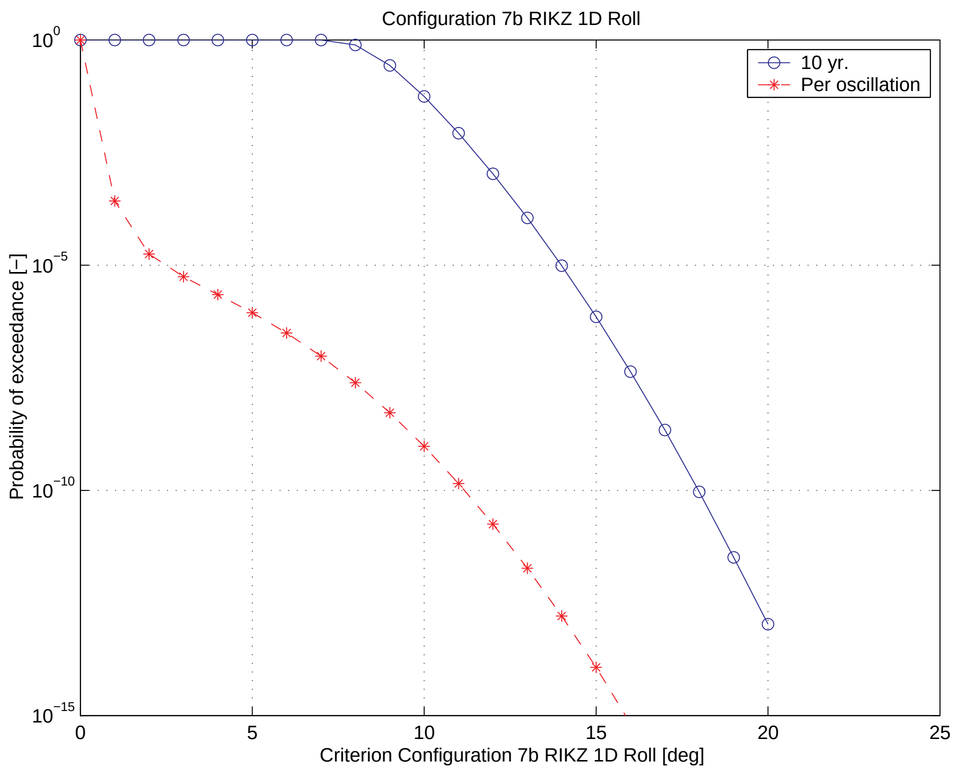

Configuration 1 RIKZ 1D
Configuration 1 RIKZ 1D H_s [m]
Configuration 1 RIKZ 1D T_2 [s]
0
0
0 0 0
2 1 0
4 10 1
4 49 7 0
1 148 79 5 0 0
89 0 0 0 56 350 153 29 9 2 1 0 0

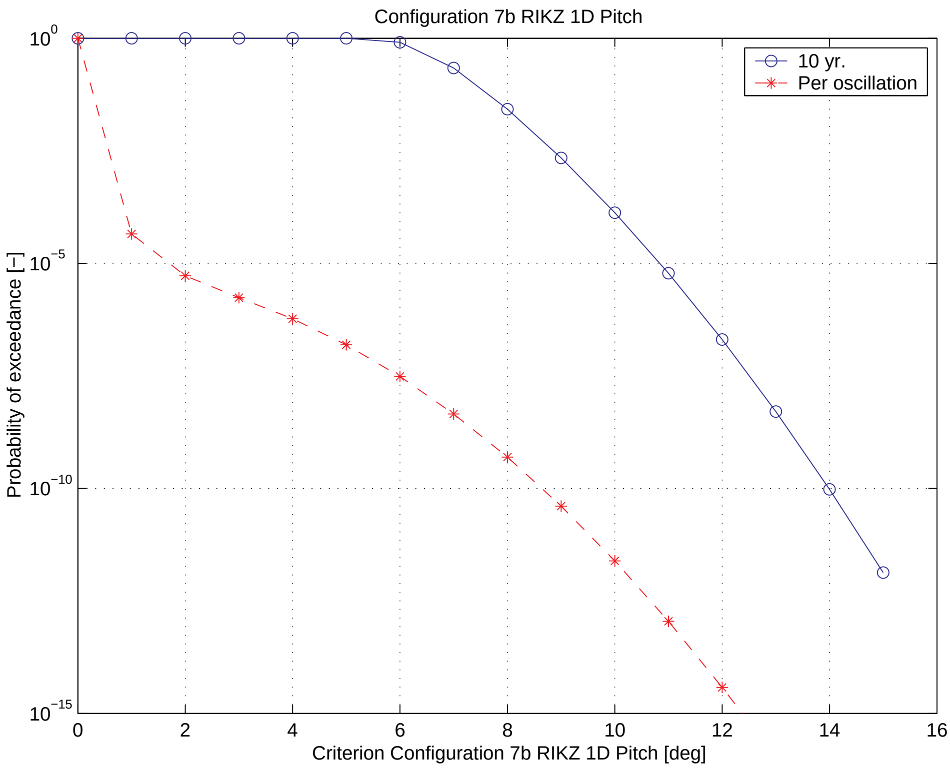

Configuration 7 RIKZ 1D Heave
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 RIKZ 1D Heave [m]


Configuration 7 RIKZ 1D Roll
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 RIKZ 1D Roll [deg]
0
2
4
6
8
10
12
14
10^0
10^−5
10^−10
10^−15

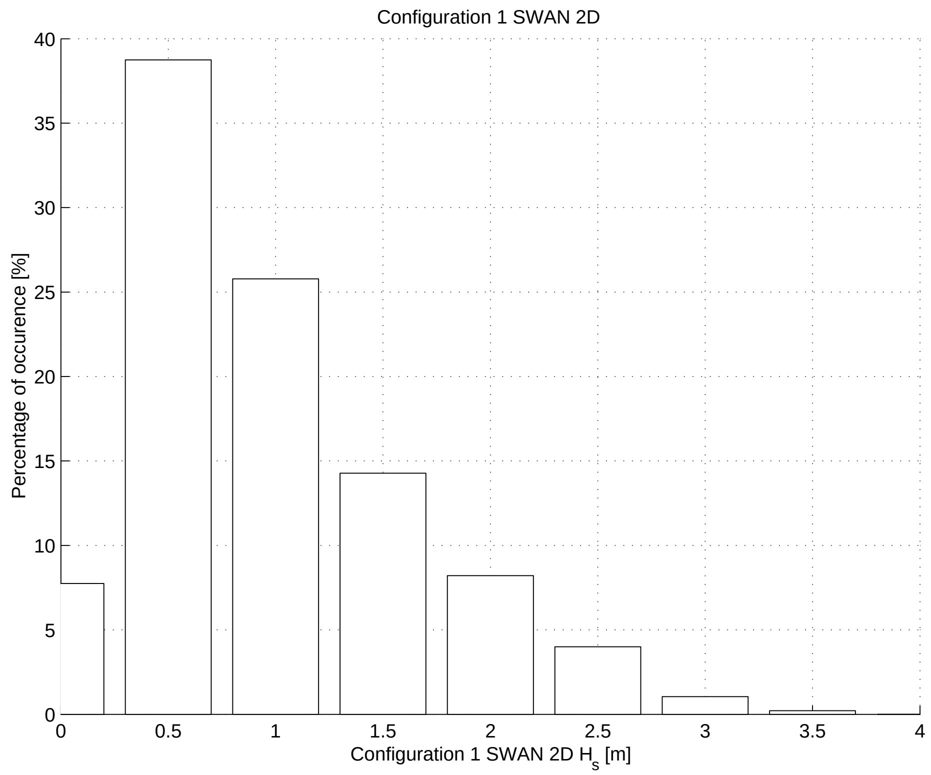

Configuration 7 RIKZ 1D Pitch
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 RIKZ 1D Pitch [deg]
0
2
4
6
8
10
12
14
10^0
10^−5
10^−10
10^−15

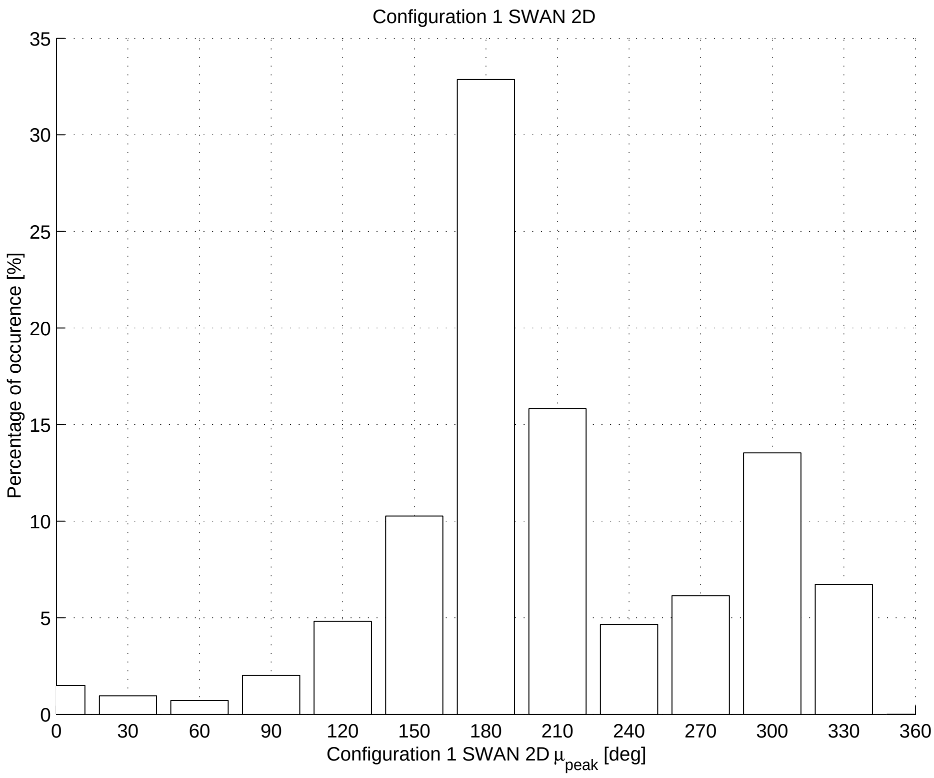

Configuration 7b RIKZ 1D Heave
10 yr.
Per oscillation
Probability of exceedance [-]
10^{0}
10^{-5}
10^{-10}
10^{-15}
0
5
10
15
20
25
Criterion Configuration 7b RIKZ 1D Heave [m]

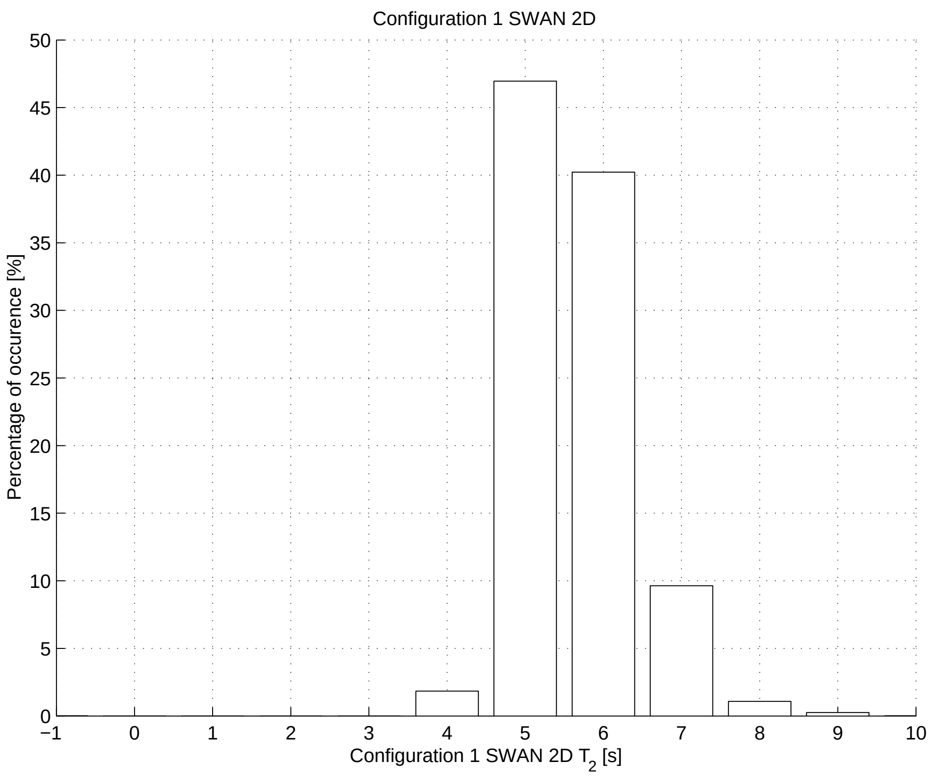

Configuration 7b RIKZ 1D Roll
10 yr.
Per oscillation
Probability of exceedance [-]
10^{0}
10^{-5}
10^{-10}
10^{-15}
0
5
10
15
20
25
Criterion Configuration 7b RIKZ 1D Roll [deg]

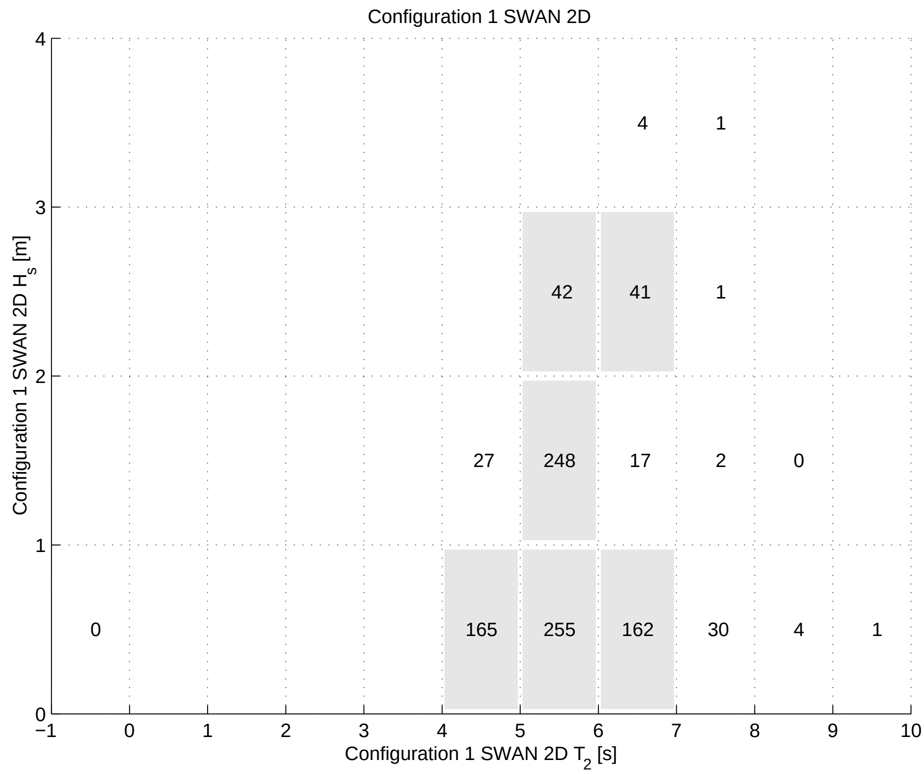

Configuration 7b RIKZ 1D Pitch
10 yr.
Per oscillation
Probability of exceedance [-]
10^{0}
10^{-5}
10^{-10}
10^{-15}
0
2
4
6
8
10
12
14
16
Criterion Configuration 7b RIKZ 1D Pitch [deg]

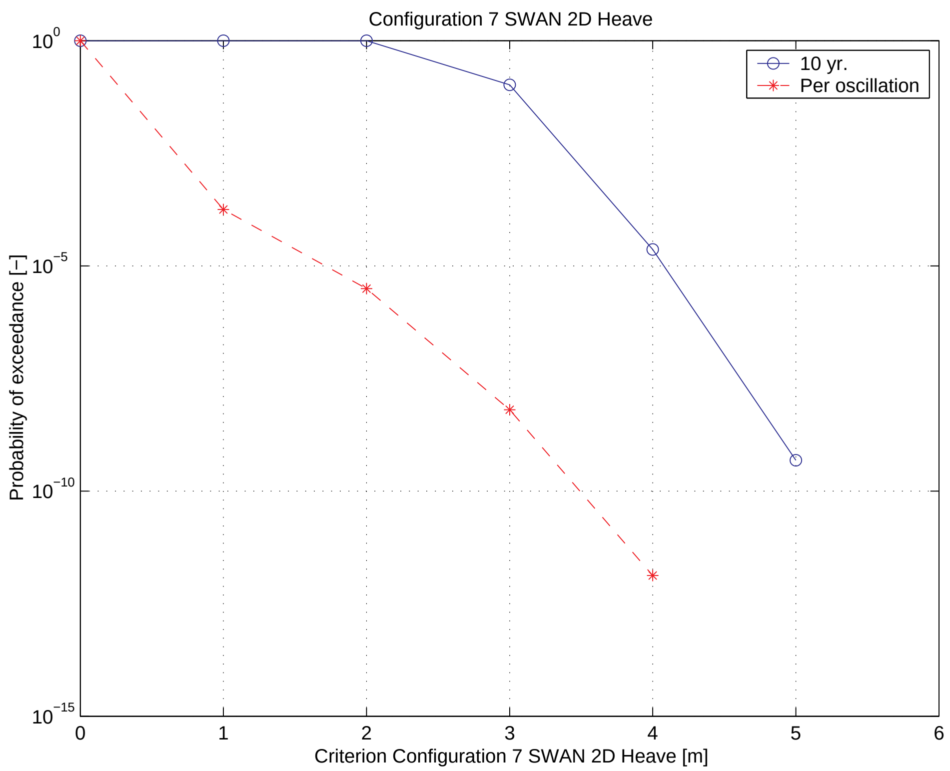
6.9.3 SWAN DATA

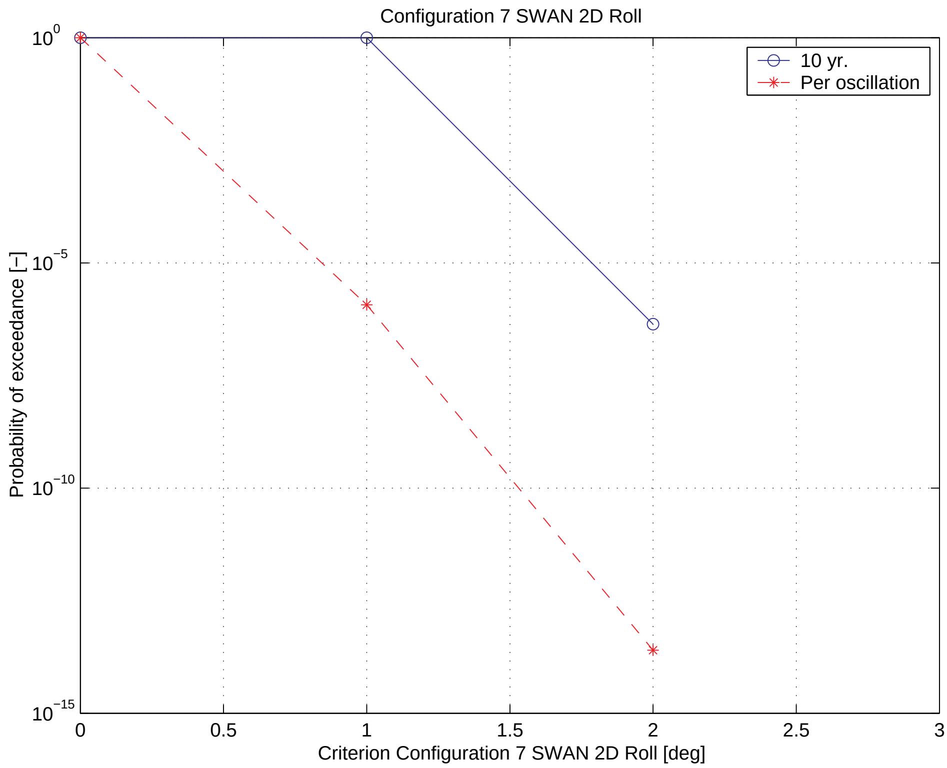



Configuration 1 SWAN 2D
Percentage of occurence [%]
35
30
25
20
15
10
5
0
0
30
60
90
120
150
180
210
240
270
300
330
360
Configuration 1 SWAN 2D μpeak [deg]

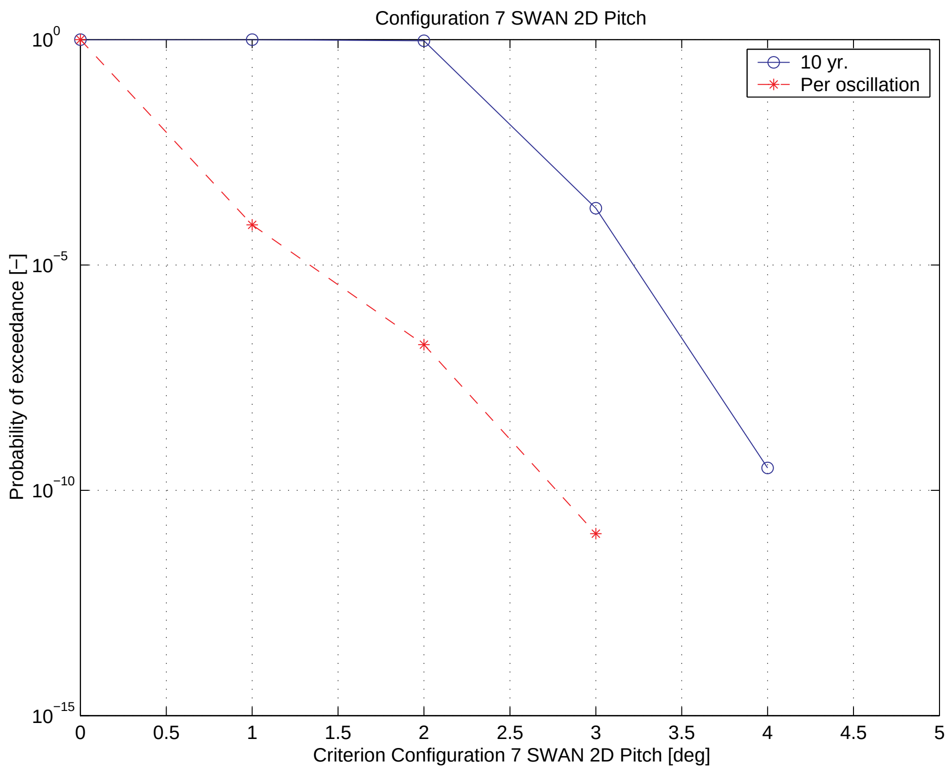

Configuration 1 SWAN 2D
Percentage of occurence [%]
50
45
40
35
30
25
20
15
10
5
0
−1
0
1
2
3
4
5
6
7
8
9
10
Configuration 1 SWAN 2D T2 [s]


Configuration 1 SWAN 2D
Configuration 1 SWAN 2D H_s [m]
Configuration 1 SWAN 2D T_2 [s]
4
1
42
41
1
27
248
17
2
0
0
165
255
162
30
4
1

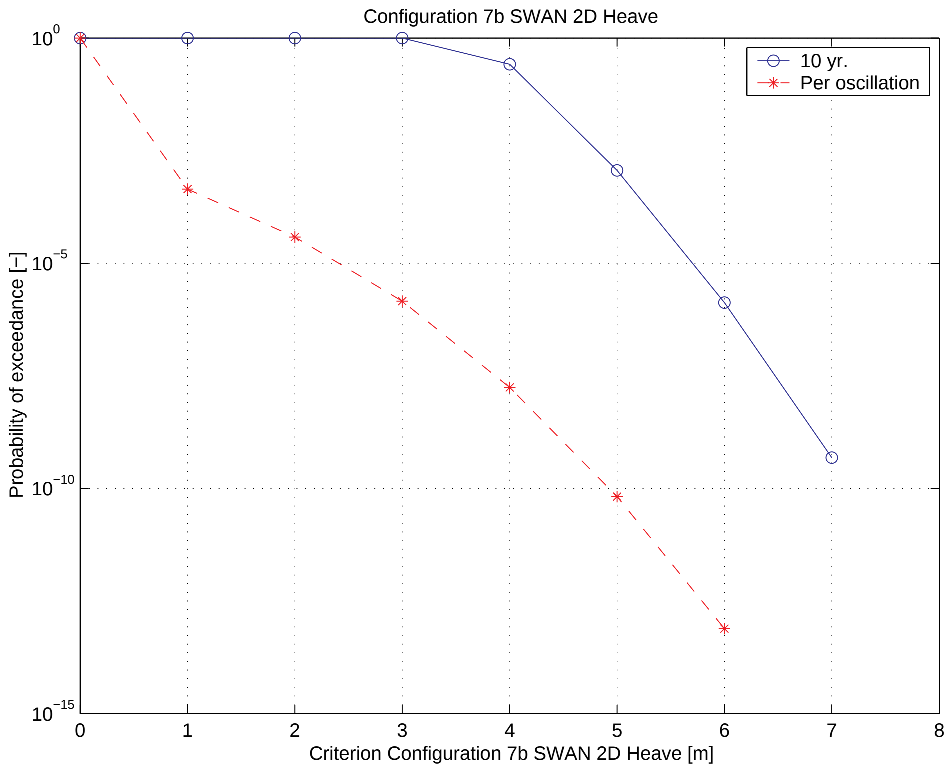

Configuration 7 SWAN 2D Heave
10 yr.
Per oscillation
Probability of exceedance [-]
Criterion Configuration 7 SWAN 2D Heave [m]

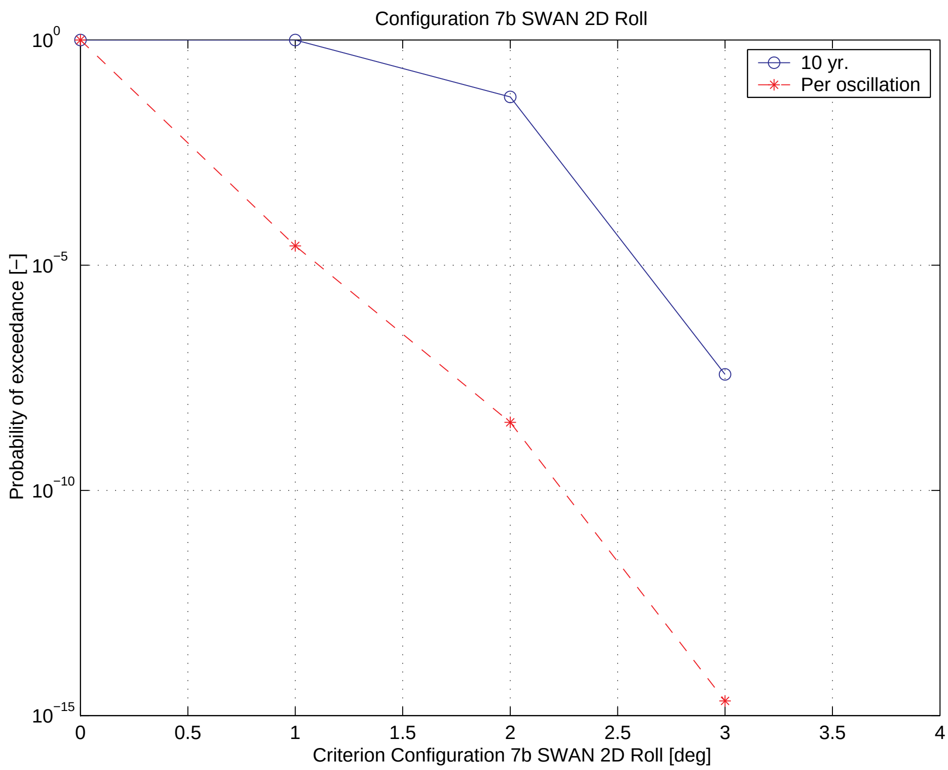


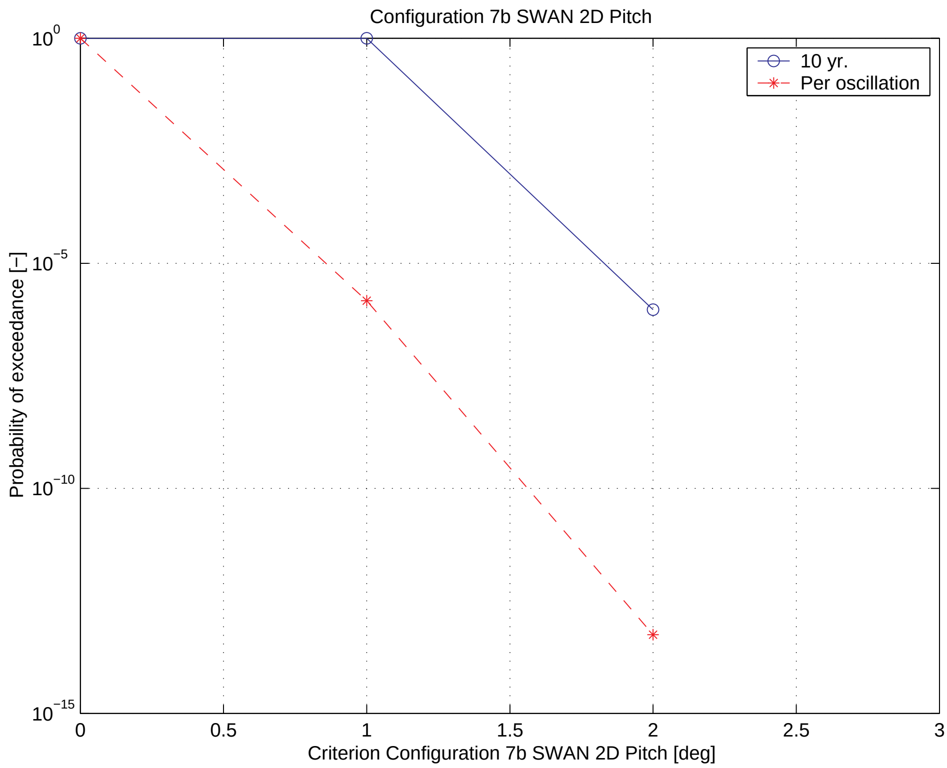
Configuration 7 SWAN 2D Roll
10 yr.
Per oscillation
Probability of exceedance [–]
10^0
10^−5
10^−10
10^−15
0
0.5
1
1.5
2
2.5
3
Criterion Configuration 7 SWAN 2D Roll [deg]



Configuration 7 SWAN 2D Pitch
10 yr.
Per oscillation
Probability of exceedance [–]
10^0
10^−5
10^−10
10^−15
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Criterion Configuration 7 SWAN 2D Pitch [deg]


Configuration 7b SWAN 2D Heave
10 yr.
Per oscillation
Probability of exceedance [-]
10^{0}
10^{-5}
10^{-10}
10^{-15}
0
1
2
3
4
5
6
7
8
Criterion Configuration 7b SWAN 2D Heave [m]


Configuration 7b SWAN 2D Roll
10 yr.
Per oscillation
Probability of exceedance [-]
10^{0}
10^{-5}
10^{-10}
10^{-15}
0
0.5
1
1.5
2
2.5
3
3.5
4
Criterion Configuration 7b SWAN 2D Roll [deg]



6.10 Appendix V: Quaestor Results

```
-Q-U-A-E-S-T-O-R-/Rev. 2000_1    Date: 14-03-2002    Time: 03:42:10
Licenced to: MARIN Ships-Propulsion    Knowledge base: Drijfwind

Solution Title: 115 m - D_Floaters=f(Dist_Float)
Page      : 1

Contents of current Solution: 41 parameter(s) and 41 expression(s)

REPORT$   Output DESIGN.REP of BLADOPT.EXE ...........[Str]
COST$     Parsed results from BLADOPT output .........[Str]
Tower_Top_Mass
          Mass of generator + turbine ..................[t]
Tower_Mass
          Mass of tower ..............................[t]
BLADOPTINPUT$
          Input of BLADOPT.EXE GEODAT.N ..............[Str]
Ch_R15    Blade chord length on 15% radius .............[m]
Ch_R25    Blade chord length on 25% radius .............[m]
Ch_R100   Blade chord length on 100% radius ............[m]
Load_Fatig
          Fatigue load on turbine ....................[kN]
Tower_F_Th
          Foot wall thickness of tower ................[mm]
Tower_T_Th
          {\rtf1\ansi\ansicpg1252\deff0\deftab720{\fo .[mm]
Tower_F_D Foot diameter of tower .......................[m]
```

```
Tower_T_D Top diameter of tower ........................[m]
DB$       Database of clustered solutions ............[Str]
VCG_Tower Vertical centre of gravity of tower ..........[m]
RatedRPM  Rated rotation rate of turbine ...........[1/min]
VOL_Floaters
          Displacement (submerged) volume of floater .[m^3]
M_Floaters
          Steel weight of floater ......................[t]
KG_Floaters
          Centre of gravity of floater above BL ........[m]
KB_Floaters
          Centre of buoyancy of floater above BL .......[m]
GM_Total  Metacentric height of floater + turbine ......[m]
Total_Mass
          Total mass of turbine, tower, floater and (w .[t]
D_Floaters
          Outside diameter of floater topside ..........[m]:  ?
H_Floaters
          Height of floater ............................[m]
Freeb_Floaters
          Freeboard of floater .........................[m]
BM_Floaters
          Metacentre above centre of buoyancy ..........[m]
KM_Floaters
          Metacenter height above keel of floater(s) ...[m]
KG_Total  Vertical centre of gravity of turbine, tower .[m]
M_Ballast (Water) ballast amount or pretension  ........[t]
KG_Ballast
          Vertical COG of ballast or ...................[m]
GZ_Max    Maximum arm of static stability ..............[m]
```

```
 -Q-U-A-E-S-T-O-R-/Rev. 2000_1    Date: 14-03-2002    Time: 03:42:10
Licenced to: MARIN Ships-Propulsion    Knowledge base: Drijfwind

Solution Title: 115 m - D_Floaters=f(Dist_Float)
Page        : 2

WindArm    Required wind arm at Phi_Max .................[m]
Ix         Moment of inertia of water plane area ......[m^4]
CVOL_Floaters
           Total construction volume of floaters + tr .[m^3]
Draft_Floaters
           Draft of floaters ...........................[m]
VOL_Truces
           Total volume of connection pipes between f .[m^3]
Steel_weight
           Total steel weight, i.e. towers + floaters ...[t]
ma         Added mass for heave ........................[t]
Tz         Natural period of heave .....................[s]:  ?
Tphi       Natural period of roll and pitch ............[s]:  ?
Kxx        Radius of gyration for roll and pitch ........[m]

REPORT$ = GET$("DESIGN.REP", "BLADOPT", PUT$("GEODAT.N", BLADOPTINPUT$),
                                        PUT$("DEFINS.DEF", DEFINS$),
                                        PUT$("DEFINE.DEF", DEFINE$),
                                        PUT$("ENGDAT.I", ENGDAT$))
COST$ = PARSE$(REPORT$)
Tower_Top_Mass = Turbs_Floater*SELECT(COST$, 1, "Tower_Top_Mass",
1)/1000
Tower_Mass = Nr_Main_Towers*SELECT(COST$, 1, "Tower_Mass", 1)/1000 +
             (Turbs_Floater-Nr_Main_Towers)*Rotor_Diam^1.5/8.4
BLADOPTINPUT$ = TEMPLATE$(QKB$("BLADOPTINPUT$", "DATA"), 1, Nr_Blades,
Ch_R15, Ch_R25, Ch_R100,
Tower_Height, C_Loss_Drive, V_Loss_Drive, IntRate,
Deprec_Period,
                 Maint_CostPercLand, Extra_Cost_Land, RatedRPM, AimPow)
Ch_R15 = 0.053*Rotor_Diam

Ch_R25 = 0.046*Rotor_Diam
Ch_R100 = 0.014*Rotor_Diam
Load_Fatig = Turbs_Floater*SELECT(COST$, 1, "Load_Fatig", 1)/1000
Tower_F_Th = SELECT(COST$, 1, "Tower_F_Th", 1)*1000
Tower_T_Th = SELECT(COST$, 1, "Tower_T_Th", 1)*1000
Tower_F_D = SELECT(COST$, 1, "Tower_F_D", 1)
Tower_T_D = SELECT(COST$, 1, "Tower_T_D", 1)
DB$ = UNFOLD#(CLUSTER#("Solution"), "Blade_Mass", 0, "BLADOPTINPUT$",
"REPORT$")
VCG_Tower = ((Tower_F_D*Tower_F_Th -
Tower_T_D*Tower_T_Th)*Tower_Height/2*Tower_Height/3 +
           Tower_T_D*Tower_T_Th*Tower_Height*Tower_Height/2)/
((Tower_F_D*Tower_F_Th +
Tower_T_D*Tower_T_Th)*Tower_Height/2)
TipSpeed = RatedRPM*Rotor_Diam*Pi/60
VOL_Floaters = Total_Mass/Rho
M_Floaters = CVOL_Floaters*VolMassConstr
KG_Floaters = H_Floaters/2
KB_Floaters = (Nr_Floaters*0.125*Pi*
(D_Floaters^2*(Draft_Floaters-H_Disc)*(Draft_Floaters
```

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+ H_Disc) + D_Disc^2*H_Disc^2) +
0.5*VOL_Truces*Draft_Floaters)/VOL_Floaters
GZ_Max = GM_Total*SIN(PhiMax*Pi/180) +
BM_Floaters*TAN(PhiMax*Pi/180)^2/2*SIN(PhiMax*Pi/180)
Total_Mass = Steel_weight + Tower_Top_Mass + M_Ballast
PhiMax = ATAN(Freeb_Floaters/(0.5*D_Floaters + 0.5*DistFloat))*180/Pi
Draft_Floaters = H_Floaters - Freeb_Floaters
Draft_Floaters = Freeb_Floaters*1.3
BM_Floaters = Ix/VOL_Floaters
KM_Floaters = KB_Floaters + BM_Floaters
GM_Total = KM_Floaters - KG_Total
KG_Total = (KG_Floaters*M_Floaters +
            (VCG_Tower + H_Floaters)*Tower_Mass +
            (Tower_Height + H_Floaters)*Tower_Top_Mass +
            M_Ballast*KG_Ballast +

1.4*VOL_Truces*VolMassConstr*1/6*SQRT(3)*D_Floaters)/Total_Mass
KG_Ballast = M_Ballast/(2*Rho*Nr_Floaters*0.25*Pi*D_Floaters^2)
StabIndex = GZ_Max/WindArm
WindArm = Load_Fatig*(H_Floaters +
Tower_Height-KB_Floaters)/(Total_Mass*g)
Ix = INCASE(Floater_Concept,EQ,1,THEN,
          0.049*D_Floaters^4,
       ELSEIF,Floater_Concept,EQ,2,THEN,
          1/2*0.25*Pi*D_Floaters^2*DistFloat^2 + 3*0.049*D_Floaters^4,
        ELSEIF,Floater_Concept,EQ,3,THEN,
          0.25*Pi*D_Floaters^2*DistFloat^2 + 4*0.049*D_Floaters^4,
       ELSEIF,Floater_Concept,EQ,4,THEN,
          1/12*D_Floaters^3*L_Floaters,
       ELSE,
1/6*D_Floaters^3*L_Floaters +
0.5*DistFloat^2*D_Floaters*L_Floaters)
CVOL_Floaters = (Draft_Floaters +
Freeb_Floaters)/Draft_Floaters*VOL_Floaters
VOL_Floaters = Nr_Floaters*INCASE(Floater_Concept,LT,4,THEN,
0.25*Pi*(D_Floaters^2*(Draft_Floaters -
H_Disc) +
                               D_Disc^2*H_Disc) + VOL_Truces,
                             ELSE,
D_Floaters*D_Floaters*Draft_Floaters +
VOL_Truces)
VOL_Truces =
Nr_Floaters*0.25*Pi*D_Truces^2*(0.333*SQRT(3)*DistFloat-(D_Floaters+Towe
_F_D)/2)
Steel_weight = M_Floaters + Tower_Mass
ma = Nr_Floaters*Pi/12*D_Floaters^3*Rho
Tz = 2*Pi*SQRT((1 + ma/Total_Mass)*Draft_Floaters/g)
Tphi = 2*Pi*Kxx/SQRT(GM_Total*g)
Kxx = SQRT((2*M_Ballast/Nr_Floaters*(DistFloat/2)^2 +
      M_Ballast*KG_Ballast^2+
```

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Tower_Mass*(VCG_Tower^2 + 0.0625*(Tower_Height+Draft_Floaters)^2)
+
      2*CVOL_Floaters*VolMassConstr/Nr_Floaters*(DistFloat/2)^2 +
      CVOL_Floaters*VolMassConstr*(H_Floaters/2)^2 +
      Tower_Top_Mass*Tower_Height^2-
      Total_Mass*KG_Total^2)/Total_Mass)

START OF INFERENCE:

 Tz is TOPGOAL and chains to:
  Tz=f(ma, Total_Mass, Draft_Floaters, g)
  ma is SUBGOAL of Tz and chains to:
   ma=f(Nr_Floaters, D_Floaters, Rho)
   D_Floaters is SUBGOAL of ma, Tz and chains to:
    PhiMax=f(Freeb_Floaters, D_Floaters, DistFloat)
    Freeb_Floaters is SUBGOAL of D_Floaters, ma, Tz and chains to:
     Draft_Floaters=f(Freeb_Floaters)
Draft_Floaters is SUBGOAL of Freeb_Floaters, D_Floaters, ma, Tz
and chains to:
VOL_Floaters=f(Nr_Floaters, Floater_Concept, D_Floaters,
Draft_Floaters, H_Disc, D_Disc, VOL_Truces)
VOL_Floaters is SUBGOAL of Draft_Floaters, Freeb_Floaters,
D_Floaters, ma, Tz and chains to:
       VOL_Floaters=f(Total_Mass, Rho)
Total_Mass is SUBGOAL of VOL_Floaters, Draft_Floaters,
Freeb_Floaters, D_Floaters, ma, Tz and chains to:
        Total_Mass=f(Steel_weight, Tower_Top_Mass, M_Ballast)
Tower_Top_Mass is SUBGOAL of Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
         Tower_Top_Mass=f(Turbs_Floater, COST$)
COST$ is SUBGOAL of Tower_Top_Mass, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          COST$=f(REPORT$)
REPORT$ is SUBGOAL of COST$, Tower_Top_Mass, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
chains to:
           REPORT$=f(BLADOPTINPUT$, DEFINS$, DEFINE$, ENGDAT$)
BLADOPTINPUT$ is SUBGOAL of REPORT$, COST$, Tower_Top_Mass,
Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters,
ma, Tz and chains to:
BLADOPTINPUT$=f(Nr_Blades, Ch_R15, Ch_R25, Ch_R100,
Tower_Height, C_Loss_Drive, V_Loss_Drive, IntRate, Deprec_Period,
Maint_CostPercLand, Extra_Cost_Land, RatedRPM, AimPow)
Ch_R15 is SUBGOAL of BLADOPTINPUT$, REPORT$, COST$,
Tower_Top_Mass, Total_Mass, VOL_Floaters, Draft_Floaters,
Freeb_Floaters, D_Floaters, ma, Tz and chains to:
             Ch_R15=f(Rotor_Diam)
            Ch_R15 inferred
Ch_R25 is SUBGOAL of BLADOPTINPUT$, REPORT$, COST$,
Tower_Top_Mass, Total_Mass, VOL_Floaters, Draft_Floaters,
Freeb_Floaters, D_Floaters, ma, Tz and chains to:
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             Ch_R25=f(Rotor_Diam)
            Ch_R25 inferred
Ch_R100 is SUBGOAL of BLADOPTINPUT$, REPORT$, COST$,
Tower_Top_Mass, Total_Mass, VOL_Floaters, Draft_Floaters,
Freeb_Floaters, D_Floaters, ma, Tz and chains to:
             Ch_R100=f(Rotor_Diam)
            Ch_R100 inferred
RatedRPM is SUBGOAL of BLADOPTINPUT$, REPORT$, COST$,
Tower_Top_Mass, Total_Mass, VOL_Floaters, Draft_Floaters,
Freeb_Floaters, D_Floaters, ma, Tz and chains to:
             TipSpeed=f(RatedRPM, Rotor_Diam)
            RatedRPM inferred
           BLADOPTINPUT$ inferred
          REPORT$ inferred
         COST$ inferred
DB$ is SUBGOAL of Tower_Top_Mass, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          DB$=f()
         DB$ inferred
        Tower_Top_Mass inferred
M_Ballast is SUBGOAL of Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
KG_Total=f(KG_Floaters, M_Floaters, VCG_Tower, H_Floaters,
Tower_Mass, Tower_Height, Tower_Top_Mass, M_Ballast, KG_Ballast,
VOL_Truces, VolMassConstr, D_Floaters, Total_Mass)
Tower_Mass is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          Tower_Mass=f(Nr_Main_Towers, COST$, Turbs_Floater, Rotor_Diam)
         Tower_Mass inferred
VCG_Tower is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
VCG_Tower=f(Tower_F_D, Tower_F_Th, Tower_T_D, Tower_T_Th,
Tower_Height)
Tower_F_Th is SUBGOAL of VCG_Tower, M_Ballast, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
chains to:
           Tower_F_Th=f(COST$)
          Tower_F_Th inferred
Tower_T_Th is SUBGOAL of VCG_Tower, M_Ballast, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
chains to:
           Tower_T_Th=f(COST$)
          Tower_T_Th inferred
Tower_F_D is SUBGOAL of VCG_Tower, M_Ballast, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
chains to:
           Tower_F_D=f(COST$)
          Tower_F_D inferred
Tower_T_D is SUBGOAL of VCG_Tower, M_Ballast, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
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chains to:
           Tower_T_D=f(COST$)
          Tower_T_D inferred
         VCG_Tower inferred
M_Floaters is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          M_Floaters=f(CVOL_Floaters, VolMassConstr)
CVOL_Floaters is SUBGOAL of M_Floaters, M_Ballast,
Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters,
ma, Tz and chains to:
           CVOL_Floaters=f(Draft_Floaters, Freeb_Floaters, VOL_Floaters)
          CVOL_Floaters inferred
         M_Floaters inferred
KG_Floaters is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          KG_Floaters=f(H_Floaters)
         KG_Floaters inferred
H_Floaters is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          Draft_Floaters=f(H_Floaters, Freeb_Floaters)
         H_Floaters inferred
KG_Total is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          GM_Total=f(KM_Floaters, KG_Total)
GM_Total is SUBGOAL of KG_Total, M_Ballast, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
chains to:
           GZ_Max=f(GM_Total, PhiMax, BM_Floaters)
BM_Floaters is SUBGOAL of GM_Total, KG_Total, M_Ballast,
Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters,
ma, Tz and chains to:
            BM_Floaters=f(Ix, VOL_Floaters)
Ix is SUBGOAL of BM_Floaters, GM_Total, KG_Total,
M_Ballast, Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters,
D_Floaters, ma, Tz and chains to:
             Ix=f(Floater_Concept, D_Floaters, DistFloat, L_Floaters)
            Ix inferred
           BM_Floaters inferred
GZ_Max is SUBGOAL of GM_Total, KG_Total, M_Ballast,
Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters,
ma, Tz and chains to:
            StabIndex=f(GZ_Max, WindArm)
WindArm is SUBGOAL of GZ_Max, GM_Total, KG_Total,
M_Ballast, Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters,
D_Floaters, ma, Tz and chains to:
WindArm=f(Load_Fatig, H_Floaters, Tower_Height,
KB_Floaters, Total_Mass, g)
Load_Fatig is SUBGOAL of WindArm, GZ_Max, GM_Total,
KG_Total, M_Ballast, Total_Mass, VOL_Floaters, Draft_Floaters,
Freeb_Floaters, D_Floaters, ma, Tz and chains to:
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              Load_Fatig=f(Turbs_Floater, COST$)
             Load_Fatig inferred
            WindArm inferred
           GZ_Max inferred
          GM_Total inferred
KM_Floaters is SUBGOAL of KG_Total, M_Ballast, Total_Mass,
VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and
chains to:
           KM_Floaters=f(KB_Floaters, BM_Floaters)
KB_Floaters is SUBGOAL of KM_Floaters, KG_Total, M_Ballast,
Total_Mass, VOL_Floaters, Draft_Floaters, Freeb_Floaters, D_Floaters,
ma, Tz and chains to:
KB_Floaters=f(Nr_Floaters, D_Floaters, Draft_Floaters,
H_Disc, D_Disc, VOL_Truces, VOL_Floaters)
           KB_Floaters inferred
          KM_Floaters inferred
         KG_Total inferred
KG_Ballast is SUBGOAL of M_Ballast, Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
          KG_Ballast=f(M_Ballast, Rho, Nr_Floaters, D_Floaters)
         KG_Ballast inferred
        M_Ballast inferred
Steel_weight is SUBGOAL of Total_Mass, VOL_Floaters,
Draft_Floaters, Freeb_Floaters, D_Floaters, ma, Tz and chains to:
         Steel_weight=f(M_Floaters, Tower_Mass)
        Steel_weight inferred
       Total_Mass inferred
      VOL_Floaters inferred
VOL_Truces is SUBGOAL of Draft_Floaters, Freeb_Floaters,
D_Floaters, ma, Tz and chains to:
VOL_Truces=f(Nr_Floaters, D_Truces, DistFloat, D_Floaters,
Tower_F_D)
      VOL_Truces inferred
     Draft_Floaters inferred
    Freeb_Floaters inferred
   D_Floaters inferred
  ma inferred
 Tz inferred
 Tphi is TOPGOAL and chains to:
  Tphi=f(Kxx, GM_Total, g)
  Kxx is SUBGOAL of Tphi and chains to:
Kxx=f(M_Ballast, Nr_Floaters, DistFloat, KG_Ballast, Tower_Mass,
VCG_Tower, Tower_Height, Draft_Floaters, CVOL_Floaters, VolMassConstr,
H_Floaters, Tower_Top_Mass, Total_Mass, KG_Total)
  Kxx inferred
 Tphi inferred
END OF INFERENCE
```

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D_Floaters


Requested Value(s)
------------------
D_Floaters
          Outside diameter of floater topside ..........[m]:  ?
Tz        Natural period of heave ......................[s]:  ?
Tphi      Natural period of roll and pitch .............[s]:  ?

Discrete Input from Operator
----------------------------
AimPow    Target power of single turbine .............[kW]:     5,000
C_Loss_Drive
          constant loss of energy in drive train (typi .[-]:      0.03
DEFINE$   Parametric cost functions ..................[Str]: currency
DEFINS$   Engineering cost functions .................[Str]: currency
Deprec_Period
          Depreciation period, e.g. 20 years ..........[yr]:    20
D_Disc    Diameter of lower part of floater (disc) .....[m]:      0.00
D_Truces  Diameter of connection pipes between floater .[m]:      3.00
ENGDAT$   .........................................[Str]:       0
Extra_Cost_Land
          Extra cost not accounted for in land opera .[EUR]:         0
Floater_Concept
          1 <EQ> circular floater .....................[ID]:    2
H_Disc    Height of disc (lower part of buoy) ..........[m]:      0.00
IntRate   Yearly interest rate .........................[%]:    5.0
L_Floaters
          Length of floater(s) .........................[m]:      0.00
Maint_CostPercLand
          Yearly maintenance cost percentage of total  .[%]:    0.0
Nr_Blades Number of turbine blades .....................[#]:    3
Nr_Floaters
          Number of floaters per island ................[#]:    3
Nr_Main_Towers
          ..............................................[#]:    1
PhiMax    Maximum allowable heel of tower ............[deg]:   10
Rotor_Diam
          Rotor diameter ...............................[m]:     115.0
StabIndex Stability moment/wind moment at Phi_Max ......[-]:  1.000
TipSpeed  Maximum tip speed of rotor .................[m/s]:     80.00
Tower_Height
          Tower height .................................[m]:      83.0
Turbs_Floater
          Number of turbines per floater ...............[#]:    1
VolMassConstr
          Construction mass per m3 of the floater  .[t/m^3]:   0.12
V_Loss_Drive
          {\rtf1\ansi\ansicpg1252\deff0\deftab720{ .[%/100]:      0.07

Multi-case Input from Operator or Knowledge base
------------------------------------------------

No.  DistFloat
             m
--------------
1        36.00
2        38.00
3        40.00
4        42.00
5        44.00
6        46.00
```

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No.	DistFloat m
7	48.00
8	50.00
9	52.00
10	54.00
11	56.00
12	58.00
13	60.00
14	62.00
15	64.00

Input from Knowledge base

g	Gravitational accelleration	[m/s^2]:	9.81
Rho	Sea water density	[t/m^3]:	1.03

Derived Discrete Values

BLADOPTINPUT$	Input of BLADOPT.EXE GEODAT.N	[Str]:	115.0
Ch_R100	Blade chord length on 100% radius	[m]:	1.61
Ch_R15	Blade chord length on 15% radius	[m]:	6.10
Ch_R25	Blade chord length on 25% radius	[m]:	5.29
COST$	Parsed results from BLADOPT output	[Str]:	24
DB$	Database of clustered solutions	[Str]:	NullStri
Load_Fatig	Fatigue load on turbine	[kN]:	1,044
RatedRPM	Rated rotation rate of turbine	[1/min]:	13.29
REPORT$	Output DESIGN.REP of BLADOPT.EXE	[Str]:	The foll
Tower_F_D	Foot diameter of tower	[m]:	7.42
Tower_F_Th	Foot wall thickness of tower	[mm]:	42
Tower_Mass	Mass of tower	[t]:	332
Tower_Top_Mass	Mass of generator + turbine	[t]:	369.5
Tower_T_D	Top diameter of tower	[m]:	4.45
Tower_T_Th	{\rtf1\ansi\ansicpg1252\deff0\deftab720{\fo .	[mm]:	10.0
VCG_Tower	Vertical centre of gravity of tower	[m]:	31.10

Derived Multi-case Values

No.	BM_Floaters m	CVOL_Floaters m^3	DistFloat m	Draft_Floaters m	D_Floaters m
1	31.7	5,529	36.00	5.69	13.59
2	32.5	5,418	38.00	5.85	12.97
3	33.2	5,354	40.00	6.01	12.42
4	33.8	5,298	42.00	6.18	11.90
5	34.3	5,260	44.00	6.36	11.43

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No.	BM_Floaters m	CVOL_Floaters m^3	DistFloat m	Draft_Floaters m	D_Floaters m
6	34.7	5,234	46.00	6.54	11.00
7	34.9	5,252	48.00	6.72	10.60
8	35.1	5,273	50.00	6.91	10.24
9	35.2	5,302	52.00	7.10	9.90
10	35.3	5,344	54.00	7.30	9.59
11	35.3	5,395	56.00	7.49	9.30
12	35.3	5,455	58.00	7.69	9.03
13	35.3	5,524	60.00	7.89	8.79
14	35.2	5,595	62.00	8.09	8.55
15	35.2	5,665	64.00	8.30	8.34

No.	Freeb_Floaters m	GM_Total m	GZ_Max m	H_Floaters m	Ix m^4	KB_Floaters m
1	4.38	16.8	3.01	10.06	98,934	2.45
2	4.50	17.2	3.08	10.35	99,603	2.45
3	4.63	17.5	3.13	10.64	100,350	2.45
4	4.76	17.7	3.17	10.94	101,090	2.45
5	4.89	17.9	3.21	11.25	101,860	2.46
6	5.03	18.1	3.23	11.57	102,641	2.47
7	5.17	18.1	3.23	11.90	103,558	2.46
8	5.32	18.1	3.23	12.23	104,553	2.47
9	5.46	18.0	3.23	12.56	105,457	2.48
10	5.61	17.9	3.21	12.91	106,491	2.49
11	5.76	17.8	3.19	13.25	107,582	2.50
12	5.92	17.7	3.17	13.61	108,734	2.51
13	6.07	17.5	3.14	13.96	110,066	2.53
14	6.23	17.4	3.11	14.32	111,222	2.54
15	6.38	17.2	3.09	14.68	112,543	2.56

No.	KG_Ballast m	KG_Floaters m	KG_Total m	KM_Floaters m	Kxx m	ma t
1	2.06	5.03	17.27	34.1	28.70	2,018
2	2.20	5.17	17.75	35.0	29.08	1,758
3	2.36	5.32	18.12	35.6	29.40	1,541
4	2.53	5.47	18.48	36.2	29.71	1,358
5	2.72	5.63	18.80	36.7	30.01	1,203
6	2.91	5.78	19.10	37.2	30.30	1,071
7	3.15	5.95	19.29	37.3	30.55	959
8	3.39	6.11	19.49	37.6	30.81	864
9	3.66	6.28	19.66	37.7	31.07	781
10	3.95	6.45	19.81	37.7	31.33	709
11	4.25	6.63	19.96	37.8	31.59	647

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-Q-U-A-E-S-T-O-R-/Rev. 2000_1    Date: 14-03-2002    Time: 03:42:10
Licenced to: MARIN Ships-Propulsion    Knowledge base: Drijfwind

Solution Title: 115 m - D_Floaters=f(Dist_Float)
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No.	KG_Ballast m	KG_Floaters m	KG_Total m	KM_Floaters m	Kxx m	ma t
12	4.58	6.80	20.09	37.8	31.86	593
13	4.92	6.98	20.25	37.8	32.12	546
14	5.29	7.16	20.35	37.7	32.43	504
15	5.66	7.34	20.51	37.7	32.74	467

No.	M_Ballast t	M_Floaters t	Steel_weight t	Total_Mass t	Tphi s	Tz s
1	1,838	664	996	3,203	14.04	6.11
2	1,787	650	983	3,139	14.06	6.06
3	1,757	642	975	3,102	14.10	6.02
4	1,732	636	968	3,070	14.16	5.99
5	1,714	631	964	3,047	14.22	5.97
6	1,703	628	960	3,033	14.30	5.97
7	1,711	630	963	3,043	14.42	5.97
8	1,718	633	965	3,053	14.54	5.97
9	1,734	636	969	3,072	14.69	5.99
10	1,753	641	974	3,096	14.84	6.01
11	1,776	647	980	3,126	15.01	6.03
12	1,804	655	987	3,160	15.20	6.06
13	1,836	663	995	3,200	15.39	6.10
14	1,869	671	1,004	3,242	15.62	6.13
15	1,900	680	1,012	3,282	15.84	6.18

No.	VOL_Floaters m^3	VOL_Truces m^3	WindArm m
1	3,125	218	3.01
2	3,063	249	3.08
3	3,026	279	3.13
4	2,995	309	3.17
5	2,973	338	3.21
6	2,959	367	3.23
7	2,969	396	3.23
8	2,980	424	3.23
9	2,997	452	3.23
10	3,020	480	3.21
11	3,049	508	3.19
12	3,083	535	3.17
13	3,122	562	3.14
14	3,162	589	3.11
15	3,202	616	3.09

6.11 Appendix IV: DIFFRAC RESULTS

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 MAritime Research Institute Netherlands   WAGENINGEN                              drijfwind case 7B  (56.0m)

 Wave direction   45.000 Degrees.                                                  Phases related to a point in the
waterline,
 Wave amplitude    1.000 m.                                                        Above the centre of gravity.
 Centre of gravity   (   16.160 ,   -28.000 ,    -8.000)                            body no  1
```

Motion response of the structure due to the waves.

Wave-Frequency	Water Depth	Surge		Sway		Heave		Roll		Pitch		Yaw	
		X-ampl	X-phase	Y-ampl	Y-phase	Z-ampl	Z-phase	P-ampl	P-phase	Q-ampl	Q-phase	R-ampl	R-phase
rad/sec	m	m/m	degrees	m/m	degrees	m/m	degrees	degr/m	degrees	degr/m	degrees	degr/m	degrees
0.050	50.0	6.254	271.	6.179	271.	1.006	360.	0.089	274.	0.110	97.	1.289	91.
0.100	50.0	3.111	272.	3.074	272.	1.028	359.	0.186	276.	0.263	105.	0.649	91.
0.150	50.0	2.053	272.	2.031	272.	1.087	358.	0.307	279.	0.608	114.	0.438	92.
0.200	50.0	1.476	272.	1.502	273.	1.775	338.	0.494	282.	5.119	126.	0.334	93.
0.250	50.0	1.212	274.	1.176	274.	1.071	12.	0.973	285.	1.058	322.	0.274	94.
0.300	50.0	0.986	275.	1.062	276.	1.419	8.	7.904	110.	0.643	342.	0.257	96.
0.350	50.0	0.821	277.	0.813	276.	4.213	6.	0.414	117.	1.396	2.	0.214	96.
0.400	50.0	0.694	276.	0.682	277.	0.671	187.	0.057	161.	0.195	190.	0.197	97.
0.450	50.0	0.589	278.	0.576	277.	0.036	12.	0.129	279.	0.060	89.	0.187	98.
0.500	50.0	0.498	278.	0.485	278.	0.189	8.	0.228	291.	0.119	75.	0.182	99.
0.550	50.0	0.417	279.	0.402	278.	0.227	7.	0.300	299.	0.155	80.	0.181	100.
0.600	50.0	0.341	279.	0.325	278.	0.219	6.	0.351	305.	0.177	85.	0.185	101.
0.650	50.0	0.269	278.	0.251	276.	0.186	3.	0.385	312.	0.186	90.	0.192	102.
0.700	50.0	0.201	273.	0.181	271.	0.143	356.	0.400	319.	0.183	95.	0.201	104.
0.750	50.0	0.142	262.	0.122	258.	0.102	341.	0.397	327.	0.168	100.	0.212	105.
0.800	50.0	0.104	238.	0.087	228.	0.075	315.	0.380	336.	0.144	103.	0.224	106.
0.850	50.0	0.104	206.	0.095	195.	0.073	286.	0.350	346.	0.114	105.	0.234	107.
0.900	50.0	0.132	186.	0.125	179.	0.081	272.	0.310	356.	0.082	104.	0.241	107.
0.950	50.0	0.162	178.	0.155	175.	0.086	268.	0.262	6.	0.052	92.	0.243	106.
1.000	50.0	0.178	175.	0.177	176.	0.086	271.	0.210	16.	0.036	55.	0.238	104.
1.050	50.0	0.176	177.	0.186	178.	0.082	278.	0.156	27.	0.043	17.	0.225	101.
1.100	50.0	0.158	183.	0.179	181.	0.073	286.	0.107	39.	0.057	2.	0.205	98.
1.150	50.0	0.137	196.	0.153	186.	0.062	294.	0.065	52.	0.064	359.	0.183	93.
1.200	50.0	0.122	210.	0.114	193.	0.045	299.	0.031	63.	0.063	360.	0.163	87.
1.250	50.0	0.104	220.	0.071	210.	0.023	310.	0.006	55.	0.055	6.	0.149	80.
1.300	50.0	0.072	229.	0.044	249.	0.011	354.	0.013	287.	0.047	13.	0.143	71.
1.350	50.0	0.031	248.	0.044	296.	0.009	49.	0.023	298.	0.039	20.	0.140	61.
1.400	50.0	0.026	356.	0.048	321.	0.009	90.	0.028	314.	0.031	22.	0.137	51.
1.450	50.0	0.056	8.	0.039	342.	0.008	121.	0.031	327.	0.024	12.	0.128	42.
1.500	50.0	0.052	1.	0.031	18.	0.007	144.	0.028	335.	0.016	351.	0.113	35.

MAritime Research Institute Netherlands WAGENINGEN drijfwind case 7B (56.0m)

Wave direction 90.000 Degrees. Phases related to a point in the waterline,
Wave amplitude 1.000 m. Above the centre of gravity.
Centre of gravity (16.160 , -28.000 , -8.000) body no 1

Motion response of the structure due to the waves.

Wave- Frequency rad/sec	Water Depth m	Surge X-ampl m/m	Surge X-phase degrees	Sway Y-ampl m/m	Sway Y-phase degrees	Heave Z-ampl m/m	Heave Z-phase degrees	Roll P-ampl degr/m	Roll P-phase degrees	Pitch Q-ampl degr/m	Pitch Q-phase degrees	Yaw R-ampl degr/m	Yaw R-phase degrees
0.050	50.0	0.001	180.	8.740	270.	1.006	360.	0.125	271.	0.016	180.	1.808	90.
0.100	50.0	0.002	180.	4.349	270.	1.030	360.	0.263	270.	0.079	180.	0.888	90.
0.150	50.0	0.005	180.	2.875	270.	1.092	360.	0.432	270.	0.286	180.	0.573	90.
0.200	50.0	0.043	181.	2.128	270.	1.709	360.	0.691	270.	3.399	180.	0.409	90.
0.250	50.0	0.010	2.	1.668	270.	1.032	360.	1.349	270.	0.919	360.	0.304	90.
0.300	50.0	0.007	2.	1.509	270.	1.398	360.	10.803	90.	0.655	360.	0.260	90.
0.350	50.0	0.016	1.	1.157	270.	4.173	359.	0.545	90.	1.420	359.	0.174	90.
0.400	50.0	0.004	176.	0.974	270.	0.667	180.	0.034	91.	0.175	181.	0.122	90.
0.450	50.0	0.002	164.	0.827	270.	0.036	1.	0.184	270.	0.008	360.	0.074	90.
0.500	50.0	0.003	156.	0.700	270.	0.189	0.	0.318	270.	0.024	360.	0.027	91.
0.550	50.0	0.003	149.	0.587	270.	0.227	360.	0.408	270.	0.008	355.	0.020	269.
0.600	50.0	0.005	141.	0.482	270.	0.219	359.	0.464	270.	0.021	184.	0.070	270.
0.650	50.0	0.006	130.	0.381	270.	0.186	358.	0.489	271.	0.056	182.	0.123	270.
0.700	50.0	0.007	115.	0.284	270.	0.139	357.	0.483	271.	0.093	182.	0.177	270.
0.750	50.0	0.008	94.	0.191	269.	0.087	357.	0.449	271.	0.128	182.	0.232	270.
0.800	50.0	0.009	66.	0.104	267.	0.041	360.	0.390	272.	0.156	182.	0.283	269.
0.850	50.0	0.009	30.	0.027	253.	0.007	42.	0.315	273.	0.174	182.	0.327	269.
0.900	50.0	0.010	348.	0.040	102.	0.018	157.	0.231	274.	0.182	182.	0.358	268.
0.950	50.0	0.011	303.	0.087	93.	0.028	170.	0.145	274.	0.179	183.	0.374	267.
1.000	50.0	0.013	260.	0.111	88.	0.031	180.	0.066	274.	0.166	183.	0.370	266.
1.050	50.0	0.014	217.	0.108	83.	0.030	189.	0.002	112.	0.145	184.	0.345	264.
1.100	50.0	0.014	172.	0.078	79.	0.026	194.	0.051	96.	0.118	185.	0.300	263.
1.150	50.0	0.012	122.	0.032	83.	0.019	184.	0.080	97.	0.088	186.	0.242	263.
1.200	50.0	0.010	65.	0.017	224.	0.010	110.	0.091	99.	0.059	186.	0.180	263.
1.250	50.0	0.008	6.	0.055	245.	0.023	31.	0.091	101.	0.033	189.	0.121	264.
1.300	50.0	0.007	309.	0.088	256.	0.030	8.	0.083	103.	0.015	200.	0.068	263.
1.350	50.0	0.006	254.	0.125	264.	0.029	4.	0.072	103.	0.006	220.	0.022	252.
1.400	50.0	0.004	194.	0.163	264.	0.025	8.	0.059	96.	0.002	337.	0.016	103.
1.450	50.0	0.002	122.	0.177	258.	0.020	17.	0.042	79.	0.004	17.	0.035	85.
1.500	50.0	0.001	271.	0.148	251.	0.016	27.	0.025	57.	0.003	19.	0.033	78.

MAritime Research Institute Netherlands WAGENINGEN drijfwind case 7B (56.0m)

Wave direction 180.000 Degrees. Phases related to a point in the waterline,
Wave amplitude 1.000 m. Above the centre of gravity.
Centre of gravity (16.160 , -28.000 , -8.000) body no 1

Motion response of the structure due to the waves.

Wave-Frequency rad/sec	Water Depth m	Surge X-ampl m/m	Surge X-phase degrees	Sway Y-ampl m/m	Sway Y-phase degrees	Heave Z-ampl m/m	Heave Z-phase degrees	Roll P-ampl degr/m	Roll P-phase degrees	Pitch Q-ampl degr/m	Pitch Q-phase degrees	Yaw R-ampl degr/m	Yaw R-phase degrees
0.050	50.0	8.844	89.	0.006	179.	1.006	0.	0.002	359.	0.155	266.	0.002	354.
0.100	50.0	4.399	88.	0.001	177.	1.026	1.	0.002	358.	0.364	261.	0.001	350.
0.150	50.0	2.903	87.	0.001	175.	1.081	3.	0.002	357.	0.815	254.	0.000	355.
0.200	50.0	2.086	86.	0.000	149.	1.844	31.	0.003	355.	6.441	246.	0.001	53.
0.250	50.0	1.714	84.	0.000	186.	1.109	343.	0.005	355.	1.192	51.	0.000	267.
0.300	50.0	1.394	82.	0.001	353.	1.441	348.	0.038	173.	0.632	26.	0.000	218.
0.350	50.0	1.162	80.	0.001	348.	4.255	348.	0.000	191.	1.363	354.	0.000	186.
0.400	50.0	0.981	79.	0.000	169.	0.676	169.	0.002	169.	0.217	166.	0.000	317.
0.450	50.0	0.832	77.	0.000	168.	0.036	343.	0.001	167.	0.085	265.	0.000	299.
0.500	50.0	0.704	74.	0.000	167.	0.189	345.	0.001	164.	0.171	280.	0.000	291.
0.550	50.0	0.588	70.	0.000	166.	0.226	342.	0.000	161.	0.233	279.	0.000	287.
0.600	50.0	0.480	65.	0.000	164.	0.216	337.	0.000	156.	0.277	276.	0.000	284.
0.650	50.0	0.379	57.	0.000	161.	0.181	330.	0.000	149.	0.303	274.	0.000	282.
0.700	50.0	0.286	45.	0.000	155.	0.136	317.	0.000	138.	0.311	271.	0.000	281.
0.750	50.0	0.212	24.	0.000	131.	0.093	294.	0.000	122.	0.302	269.	0.000	279.
0.800	50.0	0.179	353.	0.000	26.	0.073	254.	0.000	89.	0.277	267.	0.000	278.
0.850	50.0	0.197	322.	0.000	354.	0.081	219.	0.000	54.	0.240	265.	0.000	277.
0.900	50.0	0.243	302.	0.000	342.	0.097	201.	0.000	45.	0.196	263.	0.000	275.
0.950	50.0	0.293	290.	0.000	336.	0.106	193.	0.000	41.	0.149	261.	0.000	271.
1.000	50.0	0.331	280.	0.000	332.	0.108	190.	0.000	36.	0.103	256.	0.000	267.
1.050	50.0	0.347	272.	0.000	332.	0.104	190.	0.000	29.	0.060	246.	0.000	260.
1.100	50.0	0.336	265.	0.000	331.	0.098	190.	0.000	16.	0.028	221.	0.000	227.
1.150	50.0	0.300	258.	0.000	327.	0.089	189.	0.000	354.	0.020	158.	0.000	112.
1.200	50.0	0.247	252.	0.000	320.	0.076	180.	0.000	313.	0.030	126.	0.000	103.
1.250	50.0	0.185	245.	0.000	305.	0.048	163.	0.000	145.	0.038	116.	0.000	101.
1.300	50.0	0.125	235.	0.000	277.	0.021	148.	0.000	59.	0.040	114.	0.000	99.
1.350	50.0	0.078	211.	0.000	219.	0.006	115.	0.000	19.	0.040	115.	0.000	98.
1.400	50.0	0.068	155.	0.000	161.	0.006	30.	0.000	339.	0.040	112.	0.000	95.
1.450	50.0	0.100	110.	0.000	129.	0.008	19.	0.000	295.	0.036	102.	0.000	87.
1.500	50.0	0.121	86.	0.000	104.	0.010	27.	0.000	253.	0.028	90.	0.000	258.

MAritime Research Institute Netherlands WAGENINGEN drijfwind case 7 (68.0m)

Wave direction 45.000 Degrees. Phases related to a point in the waterline,
Wave amplitude 1.000 m. Above the centre of gravity.
Centre of gravity (19.630 , -34.000 , -8.000) body no 1

Motion response of the structure due to the waves.

Wave-Frequency rad/sec	Water Depth m	Surge X-ampl m/m	Surge X-phase degrees	Sway Y-ampl m/m	Sway Y-phase degrees	Heave Z-ampl m/m	Heave Z-phase degrees	Roll P-ampl degr/m	Roll P-phase degrees	Pitch Q-ampl degr/m	Pitch Q-phase degrees	Yaw R-ampl degr/m	Yaw R-phase degrees
0.050	50.0	6.250	271.	6.117	271.	1.005	360.	0.088	274.	0.099	95.	2.301	91.
0.100	50.0	3.103	272.	3.036	272.	1.020	360.	0.184	276.	0.210	100.	1.167	91.
0.150	50.0	2.043	272.	1.998	272.	1.055	359.	0.300	279.	0.359	107.	0.798	92.
0.200	50.0	1.504	273.	1.469	273.	1.136	358.	0.468	282.	0.627	115.	0.620	93.
0.250	50.0	1.166	273.	1.142	274.	1.421	352.	0.829	286.	1.608	128.	0.518	94.
0.300	50.0	0.981	277.	0.873	273.	0.925	50.	4.871	290.	3.660	329.	0.442	94.

0.350	50.0	0.790	277.	0.770	276.	2.858	11.	0.669	116.	2.198	359.	0.429	96.
0.400	50.0	0.656	276.	0.631	276.	0.672	188.	0.114	133.	0.344	201.	0.407	97.
0.450	50.0	0.542	277.	0.517	276.	0.032	13.	0.092	281.	0.089	89.	0.399	97.
0.500	50.0	0.442	277.	0.417	276.	0.167	6.	0.201	296.	0.190	81.	0.402	98.
0.550	50.0	0.352	276.	0.325	275.	0.192	3.	0.277	304.	0.246	86.	0.415	99.
0.600	50.0	0.268	274.	0.239	272.	0.172	358.	0.327	312.	0.273	91.	0.434	101.
0.650	50.0	0.192	267.	0.161	262.	0.135	348.	0.357	319.	0.275	95.	0.459	102.
0.700	50.0	0.131	249.	0.104	237.	0.100	327.	0.365	327.	0.255	98.	0.486	103.
0.750	50.0	0.110	215.	0.099	196.	0.087	296.	0.355	336.	0.216	100.	0.512	105.
0.800	50.0	0.135	187.	0.138	172.	0.098	273.	0.328	346.	0.164	99.	0.532	106.
0.850	50.0	0.174	175.	0.182	166.	0.112	264.	0.286	356.	0.108	89.	0.543	108.
0.900	50.0	0.202	171.	0.213	165.	0.119	263.	0.234	7.	0.071	55.	0.543	108.
0.950	50.0	0.207	173.	0.226	168.	0.116	268.	0.176	19.	0.083	12.	0.530	107.
1.000	50.0	0.192	179.	0.215	171.	0.105	274.	0.120	32.	0.114	355.	0.503	103.
1.050	50.0	0.169	190.	0.181	176.	0.087	281.	0.070	46.	0.134	351.	0.465	97.
1.100	50.0	0.145	204.	0.127	184.	0.060	285.	0.027	60.	0.135	353.	0.424	88.
1.150	50.0	0.114	215.	0.070	204.	0.028	301.	0.008	260.	0.123	357.	0.392	77.
1.200	50.0	0.066	228.	0.039	263.	0.013	1.	0.032	270.	0.105	3.	0.376	66.
1.250	50.0	0.025	300.	0.051	318.	0.014	63.	0.046	285.	0.082	5.	0.373	55.
1.300	50.0	0.061	355.	0.062	344.	0.016	98.	0.051	301.	0.058	359.	0.371	47.
1.350	50.0	0.071	353.	0.061	6.	0.015	120.	0.049	316.	0.035	339.	0.358	41.
1.400	50.0	0.037	352.	0.054	25.	0.012	134.	0.039	330.	0.024	303.	0.324	34.
1.450	50.0	0.009	115.	0.033	39.	0.005	116.	0.027	349.	0.022	279.	0.272	28.
1.500	50.0	0.029	159.	0.004	151.	0.005	335.	0.019	15.	0.022	274.	0.214	19.

MAritime Research Institute Netherlands WAGENINGEN drijfwind case 7 (68.0m)

Wave direction 90.000 Degrees. Phases related to a point in the waterline,
Wave amplitude 1.000 m. Above the centre of gravity.
Centre of gravity (19.630 , -34.000 , -8.000) body no 1

Motion response of the structure due to the waves.

Wave-Frequency	Water Depth	Surge X-ampl	Surge X-phase	Sway Y-ampl	Sway Y-phase	Heave Z-ampl	Heave Z-phase	Roll P-ampl	Roll P-phase	Pitch Q-ampl	Pitch Q-phase	Yaw R-ampl	Yaw R-phase
rad/sec	m	m/m	degrees	m/m	degrees	m/m	degrees	degr/m	degrees	degr/m	degrees	degr/m	degrees
0.050	50.0	0.001	181.	8.653	270.	1.005	360.	0.125	270.	0.011	180.	3.205	90.
0.100	50.0	0.001	180.	4.299	270.	1.022	360.	0.259	270.	0.047	180.	1.553	90.
0.150	50.0	0.002	180.	2.834	270.	1.060	360.	0.421	270.	0.127	180.	0.979	90.
0.200	50.0	0.005	181.	2.090	270.	1.148	360.	0.653	270.	0.323	180.	0.673	90.
0.250	50.0	0.015	182.	1.630	270.	1.450	360.	1.147	270.	1.162	180.	0.470	90.
0.300	50.0	0.042	3.	1.254	270.	0.485	360.	6.631	270.	3.517	0.	0.295	90.
0.350	50.0	0.027	3.	1.113	270.	2.734	359.	0.883	90.	2.260	359.	0.204	90.
0.400	50.0	0.005	175.	0.922	270.	0.659	180.	0.127	90.	0.272	180.	0.088	90.
0.450	50.0	0.002	153.	0.767	270.	0.031	1.	0.134	270.	0.007	358.	0.021	268.
0.500	50.0	0.003	144.	0.632	270.	0.167	360.	0.277	270.	0.001	319.	0.129	270.
0.550	50.0	0.004	138.	0.510	270.	0.192	359.	0.364	270.	0.047	182.	0.242	270.
0.600	50.0	0.005	129.	0.395	270.	0.172	359.	0.411	270.	0.107	181.	0.358	270.
0.650	50.0	0.006	115.	0.286	270.	0.130	358.	0.421	271.	0.170	181.	0.477	270.
0.700	50.0	0.006	93.	0.182	269.	0.079	358.	0.396	271.	0.230	181.	0.592	271.
0.750	50.0	0.006	59.	0.087	267.	0.031	4.	0.341	271.	0.277	181.	0.693	271.
0.800	50.0	0.005	4.	0.007	221.	0.008	133.	0.264	272.	0.308	182.	0.773	272.
0.850	50.0	0.007	302.	0.059	93.	0.028	169.	0.175	273.	0.317	182.	0.822	273.
0.900	50.0	0.010	255.	0.094	88.	0.037	179.	0.084	274.	0.306	182.	0.835	274.
0.950	50.0	0.013	214.	0.097	84.	0.037	187.	0.003	315.	0.274	183.	0.805	274.
1.000	50.0	0.013	170.	0.068	82.	0.032	191.	0.062	93.	0.227	183.	0.729	275.
1.050	50.0	0.011	117.	0.017	90.	0.019	178.	0.101	95.	0.171	184.	0.607	274.
1.100	50.0	0.009	52.	0.041	249.	0.014	63.	0.117	97.	0.114	185.	0.452	273.
1.150	50.0	0.008	344.	0.092	257.	0.039	17.	0.114	100.	0.062	188.	0.287	273.
1.200	50.0	0.008	283.	0.142	264.	0.049	4.	0.098	101.	0.027	196.	0.136	271.
1.250	50.0	0.006	223.	0.194	267.	0.047	3.	0.074	100.	0.005	219.	0.020	237.
1.300	50.0	0.003	156.	0.228	263.	0.041	9.	0.044	89.	0.007	9.	0.064	106.
1.350	50.0	0.000	321.	0.211	257.	0.034	18.	0.015	57.	0.009	15.	0.084	99.
1.400	50.0	0.005	210.	0.157	256.	0.028	24.	0.011	319.	0.004	27.	0.047	99.
1.450	50.0	0.009	145.	0.106	261.	0.020	16.	0.015	300.	0.004	190.	0.029	258.
1.500	50.0	0.012	81.	0.061	265.	0.006	6.	0.016	302.	0.010	199.	0.118	266.

MAritime Research Institute Netherlands WAGENINGEN drijfwind case 7 (68.0m)

Wave direction 180.000 Degrees. Phases related to a point in the waterline,
Wave amplitude 1.000 m. Above the centre of gravity.
Centre of gravity (19.630 , -34.000 , -8.000) body no 1

Motion response of the structure due to the waves.

Wave-Frequency rad/sec	Water Depth m	Surge X-ampl m/m	Surge X-phase degrees	Sway Y-ampl m/m	Sway Y-phase degrees	Heave Z-ampl m/m	Heave Z-phase degrees	Roll P-ampl degr/m	Roll P-phase degrees	Pitch Q-ampl degr/m	Pitch Q-phase degrees	Yaw R-ampl degr/m	Yaw R-phase degrees
0.050	50.0	8.839	89.	0.006	179.	1.004	0.	0.001	359.	0.139	267.	0.004	350.
0.100	50.0	4.388	88.	0.001	177.	1.018	0.	0.001	358.	0.294	265.	0.001	343.
0.150	50.0	2.890	87.	0.001	175.	1.050	1.	0.001	357.	0.495	261.	0.000	340.
0.200	50.0	2.127	85.	0.000	170.	1.125	3.	0.002	355.	0.835	256.	0.000	353.
0.250	50.0	1.648	84.	0.000	115.	1.391	11.	0.002	353.	1.983	246.	0.000	36.
0.300	50.0	1.390	81.	0.000	227.	1.250	305.	0.014	357.	3.831	45.	0.001	237.
0.350	50.0	1.119	79.	0.001	340.	2.994	342.	0.001	186.	2.107	359.	0.001	192.
0.400	50.0	0.926	79.	0.000	168.	0.687	167.	0.001	168.	0.420	152.	0.001	312.
0.450	50.0	0.765	75.	0.000	170.	0.032	338.	0.001	166.	0.125	264.	0.000	296.
0.500	50.0	0.625	71.	0.000	171.	0.167	342.	0.000	163.	0.285	279.	0.000	291.
0.550	50.0	0.498	66.	0.000	173.	0.188	339.	0.000	158.	0.385	278.	0.000	289.
0.600	50.0	0.381	57.	0.000	174.	0.164	332.	0.000	150.	0.445	276.	0.000	288.
0.650	50.0	0.280	42.	0.000	176.	0.121	317.	0.000	137.	0.470	275.	0.000	288.
0.700	50.0	0.213	15.	0.000	313.	0.083	285.	0.000	110.	0.462	273.	0.000	289.
0.750	50.0	0.208	341.	0.000	345.	0.082	240.	0.000	67.	0.424	272.	0.000	290.
0.800	50.0	0.257	315.	0.000	343.	0.109	213.	0.000	43.	0.361	271.	0.000	291.
0.850	50.0	0.322	301.	0.000	341.	0.133	202.	0.000	38.	0.282	269.	0.000	292.
0.900	50.0	0.376	291.	0.000	341.	0.145	198.	0.000	36.	0.195	266.	0.000	292.
0.950	50.0	0.404	284.	0.000	344.	0.147	197.	0.000	31.	0.110	257.	0.000	292.
1.000	50.0	0.399	277.	0.000	347.	0.141	197.	0.000	20.	0.043	224.	0.000	285.
1.050	50.0	0.359	271.	0.000	347.	0.129	195.	0.000	0.	0.046	141.	0.000	129.
1.100	50.0	0.292	265.	0.000	342.	0.103	187.	0.000	327.	0.078	121.	0.000	125.
1.150	50.0	0.210	257.	0.000	329.	0.060	173.	0.000	92.	0.095	117.	0.000	125.
1.200	50.0	0.132	242.	0.000	275.	0.022	158.	0.000	56.	0.098	118.	0.000	125.
1.250	50.0	0.085	197.	0.000	173.	0.007	76.	0.000	14.	0.094	119.	0.000	125.
1.300	50.0	0.115	141.	0.000	153.	0.015	34.	0.000	323.	0.081	116.	0.000	122.
1.350	50.0	0.159	113.	0.000	142.	0.020	38.	0.000	275.	0.057	110.	0.000	124.
1.400	50.0	0.170	100.	0.000	130.	0.024	47.	0.000	229.	0.034	103.	0.000	281.
1.450	50.0	0.156	94.	0.000	121.	0.027	42.	0.000	158.	0.020	85.	0.000	290.
1.500	50.0	0.125	90.	0.000	113.	0.017	22.	0.000	19.	0.014	46.	0.000	292.

7 Analysis of Tri-floater

Contents

7.1 Introduction

TNO and Marin has started a study into the feasibility of a floating wind turbine. The project was sponsored by Novem. ECN, TU-Delft and Lagerwey were invited by TNO and Marin to join the consortium.
Marine Structure Consultants (MSC) bv has been ordered by the consortium to prepare a concept design for a floating support for the wind converter.
This report presents one conceptual design for a floating wind converter and briefly treats the stability, motions, structural design and mooring.
The following items might be equally important but are not within the scope of this study:
flexible electrical cable between the wind converter and the seafloor
electric grid within the wind park and to shore
maintenance

7.1.1 Revision A

This revision includes the comments of TNO. A textual correction has been made in the introduction. A cost price estimate for construction in Asia has been added.
The General Arrangement plan has been added as appendix C.

7.2 Concept design input and assumptions

The concepts will be based on the following metocean data and information of the wind converter.

7.2.1 *metocean data*

The water depth for the concept floater is 50 m.
The metocean data has been based on the Dutch blocks K2 and G16 (water depth approx. 40 m):

condition		survival	maximum operational
return period	years	100	1/12 year
significant wave height	m	10	5.4
zero-up crossing period	s	10.2	7.5
range	s	8 - 12	6.5 – 8.5
wind velocity (1 minute sustained)	m/sec	41	25
current velocity	m/sec	1.05	0.57

The maximum operational sea state corresponds with Beaufort 8 sea state.

7.2.2 *wind convertor*

The wind converter has the following main particulars:

Power output	5 MW
Rotor diameter	115 m
Turbine location	83 m above waterline
Tower base diameter	approx. 7.5 m
Tower top diameter	approx. 4.5 m
Mass of tower	332 t
Length of tower	65 m
VCG of tower	31.1 m above base
Mass of turbine & rotor	370 t
Allowable heel[1]	10 degrees (static + dynamic)
Allowable lateral acceleration[2]	3 m/sec^2 at base of tower
	5 m/sec^2 at turbine
Thrust in operational condition	1 MN at turbine
Drag in survival condition	400 kN at 50 m above base
Ultimate moment for structural design	200 MNm at base of tower

[1] Given by Lagerwey the Windmaster
[2] Given by TU Delft

7.2.3 *rules and regulations*

A floating support for a wind converter is unprecedented (to our knowledge). There are no rules, regulations or guidelines for this type of offshore structure.

For this design study it has been decided to follow the rules and regulations for mobile offshore units (IMO-MODU, ABS-MOU).

7.2.4 coordinate system

The coordinate system that has been used in the concept design is the following right-handed system, fit for a triangular shape:

direction	*origin*	*positive direction*
perpendicular to a triangle side	centre of triangle	to (forward) column
parallel to a triangle side	centre of triangle	from starboard to portside column
vertical	keel	upwards

7.3 Conceptual design

The conceptual design is shown in the artist's impression of figure 3.1.
The GA plan is added as appendix C.
The construction is triangular with a central position of the windturbine. The buoyancy is given by the columns. The bracing system interconnects the columns and carries the windturbine.
The lower part of the column includes a water ballast tank. At the bottom of each column, a wide circular flat plate has been projected. This plate is favourable for the motions as it gives added mass and damping. Each column has two mooring lines.
The following design aspects have been considered. They are tuned to each other in a iterative design process:
main dimensions
structural design and mass
stability
motions
mooring

7.3.1 main dimensions

Distance between column centres	68 m
Column diameter	8 m
Column height	24 m
Column draft	12 m
Footplate diameter	18 m
Displacement (incl mooring and windturbine)	2480 t
Steel weight (without windturbine)	1150 t

7.4 Structural design

The structural design of the TRI-SYM floater concepts is presented by description of the main structural elements. The floater concept is a fully welded steel structure, using steel with a yield stress of 355 MPa. This steel quality is commonly used in the offshore industry.

7.4.1 Column with bottom plate

The structural design of the column is based on local scantling calculations, based on external pressure on the shell. The column structure is a spar-type structure, which is a cylindrical shell with vertical plate stiffeners and horizontal ring webs. The plating thickness and stiffener properties vary over the height of the column.
Local scantlings are:

plating thickness	8 to 10 mm
stiffener spacing	approx. 500 mm
stiffener properties	HP 140 x 7 to HP 200 x 10 (Holland profile)
ring web spacing	approx 2400 mm
ring web properties	T 1000 x 12 + FB 250 x 20 at the bottom
	T 700 x 10 + FB 150 x 15 at the top

The ring webs transfer the external pressure loading by axial/ membrane action.
The internal subdivision of the columns is related to the damaged stability of the column. It has been decided to use a watertight double shell structure instead of watertight decks at various levels to comply with damaged stability requirements. The double shell structure can be lighter as the external shell.
The lower part of the column is separated from the upper part by a watertight tank deck to fit a water ballast tank.
Typical specific column weights are:

external shell and tank deck	140 kg/m^2
internal shell	90 kg/m^2

The bottom plate of the column and the foot plate of the column, acting to have added mass and dampening effect, has been designed for a pressure of approx. 20 mwc. Plating thickness is 10 mm. The plate stiffeners run in tangential direction (HP 140 x 7) and are supported by 24 radial brackets. The specific weight of this plate is 170 kg/m^2.

7.4.2 Bracing system

The bracing system connects the columns and supports the wind converter.
At the lower ring level, three braces of OD 1500 mm x 20 mm connect the columns. These braces are capable of transferring the internal wave loading and the mooring line forces between the columns.
The spans of these three braces are broken by a triangular span breaker system (OD 1000 x 15).
The span of the lower ring braces is also broken by the vertical side span breakers (OD 1000 x 15). These pipes are connected to the crossing of the wind turbine support braces and the upper deck.

7.4.3 Wind convertor support structure

A vertical column supports the wind converter. This column has been designed to an ultimate tower bending moment at the base of 200 MNm, a shear load of 15 MN and a vertical load of 10 MN. The dimensions of this column are OD 8 m and 30 mm wall thickness.

The column is connected to three diagonal braces that transfer the load directly into the columns. Horizontal loads at the top of the braces and at the upper deck level take the moment at the base.

Each diagonal brace is designed to transfer a compressive load of 20 MN without overall buckling. This load is sufficient to cope with the ultimate moment at the base of the tower (14 MN in a brace) or with the full submersion of a column (10 MN in a brace).

The upper deck structure is designed to transfer the horizontal component of the moment (15 MN) to the columns as axial load. It will also be able to cope with a wave loading of 3 MN on the column, which acts perpendicular to its long axis.

The upper deck structure is a stiffened deck structure with stiffeners running in the direction of the nearest column. Heavy side stiffeners will cope with the transverse wave loading. Web frames support the stiffeners.

The deck plate is 10 to 12 mm; stiffeners are HP 120 x 7. The specific weight of the deck is 160 kg/m^2.

The side stiffening of the deck plate is a heavy girder T 1200 x 50 + FB 500 x 50 at the locations with maximum bending moment. The mean specific weight of all side stiffening is 400 kg/m.

7.5 Mass breakdown

The mass breakdown and vertical position of the centre of gravity is presented in the following table:

item	*mass [t]*	*VCG [m above keel]*
bottom plates	3 x 34	0.0
columns	3 x 125	11.0
mooring reinforcement	50	1.0
lower ring braces	154	2.0
lower span breakers	39	2.0
side span breakers	70	12.0
upper hull deck	154	24.0
wind converter support braces	124	18.5
wind converter support column	80	30.5
steel weight	**1148**	**12.0**
wind converter (60 m height)	670	78.4
paint	25	12.0
cathodic protection	25	6.0
miscellaneous	50	12.0
ballast	561	1.9
total	**2479**	**27.6**

The lateral position of the centre of gravity is located at the centre of the triangle. The radii of inertia are 40 m around longitudinal and transverse axis and 29 m around vertical axis.

7.6 Stability

Intact and damaged stability of the floater concept have been verified to comply with ABS and IMO rules for Mobile Offshore Units (MOU).
A stability model has been prepared for MSC stability program DAMAST. This program is based on integrating the hydrostatic pressures on the surfaces of a model in an iterative process. The model is set up as a collection of volumes or compartments.
A plot of the model of the TRI-SYM floater concept is presented in figure 6.1. The hydrostatic particulars are presented in appendix A. The main hydrostatic particulars are:

draught T	m	12.0
displacement Δ	t	2479
longitudinal position of centre of buoyancy LCB	m	0.0
transverse position of centre of buoyancy TCB	m	0.0
vertical position of centre of buoyancy VCB	m	5.3
distance between keel and metacenter KM	m	55.7

7.6.1 intact stability

The distance between the centre of gravity and the metacenter height is 28.1 m. The intact stability arms for this floater are presented in figure 6.2. The stability arms increase to the point where one column fully submerges at about 17 degrees.
In an operational condition the heeling wind moment will be approx 100 MNm at keel level (rotating point where the mooring lines are connected). The wind arm will be approx. 4.1 m. The intersection between the stability arm and the wind arm will be at approx 8.3 degrees. This will be the static heel during operations at a maximum wind speed of 25 m/sec. In a survival storm the wind will be 41 m/sec. The turbine will be stopped and the static heel will be less.
The stability in this condition complies with the regulations of IMO-MODU. The maximum allowable vertical centre of gravity AVCG for this conservative operational condition is 28.5 m, which gives approx 1 m margin to the actual estimated VCG.

7.6.2 damaged stability

The damaged stability is strongly related to the compartments inside the floater and the damages that are to be applied according the regulations. For a semi-submersible structure the following damages are to be applied:
one compartment damage for compartments adjacent to the sea
waterline damage between –3 to 5 m from waterline over a height of 3 m and a penetration of 1.5 m

The regulatory wind velocity in this condition is 50 knots. The total wind force on floater and wind converter is estimated as follows:

	lateral area [m^2]	*wind force [kN]*	*level above keel [m]*
floater above waterline	420	180	7
wind converter tower	180	110	60
wind converter rotor	-	110 (est)	97
total		**400**	**46**

The wind arm in this condition is approx. 0.75 m.
Damaged stability calculations have been performed for two conditions:
damaged ballast tank (adjacent to the sea) with 200 m^3 volume
damaged ring compartment (waterline damage) with 240 m^3 volume

The heeling angle after damage is about 10 degrees (see figure 6.3) and 12 degrees including the wind. The IMO and ABS damaged stability rules are equivalent and result in allowable VCG value of 35 m (the actual vertical centre of gravity is 27.6 m).

The current subdivision with a ballast tank of 4 m height and a ring tank between 4 and 18 m above base with 1.5 m depth complies with the rules. Other subdivisions containing only watertight decks can be made and will also be feasible.

7.7 Motions

The pitch or roll motions are the dominant motions for this type of floater because these motions cause the largest dynamic loads on the wind converter.
The motions of the floater have been calculated using the 3D diffraction analysis program MATTHEW and the MSC motion analysis program CALMOT.
The viscous effect on the damper plate and the columns has been included by adding Morrison elements.
The 3D diffraction model of the floater has been presented in figure 7.1. The bottom/damper plate of the column has been modelled with a height of 1 m although the structural concept is a plate. This has been done to avoid numerical instability of the model. The added buoyancy has been compensated for in the mass distribution.
The motions are expressed in Response Amplitude Operators (RAOs). These RAOs are calculated for a wave frequency from 0.1 to 2.0 radian/second for the wave directions 0, 30, 45, 60, 90 degrees.
The RAOs are multiplied with a Pierson-Moskowitz spectrum to derive the spectral responses in irregular waves (for H_s =2.0 m). The extreme motions are found by multiplying the spectral responses with 1.86 (for a 3-hours maximum).

7.7.1 Motion behavior

The displacement, position of center of gravity and the radii of gyration are presented below:

displacement	3240 t	(= 2480 + 760 t water in dampener)
LCG	0.0 m	
TCG	0.0 m	
VCG	21.6 m	

i_{xx}	40 m
i_{yy}	40 m
i_{zz}	35 m

The RAOs of the motions are presented in figure 7.2 through 7.4 and appendix B.
The damping is based on a survival sea state with a significant wave height H_s of 10.0 m.
The natural periods of the motions are:

motion	*natural period [s]*
heave	16.5
roll	25.9
pitch	25.9

The natural periods of pitch and roll are high so it may be expected that the roll and pitch motion of the floater is moderate or low for the dominant wave periods.
Figures 7.5 and 7.6 present the significant roll and pitch motion for a significant wave height of 10 m and a wave period between 8 and 12 seconds (survival storm condition). Figures 7.7 and 7.8 present the significant roll and pitch motion for a significant wave height of 5.4 m and a wave period between 6 and 9 seconds (operational storm condition).
The extreme amplitudes for heave, roll and pitch motion are listed in the following table:

motion		*operational*	*survival*
heave	m	2.4	9.0
roll	deg	1.4	3.1
pitch	deg	1.5	3.9

The extreme dynamic heel angle in operational condition is 1.5 degrees. This value is to be added to the static heel angle of 8.3 degrees. The extreme combined heeling angle will be less than 10 degrees.
The lateral and vertical accelerations at various locations have been calculated from the motions. The accelerations include the effect of the static roll or pitch angle.
The extreme accelerations in a survival storm condition are:

location	*level above waterline [m]*	*lateral acceleration [g]*	*vertical acceleration [g]*
base of tower	25	0.18	0.12
wind turbine	85	0.22	0.12

Accelerations at the turbine and the base of the tower are acceptable. They are much lower than the maximum allowed accelerations as given in section 7.2.2.
The extreme relative vertical motion of the upper deck of the column to the waterline has been calculated to be 12.3 m. This is slightly above the freeboard of the column (12 m). The incidental occurrence of green water at the column decks is considered acceptable.

7.7.2 Internal structural loading due to waves

The internal structural loading due to motions and waves has been calculated by MSC program DYNLOAD.
In this program the wave loads and motions are combined with the mass distribution of the floater. Every local mass will result in a force. By separation of a part of the floater structure and summation of all wave and inertia loads in that separation internal forces can be calculated.
The internal forces on the forward column have been calculated as an RAO function. This RAO has been multiplied with the Pierson-Moskowitz spectrum to achieve significant forces for a wave period between 3 and 20 seconds. This function has been multiplied with a wave steepness relation for the North Sea (between 1/7 and 1/10 wave steepness), which is cut off at the maximum wave height in the 50 years storm condition (18.6 m).

The extreme internal forces on the columns are:

perpendicular to a triangle side	8.2 MN
parallel to the triangle side	4.4 MN
vertical	3.1 MN

These forces are to be transferred by the bracing system and upper deck structure. The structure has been designed for larger loads.

7.8 Mooring

The floater is kept on site with a mooring system. A conventional hybrid mooring system has been examined.

The forces on the floater and the mooring system are caused by wind, waves and current. Furthermore, first and second order motions are imposed to the floater.

The loads that act on the floater are as follows:

force [kN]	*operational*	*survival*
current on columns and braces	60	220
wind force on tower	70	300
wind force on columns and braces	100	430
wind force on rotor	0	100
operational load wind converter	1000	0
drift force	0	20
total	**1230**	**1070**

The first and second order wave motion for a linearized system is 2.5 m in operational condition and 8 m in survival condition.

7.8.1 conventional mooring system

The conventional mooring system is a spreaded hybrid six point mooring system. Two chain-cable lines are connected to each column (in line with the lower ring braces).
The mooring system has the following particulars:
- six line spreaded mooring
- 225 m stud less chain 150 mm K3 and 225 m high grade cable 160 mm
- pretension 300 kN per line
- suction anchors at 400 m from the floater (for a full field of floating wind converters three anchors per floater are needed)

The total weight of the chain is 615 t and the cable 135 t for each floater. A lighter conventional system is not feasible on this shallow water depth of 50 m.
The vertical load on the floater is approx 160 t. This is to be subtracted from the water ballast.
Mooring calculations have been performed with MSC catenary program TCAT. The model is presented in figure 8.1. Main results are presented in the following table:

	operational	*survival*
X-direction		
displacement due to force [m]	9.8	9.1
maximum line load [kN]	1480	4400
safety factor [-]	10.8	3.7
in line(s)	2 and 4	2 and 4
angle at anchor [deg]	0	0
Y-direction		
displacement due to force [m]	10.1	9.4
maximum line load [kN]	1930	7100
safety factor [-]	8.3	2.3
in line(s)	1	1
angle at anchor [deg]	0	2.1

The safety factor is above the maximum allowable safety factor of 1.8.
A one line damaged condition has been verified by breaking the maximum loaded line for the survival condition only. The results are as follows:

	X-direction	*Y-direction*
broken line	4	1
maximum line load [kN]	9040	4120
safety factor [-]	1.8	3.9
in line(s)	2	2

In these damaged condition some of the lines are slack but the line safety factors are well above the allowable factor of 1.2.
The margin between the safety factor of 2.25 and 1.8 gives opportunity to reduce the weight of the system. It will probably feasible to design a mooring system with a chain weight of 500 t and a similar cable weight of 135 t (150 mm HG cable).
The suction anchor has to be designed for a line load equal to the braking load of the cable (14 MN).
The diameter of the chain and the steel wire cable are close to the maximum that can be produced.

7.9 Cost estimate

The cost estimate is indicative only since the technical design is not yet finished. A further development of the mooring system might result in a considerable cost reduction of that item.
The cost estimate for the fabrication and installation of the TRI-SYM floater concept is presented in the following table (the price is based on construction in Western Europe):

<table>
<tr><th>item</th><th>mass [t]</th><th>specific cost
(1000 EURO/ton)</th><th>Cost
(million EURO)</th></tr>
<tr><td>columns</td><td>477</td><td>2.5</td><td>1,192</td></tr>
<tr><td>braces</td><td>387</td><td>3.2</td><td>1,238</td></tr>
<tr><td>upper hull deck</td><td>154</td><td>3.0</td><td>0,462</td></tr>
<tr><td>support column</td><td>80</td><td>3.5</td><td>0,280</td></tr>
<tr><td>mooring reinforcement</td><td>50</td><td>3.0</td><td>0,150</td></tr>
<tr><td>paint</td><td>25</td><td>25</td><td>0,625</td></tr>
<tr><td>cathodic protection</td><td>25</td><td>10</td><td>0,250</td></tr>
<tr><td>miscellaneous</td><td>50</td><td>4</td><td>0,200</td></tr>
<tr><td>installation of windturbine</td><td>-</td><td>-</td><td>0,100</td></tr>
<tr><td>subtotal</td><td></td><td></td><td>4.5</td></tr>
<tr><td>mooring chain (6)</td><td>500</td><td>2</td><td>1,000</td></tr>
<tr><td>mooring wire (6)</td><td>135</td><td>2</td><td>0,270</td></tr>
<tr><td>suction anchors (3)</td><td>200</td><td>3</td><td>0,600</td></tr>
<tr><td>installation of suction anchors</td><td>-</td><td>-</td><td rowspan="4">0,600</td></tr>
<tr><td>installation of mooring lines</td><td>-</td><td>-</td></tr>
<tr><td>tow to site</td><td>-</td><td>-</td></tr>
<tr><td>connection to mooring system</td><td>-</td><td>-</td></tr>
<tr><td>total</td><td></td><td></td><td>7</td></tr>
</table>

The cost for construction in Asia has been estimated as follows.

The finished floater is very spacious. In order to save on transportation cost, the unit will be transported in parts and assembled on a North Sea shipyard or offshore base.

<table>
<tr><th>item</th><th>mass [t]</th><th>specific cost
(1000 EURO/ton)</th><th>Cost
(million EURO)</th></tr>
<tr><td>columns</td><td>477</td><td>1.3</td><td>0,620</td></tr>
<tr><td>braces</td><td>387</td><td>1.9</td><td>0,735</td></tr>
<tr><td>upper hull deck</td><td>154</td><td>1.5</td><td>0,230</td></tr>
<tr><td>support column</td><td>80</td><td>1.7</td><td>0,135</td></tr>
<tr><td>mooring reinforcement</td><td>50</td><td>1.5</td><td>0,075</td></tr>
<tr><td>paint</td><td>25</td><td>20</td><td>0,500</td></tr>
<tr><td>cathodic protection</td><td>25</td><td>8</td><td>0,200</td></tr>
<tr><td>miscellaneous</td><td>50</td><td>3</td><td>0,150</td></tr>
<tr><td>subtotal</td><td></td><td></td><td>2,645</td></tr>
<tr><td>transportation</td><td></td><td>0.2</td><td>0,250</td></tr>
<tr><td>assembly of floater</td><td></td><td>0.4</td><td>0,500</td></tr>
<tr><td>installation of windturbine</td><td>-</td><td>-</td><td>0,100</td></tr>
<tr><td>subtotal</td><td></td><td></td><td>3,500</td></tr>
<tr><td>mooring chain (6)</td><td>500</td><td>2</td><td>1,000</td></tr>
<tr><td>mooring wire (6)</td><td>135</td><td>2</td><td>0,270</td></tr>
<tr><td>suction anchors (3)</td><td>200</td><td>3</td><td>0,600</td></tr>
<tr><td>installation of suction anchors</td><td>-</td><td>-</td><td rowspan="4">0,600</td></tr>
<tr><td>installation of mooring lines</td><td>-</td><td>-</td></tr>
<tr><td>tow to site</td><td>-</td><td>-</td></tr>
<tr><td>connection to mooring system</td><td>-</td><td>-</td></tr>
<tr><td>total</td><td></td><td></td><td>6,0</td></tr>
</table>

Due to additional cost of transportation and assembly in Europe the total cost advantage is limited to 1 million EURO per unit.

If a series of one hundred floating windturbines will be built, a price reduction will be possible:
- by design effort 10-20%
- by series-effect during production 10-20%

Thus it might be possible to arrive at a total price between 4 and 5 million EURO per unit.

7.10 Conclusions and recommendations

The technical design of a floating windturbine appears to be feasible in terms of strength, stability and motions. The concept of the floater is close to the concepts as used in the offshore industry; thus the technical risk is low.

The mooring system with heavy chain and wire is also traditional. The system is however relatively heavy and thus expensive. It might be attractive to develop a new concept for the specific conditions of 50 m water depth.

The investment cost is estimated at approx 5 million EURO per unit. This cost is excluding the electrical system and the maintenance over the life time.

A concept of the flexible connection between the floater and the seafloor is not yet available.

Figure 3.1.: TRI-SYM floater concept.

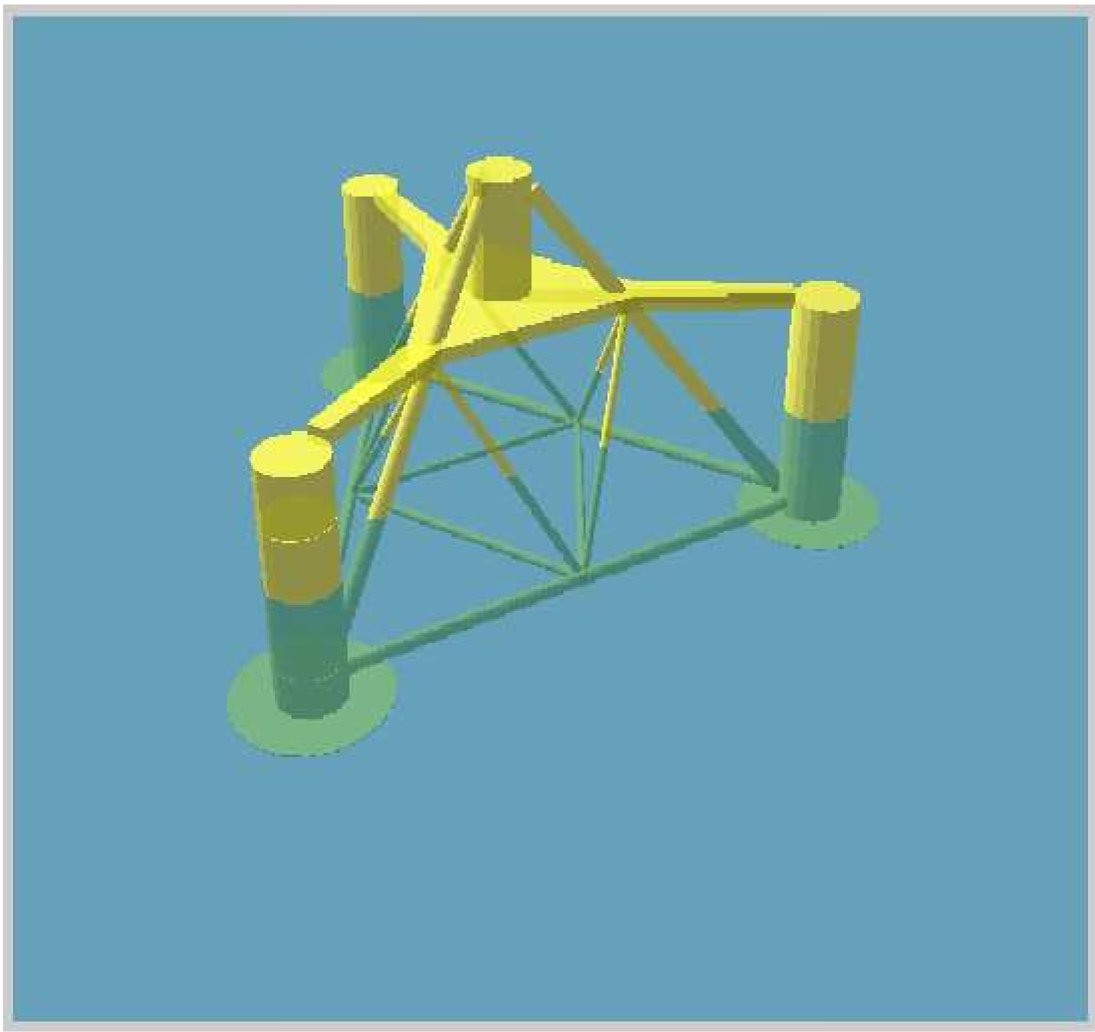


Figure 6.1.: Hydrostatic model.

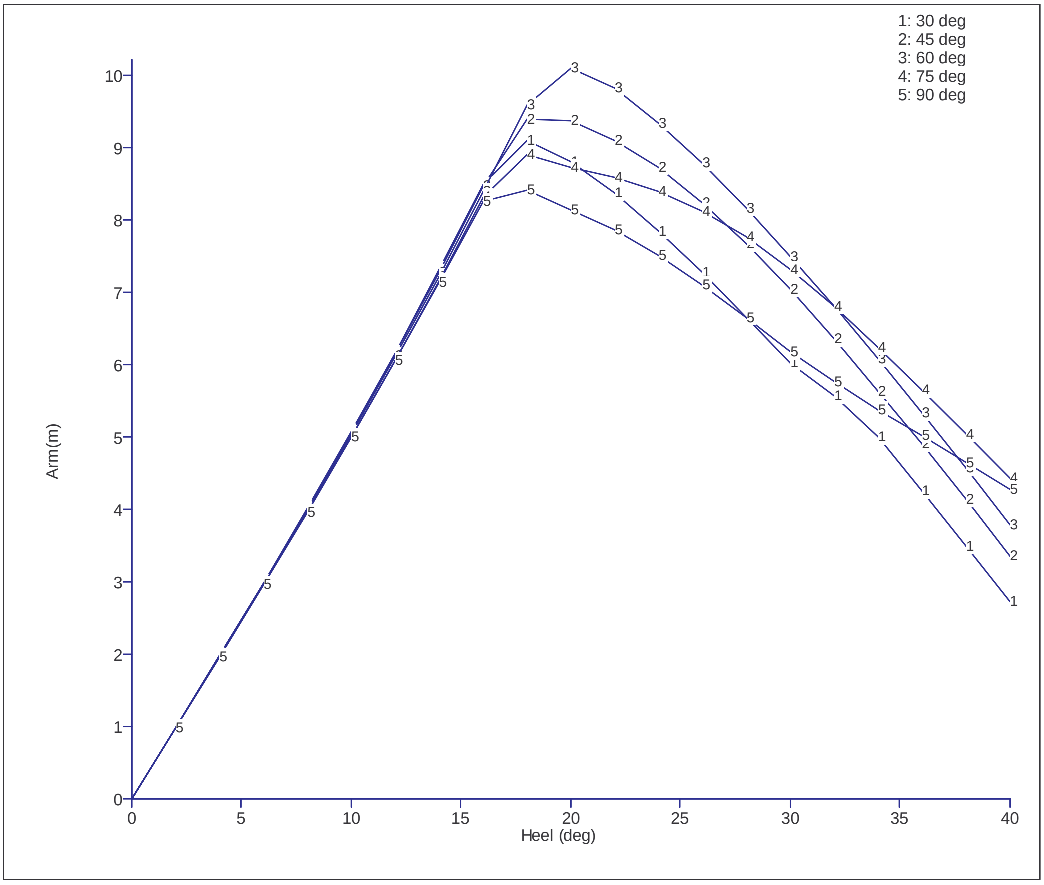


Figure 6.2.: Stability arms.

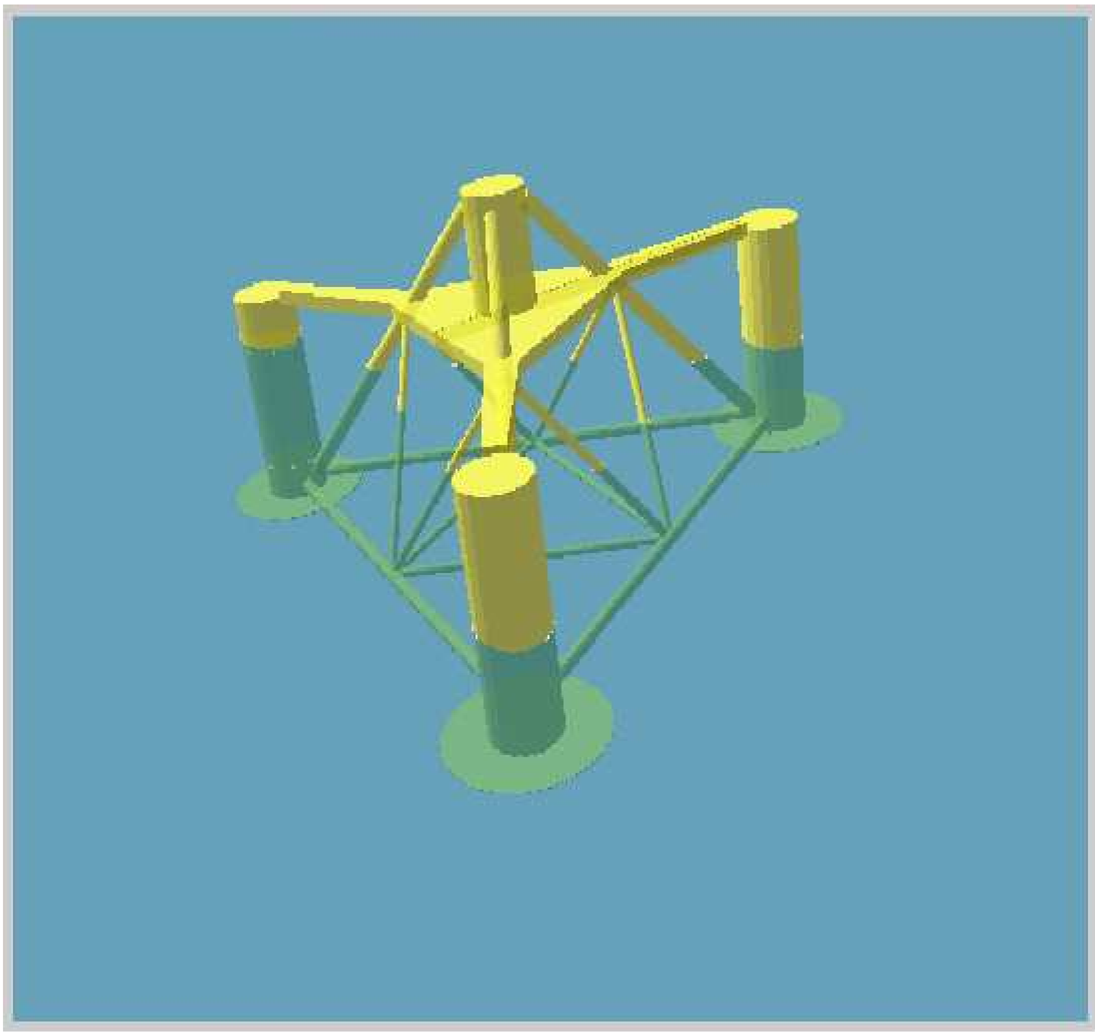


Figure 6.3.: Damaged condition.

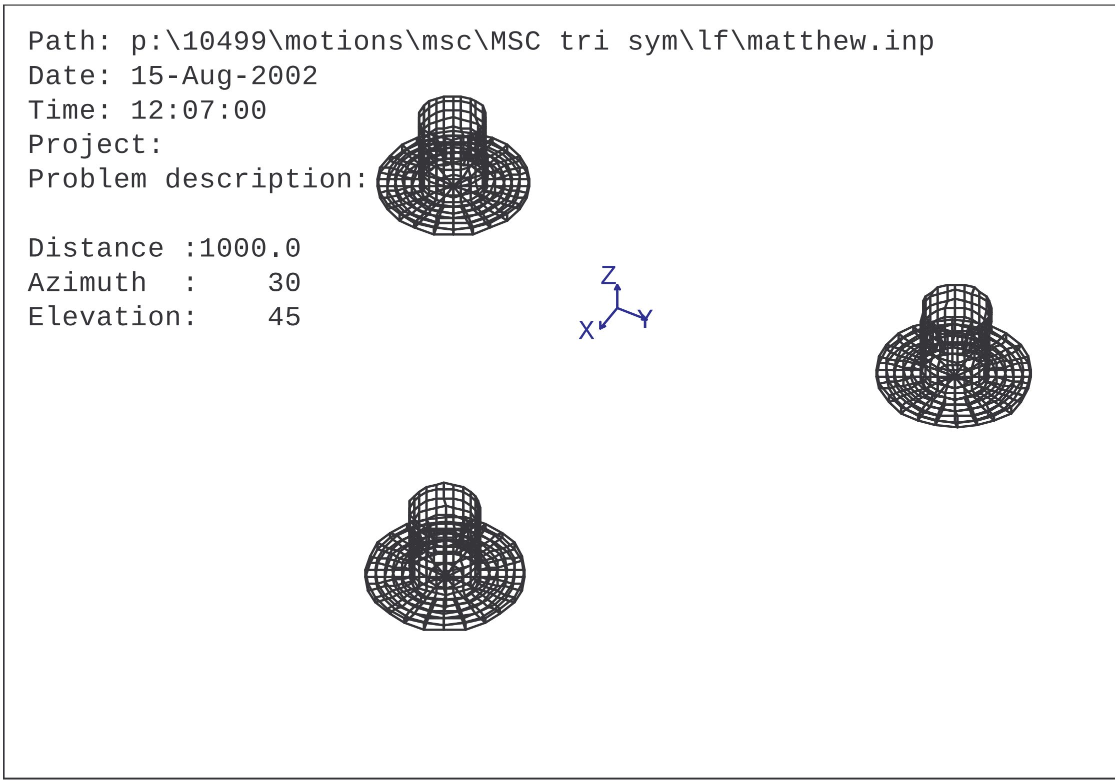


Figure 7.1.: 3D-diffraction model.

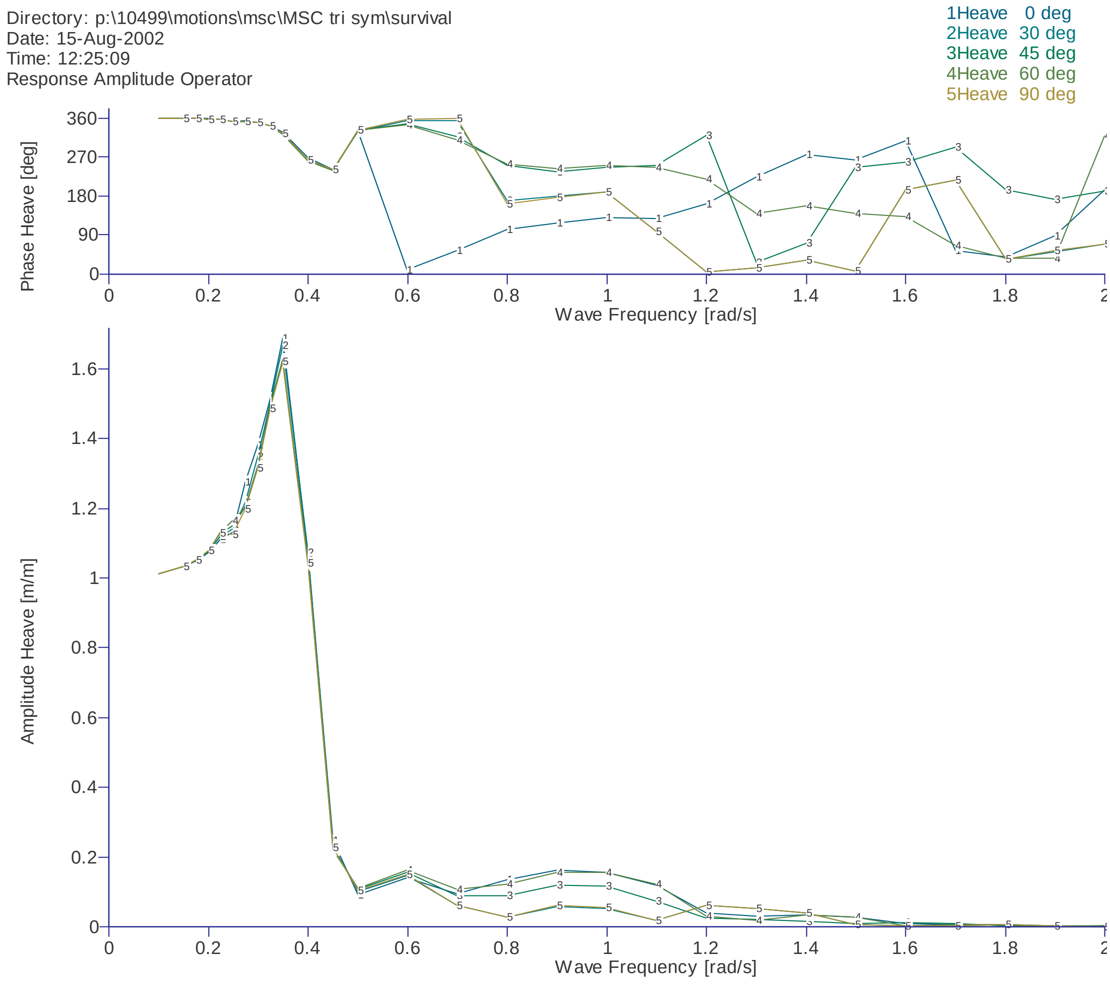


Figure 7.2.: Heave response.

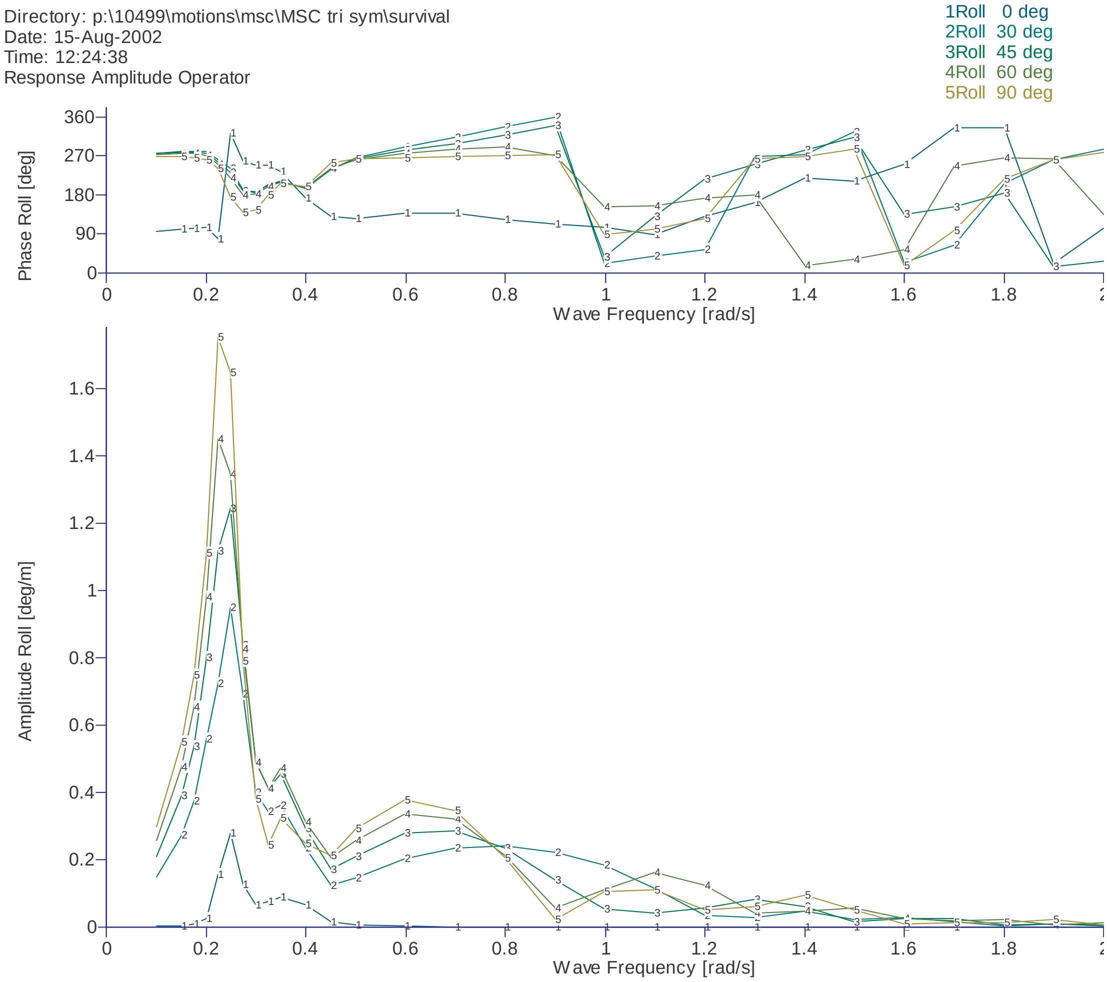


Figure 7.3.: Roll response.

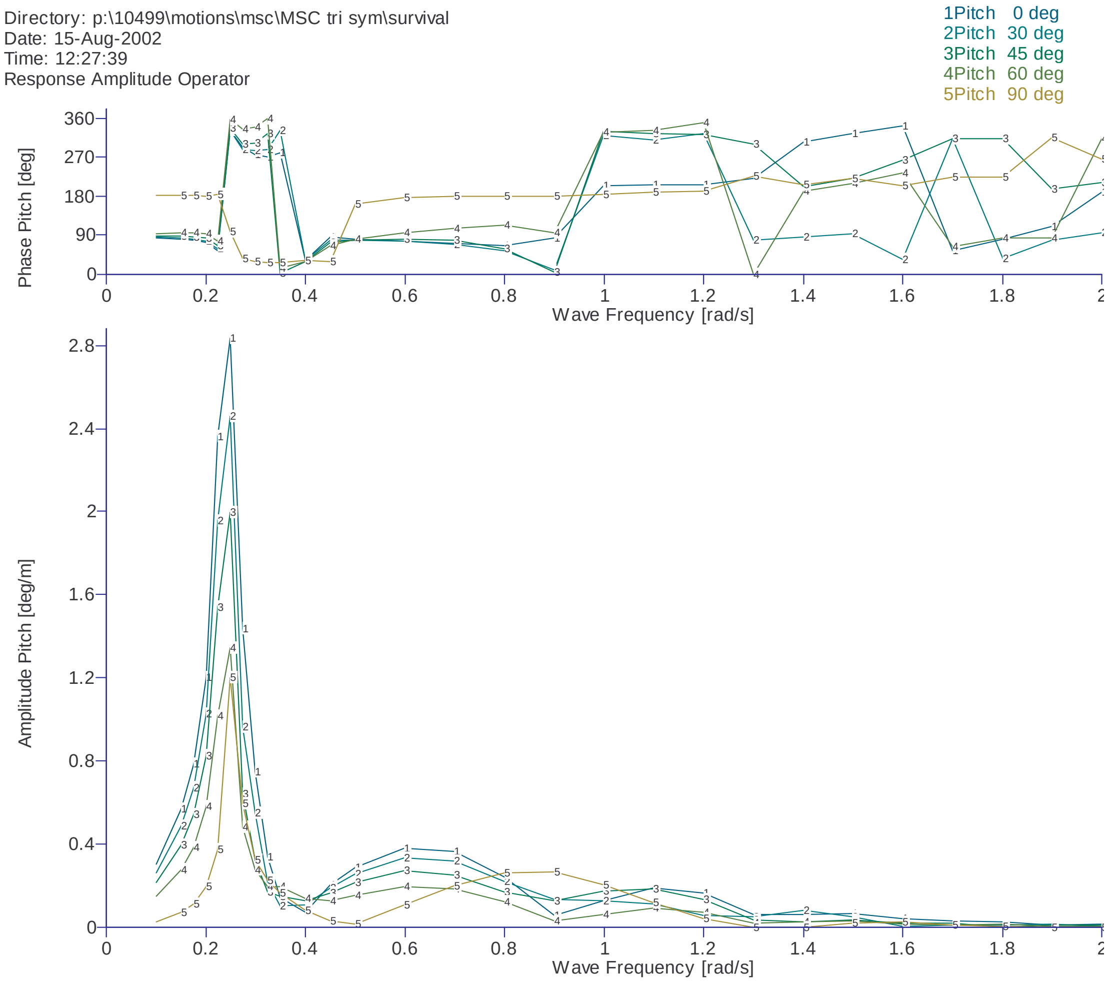


Figure 7.4.: Pitch response.

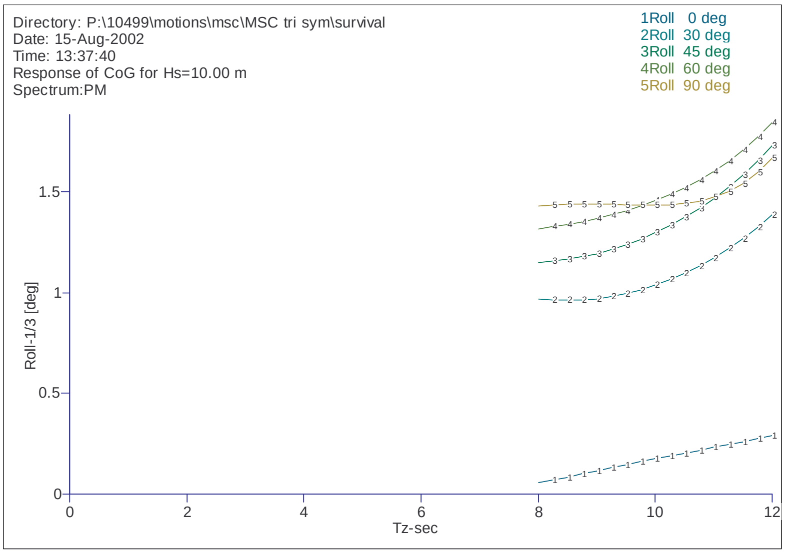


Figure 7.5.: Significant roll amplitude in survival sea state.

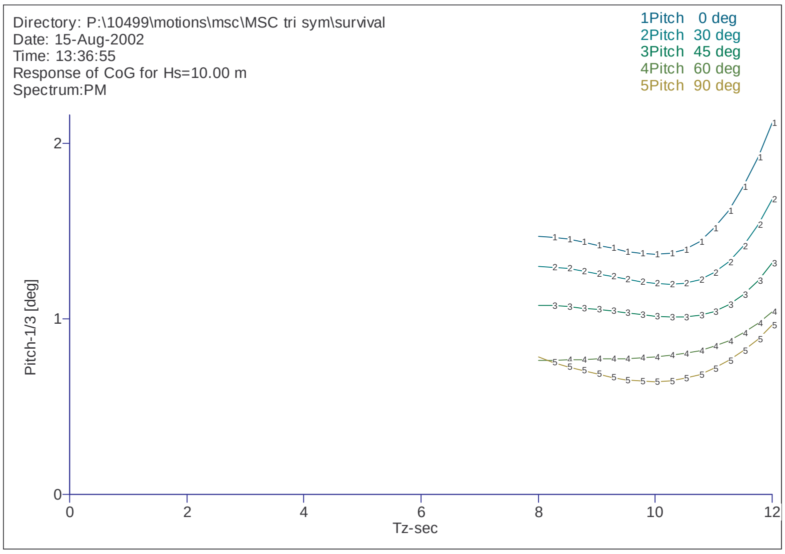


Figure 7.6.: Significant pitch amplitude in survival sea state.

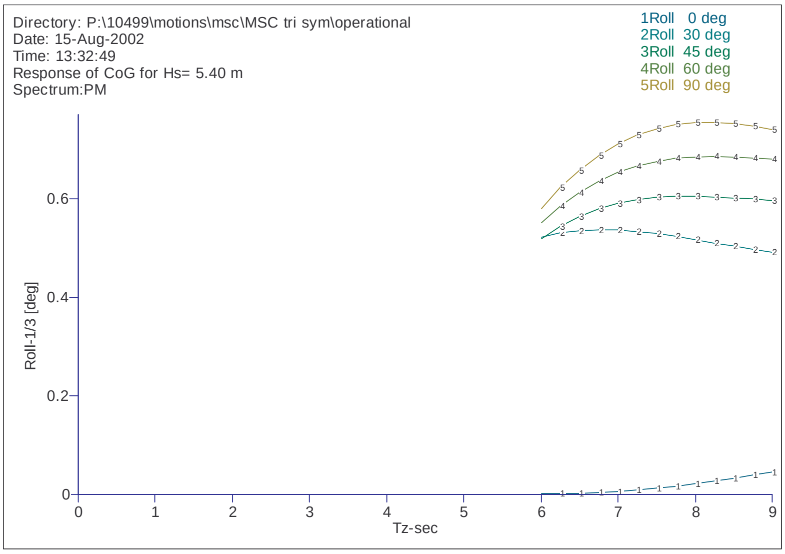


Figure 7.7.: Significant roll amplitude in operational sea state.

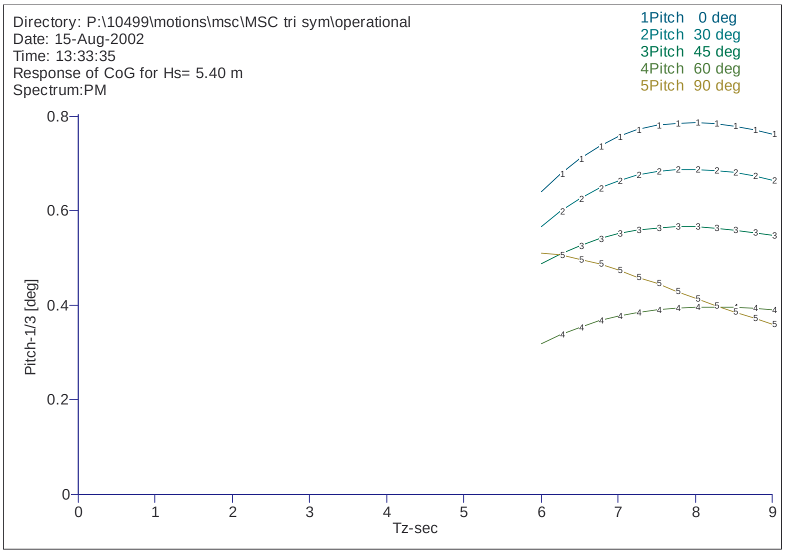
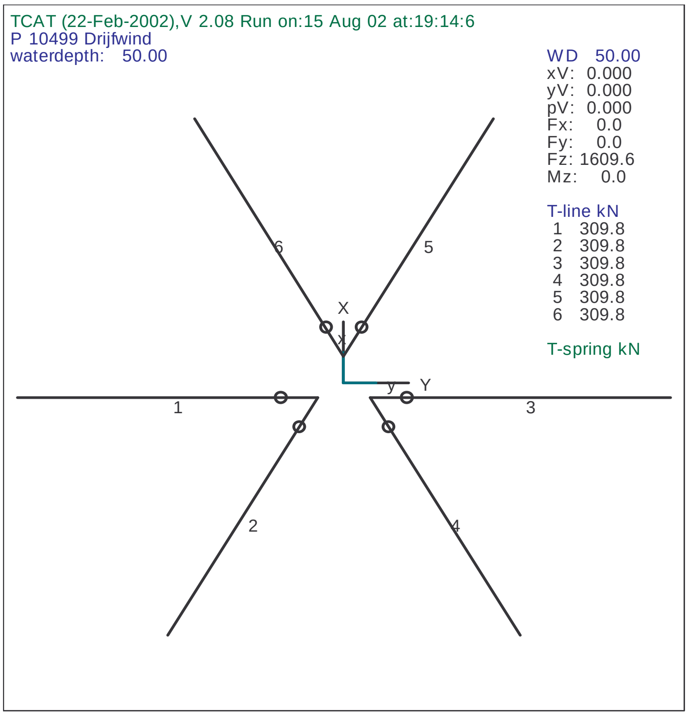


Figure 7.8.: Significant pitch amplitude in operational sea state.



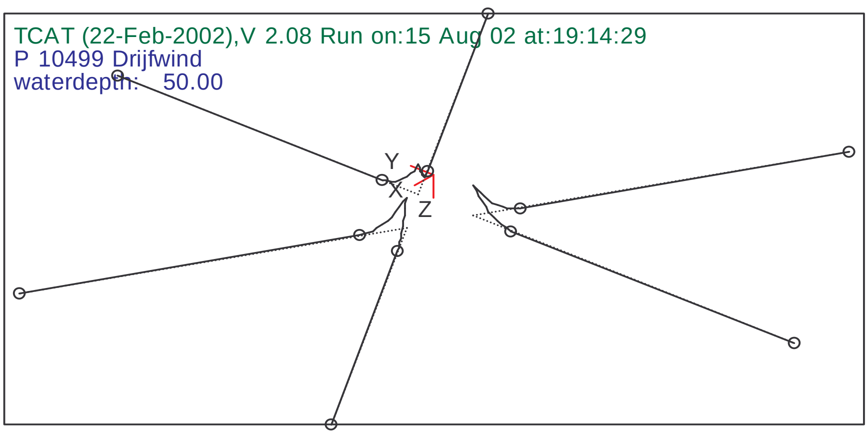


Figure 8.1.: Conventional mooring system.

Appendix A

Hydrostatics
TRI-SYM floater concept

draft	vol	displ	lcb	tcb	vcb	awl	lcf	tcf
m	m**3	t	m	m	m	m*2	m	m
-0.13	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.00
0.00	19.09	19.56	0.00	0.00	-0.01	763.4	0.00	0.00
1.00	202.55	207.62	0.00	0.00	0.53	365.9	0.00	0.00
2.00	689.25	706.48	0.00	0.00	1.22	373.2	0.00	0.00
3.00	889.18	911.41	0.00	0.00	1.49	168.9	0.00	0.00
4.00	1059.06	1085.53	0.00	0.00	1.81	170.0	0.00	0.00
5.00	1229.02	1259.74	0.00	0.00	2.18	170.0	0.00	0.00
6.00	1398.98	1433.95	0.00	0.00	2.59	170.0	0.00	0.00
7.00	1568.94	1608.16	0.00	0.00	3.01	170.0	0.00	0.00
8.00	1738.90	1782.37	0.00	0.00	3.45	170.0	0.00	0.00
9.00	1908.86	1956.58	0.00	0.00	3.90	170.0	0.00	0.00
10.00	2078.82	2130.79	0.00	0.00	4.36	170.0	0.00	0.00
11.00	2248.78	2305.00	0.00	0.00	4.82	170.0	0.00	0.00
12.00	2418.74	2479.21	0.00	0.00	5.29	170.0	0.00	0.00
13.00	2588.70	2653.42	0.00	0.00	5.76	170.0	0.00	0.00
14.00	2758.67	2827.63	0.00	0.00	6.24	170.0	0.00	0.00
15.00	2928.63	3001.84	0.00	0.00	6.72	170.0	0.00	0.00
16.00	3098.59	3176.05	0.00	0.00	7.20	170.0	0.00	0.00
17.00	3268.55	3350.26	0.00	0.00	7.69	170.0	0.00	0.00
18.00	3438.51	3524.47	0.00	0.00	8.17	170.0	0.00	0.00
19.00	3608.47	3698.68	0.00	0.00	8.66	170.0	0.00	0.00
20.00	3778.43	3872.89	0.00	0.00	9.14	170.0	0.00	0.00
21.00	3948.39	4047.10	0.00	0.00	9.63	170.0	0.00	0.00
22.00	4118.35	4221.31	0.00	0.00	10.12	170.0	0.00	0.00
23.00	4288.27	4395.48	0.00	0.00	10.61	169.2	0.00	0.00
24.00	4980.61	5105.13	0.00	0.00	12.42	822.9	0.00	0.00
25.00	5529.71	5667.95	0.00	0.00	13.61	57.1	0.00	0.00
26.00	5586.84	5726.51	0.00	0.00	13.73	57.1	0.00	0.00
27.00	5643.97	5785.07	0.00	0.00	13.86	57.1	0.00	0.00
28.00	5701.10	5843.63	0.00	0.00	13.99	57.1	0.00	0.00
29.00	5758.24	5902.19	0.00	0.00	14.14	57.1	0.00	0.00
30.00	5815.37	5960.75	0.00	0.00	14.29	57.1	0.00	0.00
31.00	5872.50	6019.31	0.00	0.00	14.45	57.1	0.00	0.00
32.00	5929.63	6077.87	0.00	0.00	14.61	57.1	0.00	0.00
33.00	5986.76	6136.43	0.00	0.00	14.78	57.1	0.00	0.00
34.00	6043.90	6194.99	0.00	0.00	14.96	57.1	0.00	0.00
35.00	6099.13	6251.61	0.00	0.00	15.14	50.7	0.00	0.00
36.00	6145.21	6298.84	0.00	0.00	15.29	44.2	0.00	0.00
37.00	6189.39	6344.12	0.00	0.00	15.44	44.2	0.00	0.00

draft	KMl	KMt	Il	It
m	m	m	m**4	m**4
-0.13	0.00	0.00	0.0	0.0
0.00	31636.98	31636.98	603797.6	603797.6
1.00	927.45	927.45	187749.7	187749.7
2.00	276.24	276.24	189563.2	189563.2
3.00	142.13	142.13	125054.1	125054.1
4.00	120.09	120.09	125264.9	125264.9
5.00	103.72	103.72	124791.4	124791.4
6.00	91.46	91.46	124334.2	124334.2
7.00	81.98	81.98	123893.4	123893.4
8.00	74.45	74.45	123469.0	123469.0
9.00	68.37	68.37	123061.0	123061.0
10.00	63.37	63.37	122669.3	122669.3
11.00	59.20	59.20	122294.0	122294.0
12.00	55.70	55.70	121935.1	121935.1
13.00	52.73	52.73	121592.5	121592.5
14.00	50.20	50.20	121266.3	121266.3
15.00	48.02	48.02	120956.5	120956.5
16.00	46.14	46.14	120663.0	120663.0
17.00	44.52	44.52	120386.0	120386.0
18.00	43.11	43.11	120125.2	120125.2
19.00	41.88	41.88	119880.9	119880.9
20.00	40.81	40.81	119652.9	119652.9
21.00	39.88	39.88	119441.3	119441.3
22.00	39.08	39.08	119246.1	119246.1
23.00	38.36	38.36	118972.7	118972.7
24.00	52.47	52.47	199502.8	199502.8
25.00	13.85	13.85	1330.9	1330.9
26.00	13.94	13.94	1168.1	1168.1
27.00	14.04	14.04	1017.5	1017.5
28.00	14.15	14.15	879.1	879.1
29.00	14.27	14.27	752.8	752.8
30.00	14.40	14.40	638.8	638.8
31.00	14.54	14.54	536.9	536.9
32.00	14.69	14.69	447.2	447.2
33.00	14.84	14.84	369.6	369.6
34.00	15.01	15.01	304.3	304.3
35.00	15.17	15.17	217.5	217.5
36.00	15.31	15.31	155.3	155.3
37.00	15.46	15.46	155.3	155.3

Appendix B

MOTIONS
TRI-SYM floater concept

```
Project:
Project Description:
Command file       :P:\10499\motions\msc\MSC tri sym\survival\calmot.cmd
File name: P:\10499\motions\msc\MSC tri sym\survival\RAOMotionTemp.txt
Date: 15-Aug-2002   Time: 12:22:43
User:sny, PC113

Number of frequencies     :   28
Number of wave directions :    5
Waterdepth                :   50 [m]
Density                   :1.000 [t/m3]
Density                   :1.000 [t/m3]

DATA OF VESSEL
                       x [m]   y [m]   z [m]
Matthew Origin     :    0.00    0.00    0.00
Shift to CoG       :    0.00    0.00    9.60
Waterline position :                   -9.60
Displacement       =   3240.00 [t]
Radii of Inertia   :
             -kxx  =     39.00 [m]
             -kyy  =     39.00 [m]
             -kzz  =     35.00 [m]

MGT,MGL and Awl with mooring influence included!
MGT                =     19.71 [m]
MGL                =     19.71 [m]
Awl                =    144.00 [m2]

Natural frequencies and periods for heave, roll and pitch motion (mooring influence included)!
                     frequency    period
                      [rad/s]       [s]
Surge              : No spring stiffness found!
Sway               : No Spring stiffness found!
Heave              :   0.382      16.452
Roll               :   0.243      25.873
Pitch              :   0.243      25.873
Yaw                : No spring stiffness found!

Legs are used. Motions (viscous damping) are calculated for a selected wave amplitude.
Wave amplitude     =   5.000 [m]
```

```
Response Amplitude Operators!

Wave angle: 0 [deg]
```

Frequency	x [m/m]		y [m/m]		z [m/m]		phi [deg/m]		theta [deg/m]		psi [deg/m]	
[rad/sec]	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
0.100	3.647	269.4	0.000	287.2	1.013	359.8	0.002	95.2	0.305	84.3	0.021	221.2
0.150	2.375	269.4	0.001	288.3	1.032	359.6	0.005	100.1	0.568	81.0	0.012	248.7 *
0.175	1.987	269.5	0.001	290.8	1.049	359.4	0.009	103.2	0.785	78.6	0.012	266.8 *
0.200	1.662	269.6	0.003	293.8	1.073	358.9	0.025	105.5	1.201	73.8	0.017	287.5
0.225	1.286	271.0	0.016	271.4	1.111	356.9	0.156	79.0	2.363	55.3	0.069	298.4 *
0.250	1.380	284.2	0.027	152.3	1.130	353.2	0.280	322.7	2.834	331.8	0.142	239.2 *
0.275	1.385	273.9	0.013	81.4	1.275	354.2	0.125	257.8	1.438	292.5	0.038	219.1 *
0.300	1.224	271.0	0.007	71.7	1.382	351.2	0.067	249.5	0.751	276.8	0.022	222.9 *
0.325	1.093	269.8	0.008	72.2	1.514	343.4	0.075	248.3	0.340	271.8	0.021	239.7 *
0.350	0.992	269.2	0.009	58.3	1.688	327.1	0.088	234.0	0.142	281.3	0.022	255.6 *
0.400	0.828	268.6	0.007	351.9	1.064	269.2	0.067	172.3	0.070	33.0	0.022	273.5
0.450	0.668	269.6	0.002	310.0	0.247	242.7	0.016	130.8	0.206	85.6	0.010	284.3 *
0.500	0.541	272.1	0.001	307.1	0.093	331.2	0.006	126.8	0.290	82.4	0.007	291.2
0.600	0.326	283.9	0.000	320.0	0.142	10.6	0.002	138.0	0.380	76.1	0.004	299.2
0.700	0.201	326.6	0.000	318.1	0.095	55.2	0.001	137.8	0.365	71.1	0.002	300.3
0.800	0.290	13.9	0.000	299.3	0.135	104.4	0.000	122.4	0.241	66.7	0.000	230.8
0.900	0.437	24.2	0.000	287.1	0.161	119.5	0.000	113.4	0.054	84.9	0.002	135.1
1.000	0.470	21.1	0.000	272.3	0.155	131.8	0.001	105.3	0.129	205.5	0.005	123.4
1.100	0.359	21.8	0.000	244.5	0.119	129.4	0.001	89.0	0.192	207.2	0.005	120.6
1.200	0.190	33.2	0.000	282.9	0.038	163.1	0.000	130.8	0.163	207.9	0.002	128.4
1.300	0.149	128.2	0.000	335.6	0.031	224.0	0.000	163.4	0.063	221.0	0.000	231.0
1.400	0.286	127.3	0.000	10.7	0.034	276.1	0.000	219.2	0.063	306.4	0.003	238.7
1.500	0.221	128.0	0.000	6.6	0.028	263.6	0.000	212.4	0.069	325.9	0.002	236.6
1.600	0.083	147.1	0.000	49.8	0.008	308.1	0.000	251.3	0.041	342.4	0.000	259.4
1.700	0.158	235.1	0.000	120.2	0.007	54.6	0.000	335.1	0.028	55.2	0.001	345.2
1.800	0.153	232.3	0.000	156.2	0.008	38.7	0.000	336.4	0.026	80.8	0.001	340.3
1.900	0.058	252.9	0.000	175.3	0.001	87.8	0.000	21.1	0.012	110.3	0.000	3.6
2.000	0.118	341.8	0.000	228.0	0.002	195.2	0.000	104.7	0.014	189.3	0.001	87.4

Response Amplitude Operators!

Wave angle: 30 [deg]

Frequency	x [m/m]		y [m/m]		z [m/m]		phi [deg/m]		theta [deg/m]		psi [deg/m]		
[rad/sec]	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	
0.100	3.169	269.4	1.833	268.8	1.013	359.8	0.149	277.2	0.262	86.1	0.032	130.0	
0.150	2.067	269.3	1.196	268.7	1.033	359.5	0.274	281.1	0.487	84.0	0.033	112.2	*
0.175	1.733	269.3	1.005	268.4	1.050	359.3	0.375	282.0	0.672	82.0	0.043	105.3	*
0.200	1.455	269.2	0.848	267.9	1.075	358.8	0.558	280.1	1.025	77.6	0.052	100.4	
0.225	1.155	270.5	0.723	268.6	1.120	356.8	0.723	261.0	1.954	59.7	0.055	96.2	*
0.250	1.239	282.7	0.620	270.5	1.141	352.4	0.947	241.0	2.461	332.9	0.056	140.1	*
0.275	1.204	272.1	0.630	274.7	1.215	352.8	0.690	192.3	0.963	288.9	0.079	104.4	*
0.300	1.066	270.6	0.582	272.4	1.348	350.0	0.398	184.8	0.549	285.0	0.091	104.7	*
0.325	0.954	269.5	0.525	271.6	1.500	342.5	0.341	205.2	0.215	289.6	0.088	97.7	*
0.350	0.865	268.8	0.480	271.6	1.667	325.1	0.362	211.1	0.105	334.0	0.090	92.4	*
0.400	0.721	267.7	0.417	270.4	1.073	264.1	0.234	195.1	0.107	31.9	0.118	87.5	
0.450	0.583	267.2	0.337	268.1	0.234	241.5	0.123	238.0	0.189	79.0	0.163	88.8	*
0.500	0.474	267.7	0.273	267.4	0.102	331.2	0.145	265.9	0.257	80.1	0.199	90.0	
0.600	0.280	268.4	0.159	263.7	0.148	356.1	0.204	292.1	0.332	76.8	0.291	89.7	
0.700	0.100	272.2	0.055	247.9	0.063	356.2	0.235	313.6	0.316	70.1	0.410	88.4	
0.800	0.063	77.6	0.043	118.9	0.027	170.5	0.240	336.8	0.223	53.8	0.524	87.0	
0.900	0.157	77.7	0.083	103.9	0.059	180.7	0.223	359.9	0.132	9.3	0.579	85.3	
1.000	0.116	66.3	0.069	103.1	0.053	191.0	0.183	21.4	0.128	320.3	0.524	83.4	
1.100	0.030	259.2	0.010	210.1	0.019	97.8	0.115	39.3	0.115	311.9	0.356	82.1	
1.200	0.159	255.8	0.103	257.3	0.060	4.6	0.035	54.3	0.058	326.1	0.150	81.0	
1.300	0.283	256.7	0.161	256.0	0.052	14.3	0.029	268.4	0.054	77.8	0.017	73.1	
1.400	0.221	246.8	0.133	246.2	0.040	32.0	0.046	272.7	0.081	86.7	0.020	66.8	
1.500	0.084	252.7	0.030	240.8	0.007	8.3	0.023	325.6	0.050	93.7	0.137	70.1	
1.600	0.053	79.3	0.025	21.7	0.004	195.6	0.027	24.3	0.006	35.5	0.240	64.3	
1.700	0.040	28.7	0.015	83.2	0.003	217.2	0.014	65.2	0.008	314.2	0.209	57.9	
1.800	0.075	224.8	0.039	227.0	0.005	34.1	0.003	208.3	0.013	36.6	0.067	51.4	
1.900	0.127	228.4	0.072	229.5	0.003	52.7	0.010	260.5	0.018	78.2	0.001	256.9	
2.000	0.053	220.5	0.030	211.5	0.001	69.9	0.003	285.3	0.007	96.8	0.055	50.5	

Response Amplitude Operators!

Wave angle: 45 [deg]

Frequency	x [m/m]		y [m/m]		z [m/m]		phi [deg/m]		theta [deg/m]		psi [deg/m]		
[rad/sec]	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	
0.100	2.592	269.3	2.593	268.8	1.013	359.8	0.211	275.8	0.213	88.7	0.027	127.0	
0.150	1.693	269.2	1.693	268.8	1.033	359.5	0.390	278.7	0.395	88.1	0.027	110.0	*
0.175	1.422	269.0	1.422	268.5	1.051	359.2	0.535	279.1	0.544	86.9	0.034	103.0	*
0.200	1.197	268.7	1.199	268.1	1.077	358.6	0.800	276.6	0.828	83.2	0.041	97.0	
0.225	0.961	269.6	1.022	269.5	1.128	356.7	1.117	256.5	1.540	66.0	0.050	101.6	*
0.250	1.021	281.9	0.910	272.1	1.151	352.0	1.242	230.9	1.996	337.3	0.045	113.3	*
0.275	0.970	271.9	0.914	273.9	1.204	352.1	0.837	189.0	0.644	301.5	0.057	98.9	*
0.300	0.863	270.4	0.836	271.9	1.322	349.7	0.493	188.1	0.324	303.0	0.063	99.4	*
0.325	0.777	269.6	0.756	271.1	1.496	341.9	0.413	203.0	0.167	324.3	0.066	96.1	*
0.350	0.704	268.8	0.688	270.9	1.628	323.1	0.452	210.0	0.149	3.5	0.068	91.0	*
0.400	0.588	267.1	0.590	269.3	1.050	262.5	0.291	196.9	0.130	29.4	0.089	87.1	
0.450	0.477	265.6	0.477	266.5	0.225	240.4	0.173	239.9	0.165	73.1	0.119	88.5	*
0.500	0.390	264.4	0.389	264.7	0.106	331.8	0.208	262.9	0.213	79.3	0.144	89.5	
0.600	0.237	257.0	0.236	255.2	0.156	347.8	0.279	283.6	0.270	81.6	0.209	88.8	
0.700	0.114	224.3	0.122	217.8	0.089	318.3	0.287	299.6	0.250	78.0	0.291	86.8	
0.800	0.137	154.0	0.156	157.4	0.088	250.5	0.233	317.5	0.169	60.2	0.370	83.6	
0.900	0.219	135.5	0.238	142.7	0.118	237.6	0.139	340.8	0.128	5.6	0.410	77.3	
1.000	0.216	137.0	0.256	141.0	0.116	246.5	0.053	36.9	0.176	330.7	0.382	65.3	
1.100	0.166	155.7	0.172	145.5	0.074	252.7	0.041	130.4	0.186	325.5	0.311	40.3	
1.200	0.082	176.2	0.070	197.2	0.025	320.0	0.058	217.0	0.132	323.7	0.299	2.0	
1.300	0.088	289.0	0.067	260.3	0.020	26.0	0.082	252.4	0.038	300.3	0.343	331.2	
1.400	0.067	276.4	0.057	315.7	0.014	72.6	0.059	282.5	0.024	202.3	0.320	308.9	
1.500	0.048	79.4	0.026	81.2	0.010	246.2	0.017	313.8	0.039	222.1	0.205	281.6	
1.600	0.097	121.8	0.117	117.8	0.012	257.8	0.025	136.5	0.020	264.2	0.131	230.1	
1.700	0.117	113.7	0.101	113.0	0.009	293.3	0.026	152.3	0.018	313.5	0.123	193.1	
1.800	0.033	45.7	0.029	50.6	0.003	194.2	0.005	185.9	0.001	314.2	0.058	197.2	
1.900	0.090	348.9	0.085	352.1	0.002	171.8	0.011	15.5	0.012	196.4	0.035	261.6	
2.000	0.068	341.9	0.070	339.4	0.002	193.3	0.008	27.0	0.009	210.8	0.040	217.3	

Response Amplitude Operators!

Wave angle: 60 [deg]

Frequency	x [m/m]		y [m/m]		z [m/m]		phi [deg/m]		theta [deg/m]		psi [deg/m]	
[rad/sec]	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
0.100	1.836	269.3	3.177	268.8	1.013	359.8	0.258	274.0	0.150	93.1	0.011	141.4
0.150	1.201	269.1	2.075	268.8	1.033	359.5	0.477	275.7	0.278	95.3	0.007	110.2 *
0.175	1.010	268.7	1.742	268.7	1.051	359.1	0.654	275.4	0.383	95.6	0.007	90.9 *
0.200	0.853	267.9	1.469	268.5	1.078	358.5	0.980	272.1	0.581	93.4	0.009	64.1
0.225	0.694	268.0	1.253	270.4	1.133	356.6	1.449	251.8	1.014	77.0	0.006	78.5 *
0.250	0.690	280.8	1.172	273.5	1.165	352.0	1.344	218.8	1.345	357.2	0.007	74.0 *
0.275	0.665	273.2	1.148	273.0	1.201	352.1	0.826	180.7	0.484	336.1	0.002	69.5 *
0.300	0.600	271.4	1.040	271.3	1.317	349.7	0.489	181.7	0.275	339.2	0.003	110.6 *
0.325	0.542	270.4	0.938	270.7	1.493	341.8	0.413	200.7	0.196	358.9	0.004	93.4 *
0.350	0.492	269.5	0.852	270.5	1.618	322.4	0.473	209.5	0.193	16.0	0.005	75.0 *
0.400	0.413	267.2	0.724	268.7	1.036	261.9	0.312	197.8	0.137	29.2	0.006	78.0
0.450	0.338	265.0	0.585	265.9	0.220	240.1	0.206	242.6	0.130	67.0	0.006	77.6 *
0.500	0.277	262.9	0.480	263.8	0.109	332.7	0.257	261.2	0.153	81.1	0.004	70.7
0.600	0.172	251.2	0.296	252.8	0.161	345.0	0.335	275.9	0.194	95.3	0.003	64.7
0.700	0.103	210.9	0.175	212.7	0.106	310.0	0.320	285.2	0.184	105.0	0.002	70.7
0.800	0.143	160.2	0.242	160.9	0.122	254.7	0.213	291.5	0.121	112.3	0.000	159.0
0.900	0.213	145.6	0.365	146.3	0.156	243.5	0.056	272.4	0.029	96.8	0.001	254.4
1.000	0.233	141.4	0.398	142.6	0.155	250.9	0.110	152.9	0.063	327.6	0.003	251.6
1.100	0.180	137.8	0.307	139.3	0.123	247.1	0.161	155.6	0.093	332.7	0.003	254.3
1.200	0.085	122.2	0.145	123.0	0.031	220.6	0.123	172.0	0.071	350.9	0.001	262.1
1.300	0.081	35.7	0.140	36.0	0.020	139.9	0.040	179.5	0.023	0.2	0.000	143.2
1.400	0.139	8.2	0.238	9.2	0.034	158.9	0.048	17.2	0.028	192.6	0.001	121.0
1.500	0.106	5.5	0.182	6.4	0.028	139.7	0.056	32.8	0.032	210.2	0.001	119.7
1.600	0.044	338.0	0.076	338.3	0.004	132.8	0.026	53.7	0.015	233.2	0.000	103.8
1.700	0.078	239.2	0.135	239.8	0.007	67.4	0.018	247.6	0.011	64.7	0.000	349.3
1.800	0.076	232.2	0.130	232.7	0.007	37.9	0.023	266.5	0.013	84.4	0.000	341.3
1.900	0.030	203.3	0.052	203.5	0.001	36.3	0.007	263.5	0.004	82.8	0.000	316.7
2.000	0.059	102.7	0.101	103.3	0.002	321.0	0.011	135.6	0.006	312.2	0.000	209.3

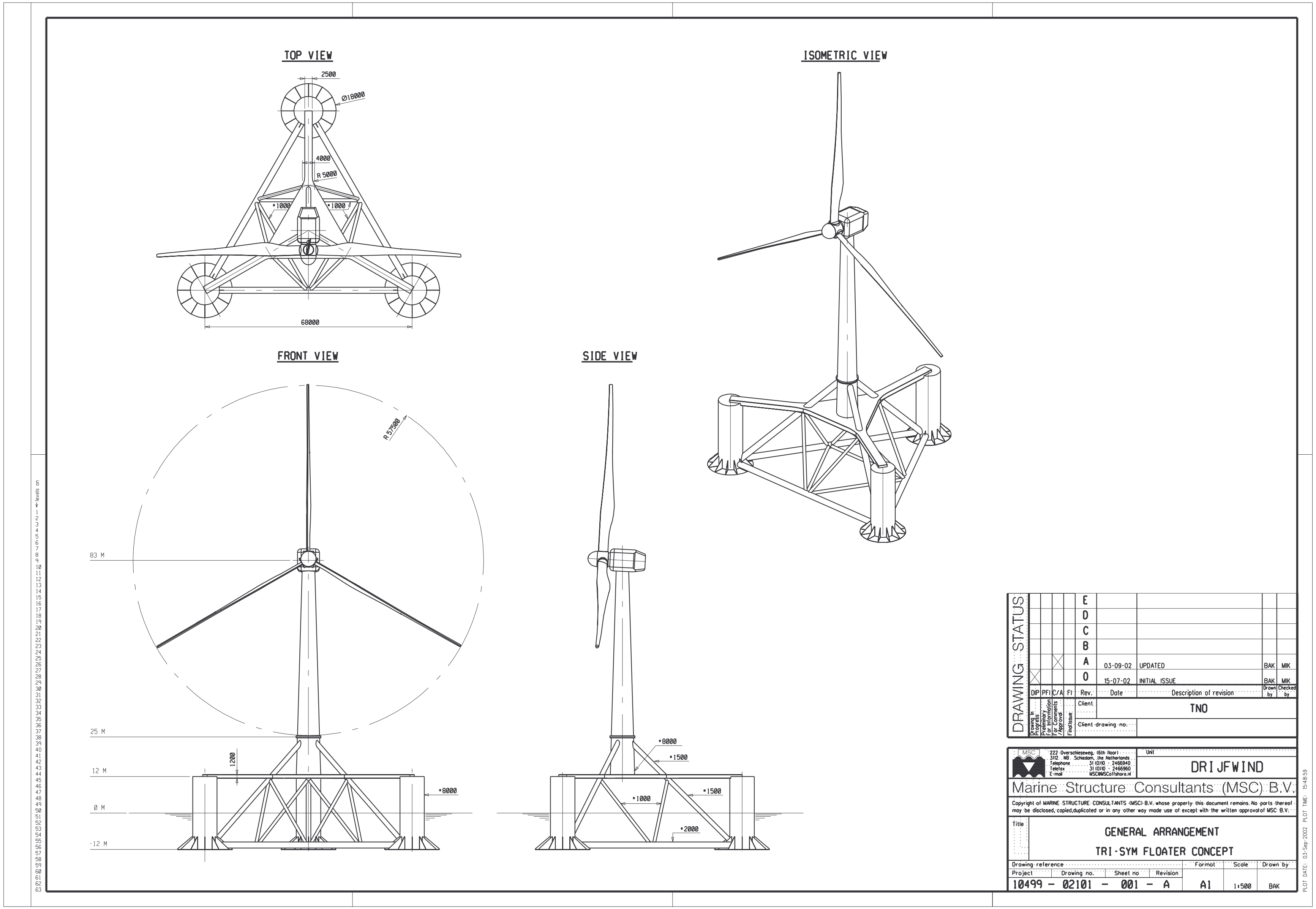
Response Amplitude Operators!

Wave angle: 90 [deg]

Frequency	x [m/m]		y [m/m]		z [m/m]		phi [deg/m]		theta [deg/m]		psi [deg/m]	
[rad/sec]	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	Phase
0.100	0.003	194.4	3.666	268.8	1.013	359.8	0.298	269.5	0.023	181.9	0.025	288.0
0.150	0.008	195.8	2.392	269.0	1.033	359.5	0.548	268.3	0.069	182.8	0.030	286.5 *
0.175	0.012	196.4	2.008	269.1	1.051	359.2	0.748	266.7	0.112	182.6	0.041	284.0 *
0.200	0.022	197.6	1.695	269.5	1.078	358.6	1.110	261.7	0.195	181.0	0.050	283.7
0.225	0.043	205.4	1.444	272.0	1.129	356.4	1.751	241.4	0.375	185.1	0.066	281.6 *
0.250	0.139	120.2	1.464	275.3	1.124	352.0	1.647	175.1	1.204	97.6	0.076	271.9 *
0.275	0.067	53.4	1.361	271.6	1.198	353.2	0.788	141.6	0.594	36.4	0.081	275.9 *
0.300	0.038	47.2	1.211	270.4	1.316	350.3	0.381	146.5	0.325	30.1	0.086	277.0 *
0.325	0.027	45.8	1.090	270.0	1.487	342.8	0.245	180.9	0.226	28.1	0.089	274.5 *
0.350	0.020	45.2	0.991	270.1	1.619	324.5	0.323	206.5	0.163	26.6	0.094	270.7 *
0.400	0.011	43.7	0.841	269.5	1.042	264.3	0.249	199.1	0.080	32.3	0.122	267.1
0.450	0.004	42.1	0.674	268.4	0.227	242.8	0.214	252.8	0.031	30.6	0.163	268.4 *
0.500	0.002	127.0	0.547	268.7	0.104	333.3	0.293	262.6	0.016	161.9	0.198	269.5
0.600	0.011	167.7	0.321	269.4	0.149	357.2	0.378	267.1	0.107	177.2	0.290	269.1
0.700	0.019	167.8	0.111	271.5	0.062	359.4	0.346	269.1	0.198	179.4	0.409	267.8
0.800	0.022	178.9	0.072	84.8	0.029	163.5	0.206	270.2	0.263	180.6	0.523	266.6
0.900	0.031	194.6	0.174	83.2	0.061	178.0	0.021	273.5	0.266	181.1	0.579	264.8
1.000	0.033	170.5	0.130	75.3	0.054	189.1	0.104	89.5	0.204	183.9	0.524	262.7
1.100	0.011	107.3	0.030	253.6	0.019	97.8	0.113	100.5	0.119	189.2	0.356	261.6
1.200	0.010	262.2	0.190	256.6	0.060	4.3	0.051	125.7	0.042	191.7	0.150	261.3
1.300	0.005	162.4	0.324	257.1	0.052	13.7	0.061	263.8	0.003	225.7	0.016	262.6
1.400	0.007	215.3	0.256	247.4	0.040	31.8	0.094	269.7	0.002	206.6	0.019	253.6
1.500	0.017	91.7	0.088	251.4	0.007	8.1	0.051	285.0	0.020	221.7	0.137	250.4
1.600	0.024	311.0	0.054	67.9	0.004	194.5	0.008	17.1	0.027	204.2	0.240	244.1
1.700	0.016	167.3	0.040	37.9	0.003	216.5	0.012	98.8	0.012	224.3	0.209	237.8
1.800	0.003	26.1	0.084	225.6	0.005	34.3	0.012	217.1	0.004	224.0	0.067	231.6
1.900	0.001	20.2	0.145	229.2	0.003	53.1	0.021	261.2	0.000	316.4	0.001	29.9
2.000	0.004	117.4	0.060	218.5	0.001	70.0	0.008	278.9	0.002	265.4	0.055	230.7

Appendix C

GA Plan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4000
R 5000
•1000
•1000
68000
ISOMETRIC VIEW
FRONT VIEW
R 57500
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25 M
12 M
0 M
-12 M
1200
•8000
SIDE VIEW
•8000
•1500
•1000
•1500
•2000
DRAWING STATUS
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Rev. Date Description of revision Drawn by Checked by
A 03-09-02 UPDATED BAK MIK
0 15-07-02 INITIAL ISSUE BAK MIK
Client TNO
Client drawing no.
222 Overschieseweg, (6th floor) 3112 NB Schiedam, the Netherlands
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TRI-SYM FLOATER CONCEPT
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Format A1
Scale 1:500
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8 Electrical infrastructure

Abstract
An important aspect in the determination of the feasibility of an offshore wind farm is the choice of the electrical system, necessary to collect the power in the farm and transport it to shore. This report describes how this choice was made for the Drijfwind concept. Based on the results of the ERAO project the two most promising system types for Drijfwind have been chosen: individual variable speed and park variable speed. For these options, two park layouts based on platforms with 1 and 5 turbines have been investigated. These layouts correspond to different cable layouts inside the park: string and star. The second parameter investigated is the distance between the wind farm and the shore. The *EEFARM* computer program has used to calculate the electrical and economic performance of these options.

Based on economics only, the best choice for the Drijfwind 500 MW wind farm will be the Individual Variable speed system for distances below 140 km and the Park Variable speed system for distance above 140 km. Differences in controllability and stability of the two options may influence the choice, but has not been investigated.

Keywords: offshore wind energy, electrical models, economic models, power performance

Contents

8.1 INTRODUCTION

The objective of Drijfwind Work Package "Electric infrastructure" is to make an assessment of the electrical layout inside the wind farm and the connection to the onshore grid. For this purpose, the *EEFARM* computer program is used to calculate the electrical and economic per-formanceof a number of electrical architectures and layouts (see appendix B). A single *EE-FARM* run gives the load flow (voltages, currents, active and reactive powers) in all system nodes as well as the electrical losses for all wind speed bins. *EEFARM* also estimates the contri-bution of the electrical system to the kWh price, averaged over the life time of the wind farm. The economic evaluation is based on budget prices for the electrical components, received from manufacturers, and aerodynamic performance of the wind farm calculated by *FYNDFARM* .

Prior to the *EEFARM* calculations for Drijfwind turbine and wind farm layouts, a preliminary choice of the most promising electrical architectures has to be made, since a large number of suitable electrical architectures exist for the connection of large wind farms to shore. The preliminary choice will be based on the results of a case study in the ERAO project [2]. In this project *EEFARM* has been used to evaluate 13 electrical architectures for 2 wind farm sizes and 2 distances to shore. The calculations were based on a 5 MWwind turbine. Chapter 3 summarizes the ERAO case study results and makes a preliminary choice.

The two most promising electrical options, suitable for the Lagerwey turbine, will be evaluated for the Drijfwind 5 MWwind turbine and a farm size of 500 MW(100 turbines). These options are the Individual Variable Speed system (IV) and the Park Variable Speed system (PV). Two platform options will be considered: platforms with 1 or 5 turbines. The evaluation will take into account distances to shore between 50 and 200 km. Chapter 4 gives the Drijfwind results.

8.2 ELECTRICAL ARCHITECTURES

The electrical system[1] concerns the electrical power components between the generator shaft and the grid connection and it concerns the way these components are interconnected and operated. Its function is to convert mechanical power to electric power, to collect electric power from individual turbines, to transmit it to the shore and to convert it to the appropriate voltage and frequency. The system consists amongst other of generators, cables, transformers and power electronic converters. Systems are mainly characterised by the type of voltage (AC or DC) and the frequency (fixed or variable) of the electrical quantities.

The way to interconnect the, often variable speed, generators with the high-voltage 50 Hz power system is not trivial. Depending on the ratio between the individual turbine power (typical 5 MW) and the wind farm power it will be necessary to collect the power at least at one or more collection levels with each a different voltage level. The number of collection levels is a trade off between investment costs and losses. The minimum voltage level is limited by the current carrying capability (’ampacity’) of cables, being roughly 1000 to 1500 A. Choosing a low voltage will cause high losses and brings the necessity of parallel cables. On the other hand the application of high-voltage equipment is expensive because of the extra costs for space and insulation. Two types of wind farms are distinguished: wind farms with constant speed turbines and wind farms with variable speed turbines. Wind farms with variable speed turbines require some adaptation of the variable turbine frequency to the constant grid frequency.

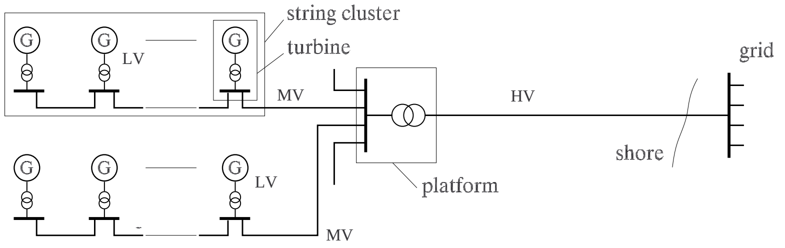
8.2.1 Constant speed and type of clustering

Several methods to collect the power can be distinguished. In figure 1 two constant speed configurations are shown, one with string clustering and one with star clustering. The busbar on the right hand platform will be referred to as the ’park nodal point’ and the busbar on the left platform in figure 1b as the ’cluster nodal point’. The power and voltage rating of the MV cable is comparable in both cluster options. The power rating of the LV cable in the star cluster is substantially lower than the power rating of the MV cable.

The necessity of transformers near the turbines depends on the voltage rating of the cable and the voltage rating of the generators. With star clustering a turbine transformer can possibly be left out (as indicated in figure 1b) if the generator voltage is sufficiently high (about 5 kV). With string clustering the transformer can only be left out if the generator voltage is at least several tens of kV because of the limited current rating of cables. These generators arepresently not available, so for the moment a transformer will be needed (as indicated in figure 1a). This means that the number of transformers with star clustering can possibly be lower then with string clustering. On the other hand the number of platforms with star clustering is higher then with string clustering as each cluster needs its own nodal platform for switch gear and a transformer. As the figure shows the type of clustering does not directly affect the architecture of the rest of the park, however the type of clustering is important for the voltage rating of converters in the cluster. The costs of converters is more or less linear with the apparent power of the converter however it also rises progressively with the voltage rating because of the spacious equipment needed for insulation. This means that low power high voltage converters are relatively expensive.

1 This chapter is based on the ERAO report [2]

a.



b.

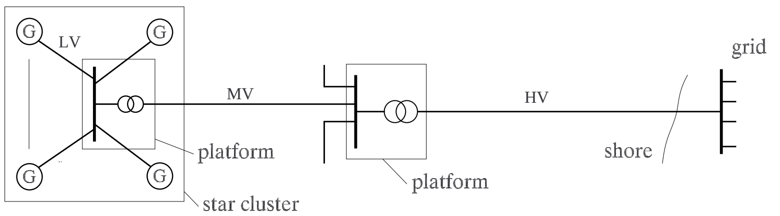
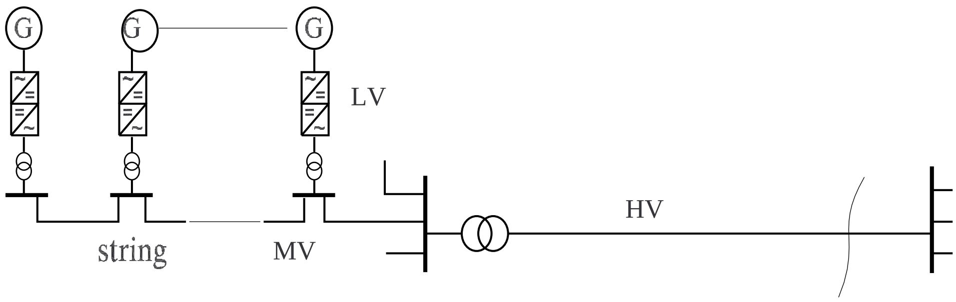


Figure 1 Constant speed system

a.



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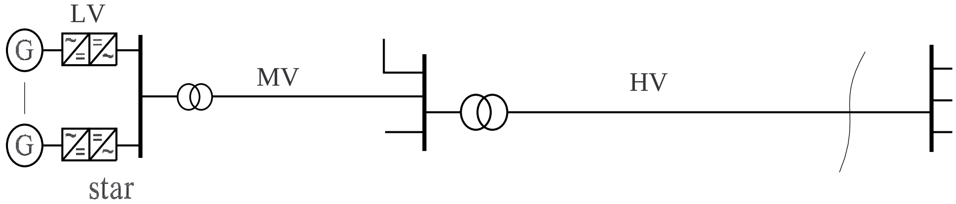

Figure 2 Individual variable speed with back-to-back converters

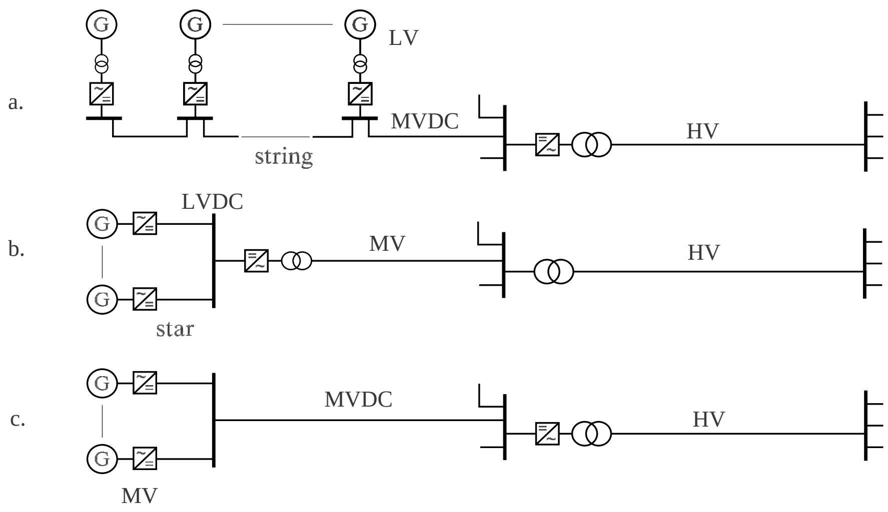

Figure 3 Individual variable speed with multi-terminal DC-light system

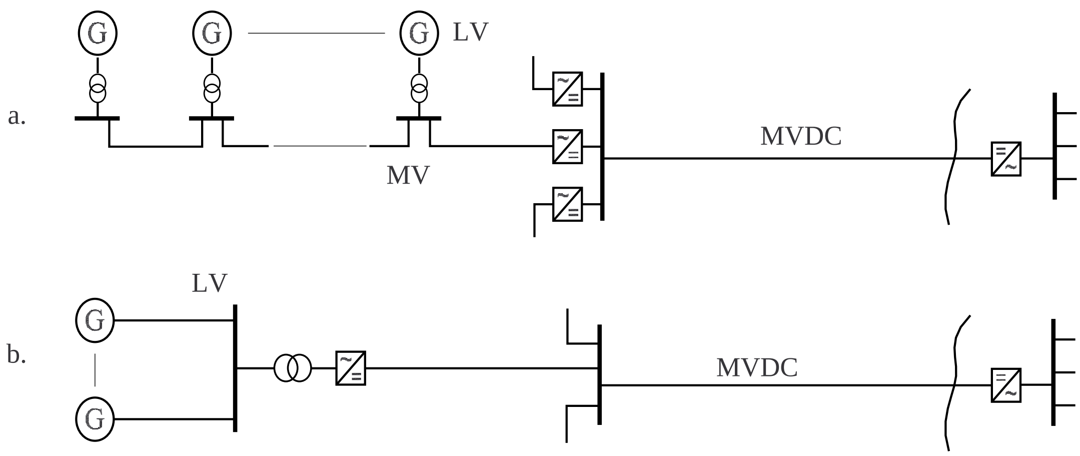

Figure 4 Cluster-coupled variable-speed with DC-light

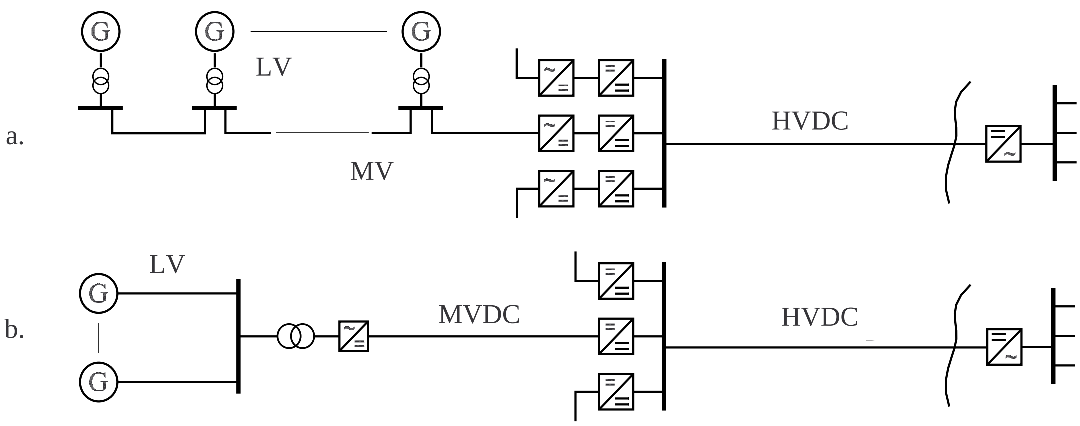

Figure 5 Cluster-coupled variable-speed DC-systems with step-up chopper or DC-transformer

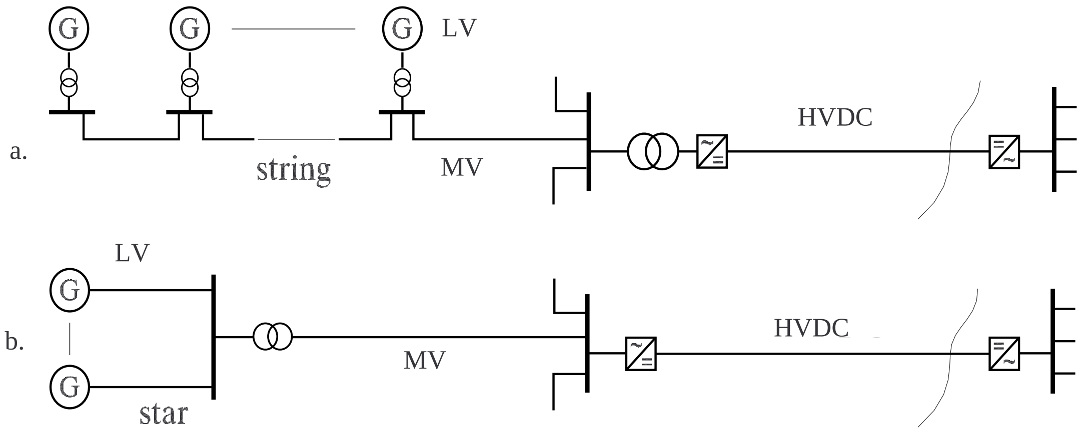

Figure 6 Park-coupled variable-speed system with DC

8.2.2 *Individual variable speed*

Two options for individual variable speed are shown in figure 2 and 3. The systems of figure 2 consist of traditional variable speed turbines with back-to-back low voltage (about 1 kV) converters. In figure 2b medium voltage converters will be required (2-10 kV) when the converters are directly connected to the cable.

In figure 3a the back to back converter is split in separate AC/DC converters and DC/AC con-verters. The voltage rating of the DC-system is in the medium voltage range (10-50 kV). These medium voltage DC systems, also referred to as DC-Light systems, are being developed by ABB amongst other and are based on voltage source converters. DC-system with multiple DC-inputs (multi-terminal DC light) are not available yet and will require an extensive devel-opment program. In figure 3b the DC/AC converter is placed near the cluster node whilst in figure 3c the DC/AC converter is placed down stream of the collection point of all clusters, which results in the elimination of a cluster transformer. On the other hand the power rating of the DC/AC converter and the DC-cable will be much higher and so is the required voltage level. Because of the high voltage level of the turbine sided converters and because of the limited power rating these converters will have relatively high costs per kVA.

8.2.3 *Cluster-coupled variable speed*

When all turbines in a cluster have a common AC/DC converter, we call this ’cluster coupled variable speed’. In such a system the speed and electrical frequency vary more or less propor-tional with the average wind speed in the cluster. The fatigue loads on turbine components are possibly higher than in an individual variable speed system. In figure 4 two systems are shown with the DC/AC converter placed on shore. Instead of placing the DC/AC converter on shore, the converter can also be placed on the park nodal platform. In that case probably a lower DC voltage can be applied at the expense of an extra step up transformer at the park nodal platform. Moreover the cluster nodal transformer can be eliminated in system 4b if the DC voltage can be lowered sufficiently. Both for the DC-Light system as well as for high-voltage generators a development effort is required.

By inserting a step-up chopper or an electronic DC-transformer in the DC-link, as shown in figure 5 a relatively low DC voltage near the turbines can be combined with a higher DC-voltage for the transmission cable. The DC-transformer is a power electronic subsystem with an intermediate high-frequency link inside. For this option a high power DC-DC converter is needed that has to be developed. A system with step-up chopper might be costly as the apparent power is approximately equal to the product of step-up ratio and real power when the step ratio is high. Note that a step-up chopper can also be used in the systems of figure 3 and figure 6.

8.2.4 Park-coupled variable speed

Figure 6 shows some systems for park coupled variable speed. All generators have the same
electrical frequency. The electrical frequency can either be constant or can be controlled more
or less proportional to the average wind speed in the park. The fatigue loading will be higher
then with individual variable speed, and energy yields will be less, due to the fact that some
machine will not run at optimal tip speed ratio.

8.3 PRELIMINARY CHOICE BASED ON ERAO STUDY

In the ERAO project a technical and economic analysis of 13 different electrical architectures
in chapter 2 has been made for 2 park sizes (100 and 500 MW) and 2 distances to shore (20 and 60 km) [2]. These results are used to limit the number of architectures that will be evaluated in the Drijfwind study.

The analysis in the ERAO projects is based on:
• the average aerodynamic performance;
• the load flow and electrical losses;
• the cost of the electrical system.

The cost calculations exclude the turbine and turbine generator costs as well as the turbine installation costs. The cost calculation focuses on the major electrical equipment between turbine and shore: transformers, cables (including laying) and power electronic converters. Small auxiliary electrical equipment, e.g. switches and safety equipment, is not taken into account.

The economic parameters in the ERAO case study have been:

• operation and maintenance cost as percentage of the investment: 5%;
• nominal interest rate: 7%;
• rate of inflation: 2%;
• economic life time of the wind farm: 12 years;
• an availability of 90%.

To facilitate the comparison of the electrical options in the ERAO study, a single power curve (Erao5000Var) of a 5 MW turbine was chosen for all configurations. Two wind farm layouts have been chosen: a square layout with turbines in straight rows (strings) and a circular layout (stars). The distance between turbines is 8D. The intermediate voltage level for the 100 Mwas well as the 500 MWfarm is 33 kV. The rectifiers and inverters in systems with a DC connection are based on IGBTs. Capacitive currents in the cables are not compensated by shunt inductors.

8.3.1 Preliminary choice

The ERAO case study has shown that the systems C1 (string layout) and C2 (star layout), operating on AC only, have the lowest contribution of the electrical system to the price per kWh for both farm sizes and distances to shore. For the 100 and 500 MW farm at 20 km and the 500 MW farm at 60 km, the C1 system also generates the lowest electrical losses. The ERAO evaluation did not consider differences in aerodynamic power performance caused by different turbine designs. The only aerodynamic performance differences taken into account were those caused by the wind park layout: the string and the star layout, and these differences were small. The reason not to consider separate constant and a variable speed turbine designs is that it would conceal the effect of the electrical system on the performance and make a generic comparison of the electrical architectures more difficult. In Drijfwind evaluation different tur-bine designs should be taken into account. In those cases where a DC connection to shore is preferred (longer distance to shore or avoid-ance of grid stability problems), the PV1 configuration appears to be the best alternative. For the investigated distances and park sizes this currently increases the investment costs and con-tribution of the electrical system to the price per kWh by a factor 2 or more. The electrical losses of concepts C1 and PV1 are of the same magnitude.

The options with individual turbine speed control, IV1 and IV2, although more expensive than the constant speed systems C1 and C2, should not be discarded based on the ERAO case study alone. The reason is that they may be preferred by a large number of turbine manufacturers (due to their potential in load reduction and increased controlability) and a potentially better aerodynamic performance, which was not taken into account in the ERAO case study.

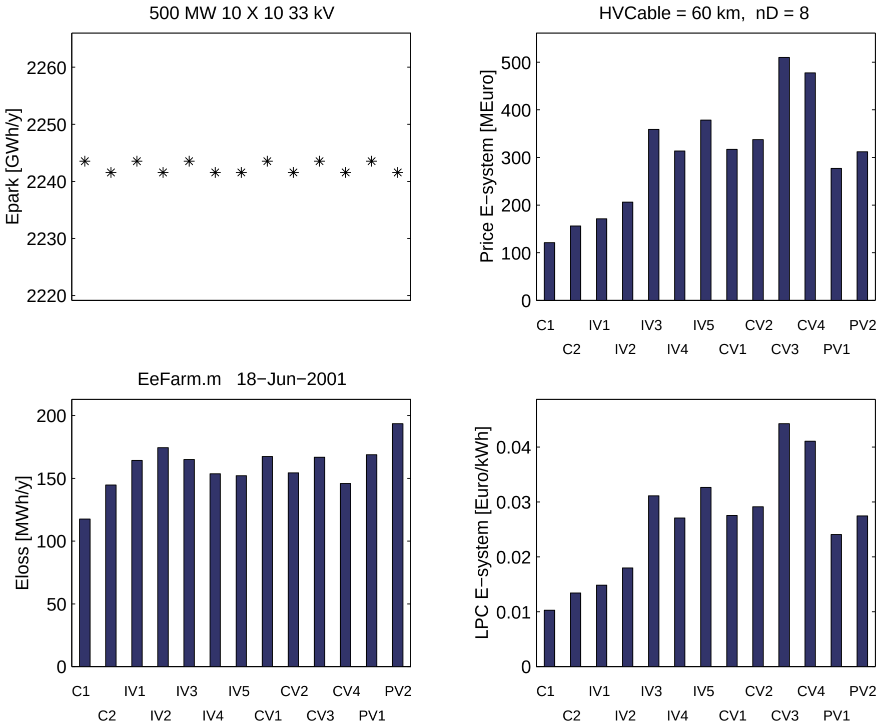

Figure 7 ERAO Results 500MW wind farm (10x10 turbines) 33kV and 60 km to shore

Table 8.1 ERAO Results 500MW wind farm (10x10 turbines) 33kV and 60 km to shore

Distance to shore 60.00 km

Description	Config name	Config type	Yearly losses [MWh/y]	Price [MEuro]
500 MW 10 X 10 33 kV	C1	string	117555.3	132.95
500 MW 10 X 10 33 kV	C2	star	144735.4	150.67
500 MW 10 X 10 33 kV	IV1	string	164345.5	182.95
500 MW 10 X 10 33 kV	IV2	star	174440.3	200.67
500 MW 10 X 10 33 kV	IV3	string	164980.7	364.98
500 MW 10 X 10 33 kV	IV4	star	153718.9	310.22
500 MW 10 X 10 33 kV	IV5	star	152155.8	375.47
500 MW 10 X 10 33 kV	CV1	string	167383.7	328.83
500 MW 10 X 10 33 kV	CV2	star	154405.4	331.87
500 MW 10 X 10 33 kV	CV3	string	166762.3	521.73
500 MW 10 X 10 33 kV	CV4	star	145944.4	477.41
500 MW 10 X 10 33 kV	PV1	string	168851.2	288.83
500 MW 10 X 10 33 kV	PV2	star	193584.7	306.55

In figure 7 the results for the 500 MW options at 60 km are summarized. The contribution of the electrical system to the price of one kWh is in the range of 1.0 EuroCent (C1) to 4.5 EuroCent (CV3).

Conclusion: The most promising electrical options are constant speed (C1-C2), individual variable speed (IV1-IV2) and park variable speed (PV1-PV2). In the analyses of the electrical system options for Drijfwind two architectures will be compared: **individual variable speed (IV)** and **park variable speed (PV**), since these options can be combined with the Direct Drive Variable Speed concept of Lagerwey.

8.4 EEFARM RESULTS FOR DRIJFWIND WIND FARM DESIGN

The reference conditions in the Drijfwind study are:

1. Turbine rated power of 5 MW;

2. P(V) curve according to Terms of Reference [1];

3. Platform rated power: 5 and 25 MW (1 and 5 turbines per platform);

4. Park size 500 MW (100 and 20 platforms);

5. String layout for single turbine platform (10 strings of 10 platforms);

6. Star configuration for five turbine platform (MV cables connect to central platform).

This choice is caused by the rating of the cables. Sting layout would result in increasing the number of parallel cables to be able to transport the power;

7. Distance between single turbine platforms: 1 km (about 8D);

8. Distance between five turbine platforms: 3 km (this platform is 3 turbine wide);

9. Distance to shore: between 50 and 200 km;

10. Two system architectures based on chapter 3:
- Individual Variable speed with back to back converters based on IGBTs in each turbine:
    - option IV1: single turbine platforms in strings;
    - option IV2: five turbine platforms in star.

The IV-options have an AC connection to shore. Shunt reactors will be included if necessary;
- Park Variable speed:
    - option PV1: single turbine platforms in strings;
    - option PV2: five turbine platforms in star.

    The PV-options have a DC connection to shore based on IGBTs. Thyristor based converters of the same rated power would need more space, produce more harmonics and their controllability is less good. The converter operating as a rectifier is located on the central platform and the one operating as inverter is placed in the grid feed-in substation on shore. The connection to shore is often referred to as HVDC Light (ABB) or HVDC Plus (Siemens).

11. Average Annual Energy Production of single turbine: 15.7 GWh/y. This is considerably lower than the estimation in ERAO. It should be emphasized that, although the energy production of the Individual Variable speed system is expected to be better than of the Park Variable speed system, this is not taken into account in this study;

12. Array efficiency: 95%;

13. Economic evaluation includes all main electrical components between turbine generator and the grid feed-in substation (generators, substation extension and switching gear are excluded);
14. Cable laying included, additional platform for shunts excluded;

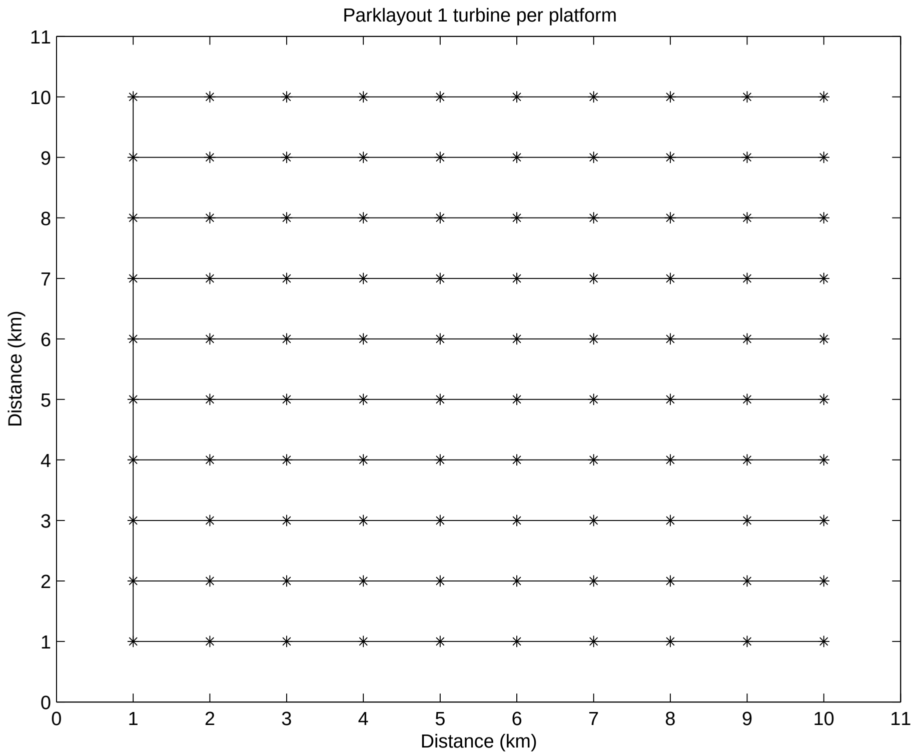

Figure 8 Layout of string configurations IV1 and PV1 (1 turbine per platform)

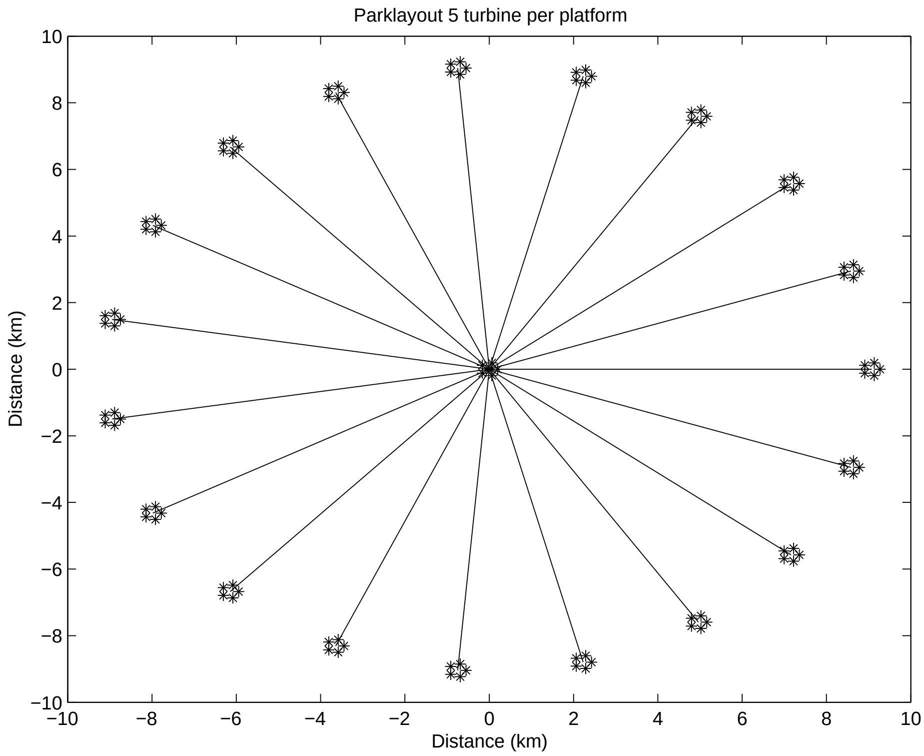

Figure 9 Layout of star configurations IV2 and PV2 (5 turbines per platform)

Budget prices of the year 2001, supplied by component manufacturers, have been used in the presented study. Unfortunately it was not possible to compare prices from different manufacturers. The number of suppliers of some of the larger components is very small and some suppliers are not willing to supply price information. A comparison was made during the ERAO study for two system types (C1 and PV1) with an evaluation performed by a turbine manufacturer. The results, also based on budget prices, did match. Budget prices probably represent more the upper limit, final price will depend on the number of component purchased and uncertain conditions during the negotiation process. The presented costs and kWh-price information should be considered as an indication only.

8.4.1 EeFarm results for Drijfwind

Figure 10 gives the price range of the four options in relation to the distance to shore. The difference between the one and five turbines per platform (string and star layout) is explained by the increased cable length inside the farm in the star layout: about 191 km compared to 110 km. Based on a *FYNDFARM* evaluation the platforms in the star layout could probably be spaced more closely together, bringing the prices of the star configurations down to those of the corresponding string layouts.

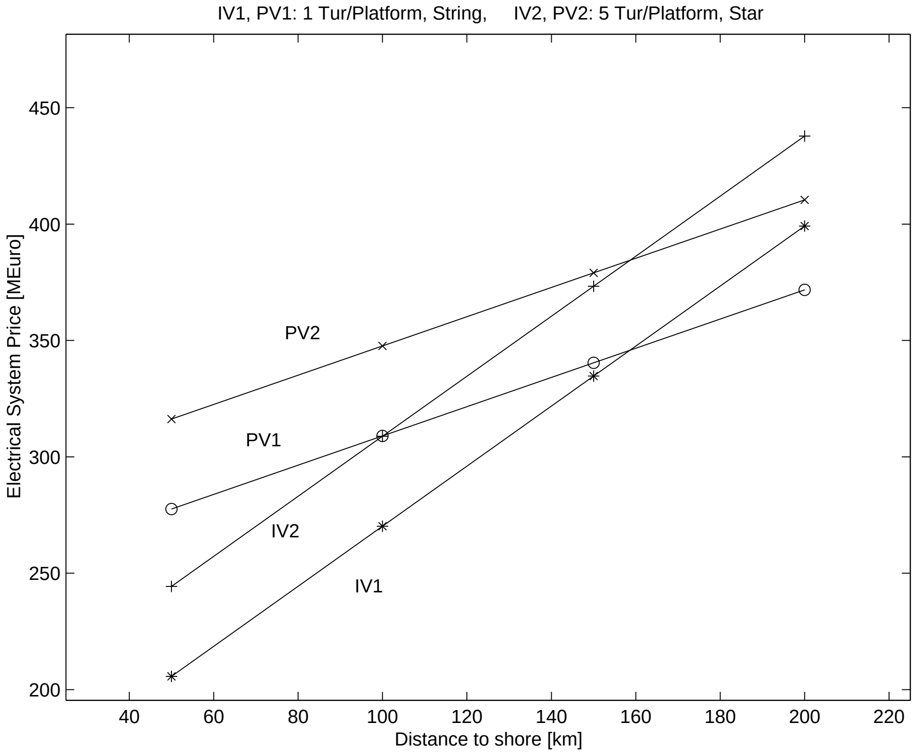

Figure 10 Electrical system prices

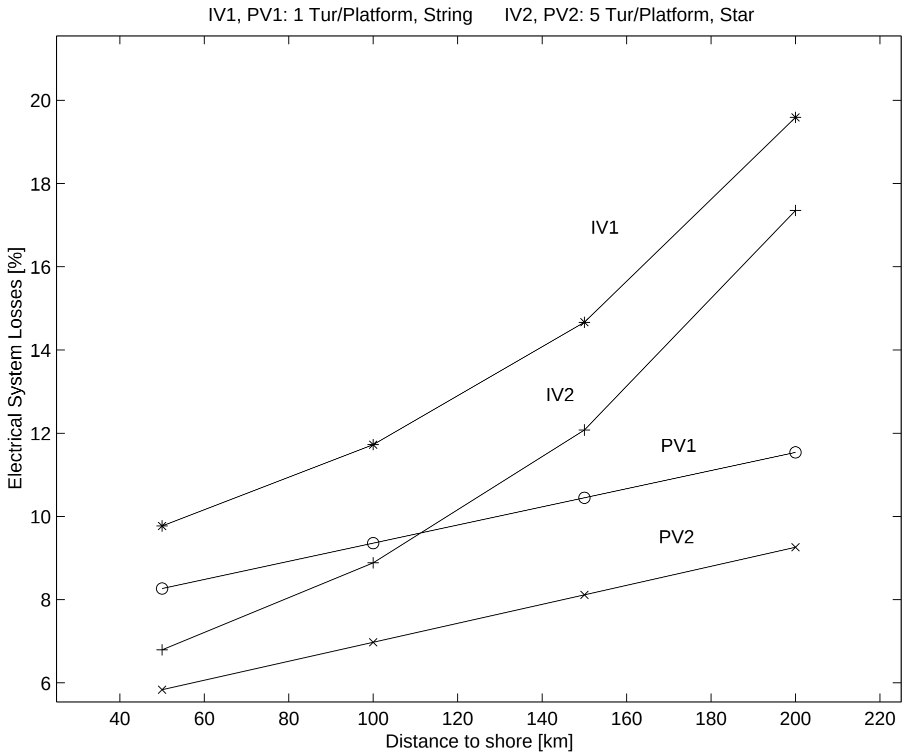

Figure 11 Electrical system losses Drijfwind turbine

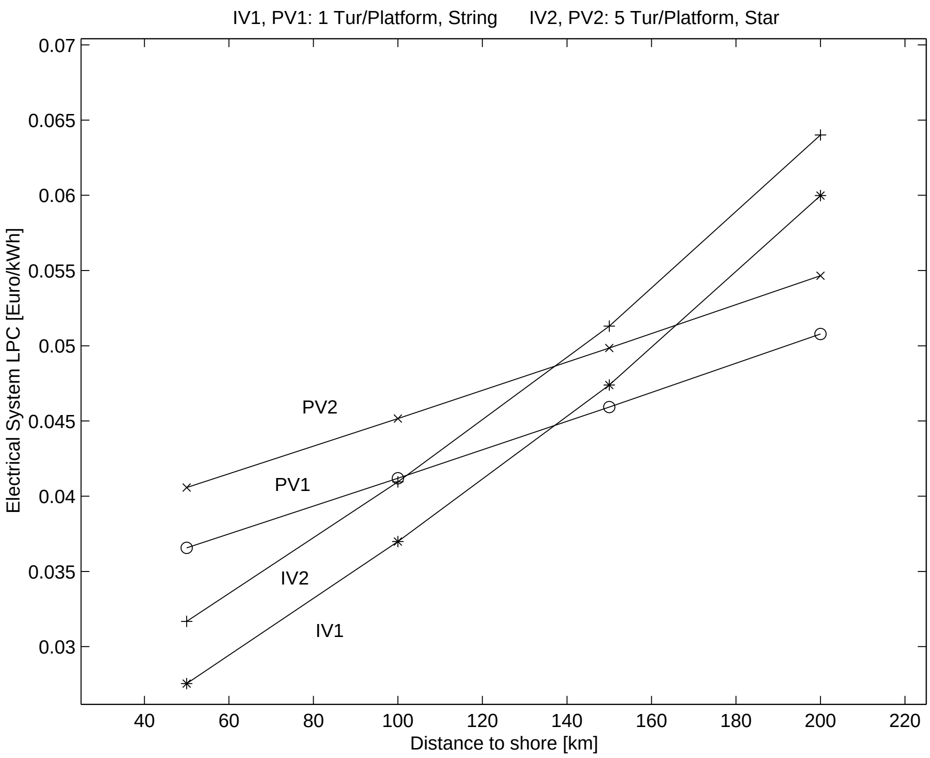

Figure 12 Electrical system LPC Drijfwind turbine

The load flow results (voltages and currents in all system components, not included in thisreport) show that the AC solutions IV1 and IV2 are still a valid options at long distances to shore. At 200 km the capacitive current is considerable. At full load of 500 MW the loading of the cable is given in the following table:

Table 2: AC cable loading for configuration IV2 and 200 km to shore

	Power (MW)	Reactive Power (MVA)	Apparent Power (MVA)	Voltage vector (kV_{rms})	Voltage (kV_{rms})	Current vector (Arms)	Current (Arms)
Cable in	484	-264	552	150-0.3j	150	1868+1015j	2126
Cable out	454	386	596	134-24.4j	136	1605-1963j	2535

Due to compensation of the capacitive cable current from the wind farm side as well as from the shore, the cable is still able to transport the full power without overloading (the rated current is 2196 A) if the voltage in the park can be increased by about 5% (resulting in an onshore voltage of about 145 kV instead of 136 kV) and the park reactive power is decreased by about 10%. For the layout and components chosen in this study, 200 km is the limit for the AC connection to shore. Above this distance the AC cable is overloaded and either shunts have to be included half way (which results in an additional platform or a special seabed construction) or the DC option (PV1 and PV2) has to be adopted. At 200 km and full load the phase shift in the AC cable between the voltage at the wind farm and the voltage at shore is about 10 degrees. The voltage drop is 14 kV.

The cable losses play an important role for the AC connection, see figure 11, since these in-crease for an AC connection more rapidly with distance that for the DC case. The rated energy density of the rotor is $\frac{5000}{\left(\pi \cdot 115^2/4\right)} = 0.481 kW/m^2$, which is relatively high. This will have a negative effect on the relative losses and on the contribution of the electrical system to price of a kWh (LPC), see figure 12. The energy production (0.95*1.57 GWh/y) is relatively low compared to the losses in the electrical system and the system price. This leads for the current design to relative losses: as high as 20% in the most unfavourable situation of the IV1 system at 200 km. Therefore, the rotor specific power should be optimized to make a better use of the electrical system by increasing the average loading. To investigate this effect, the turbine characteristics used in the ERAO study were taken as a reference: rotor diameter 124 m with rated energy density of 0 414 kW/m^2 and an energy production of 0.95*23.4 GWh/y. Figures 13 and 14 show the effect of the reduction in energy density and increase in production: the LPC roughly reduces with 1.5 Eurocent and the losses reduce by 1 to 6 percent points. The distances between the platforms (1 km for one turbine per platform and 3 km for five turbines per platform) the turbine rated power remained the same. Therefore, the system prices for the 124 m diameter options are equal to the 115 m diameter options (see figure 10).

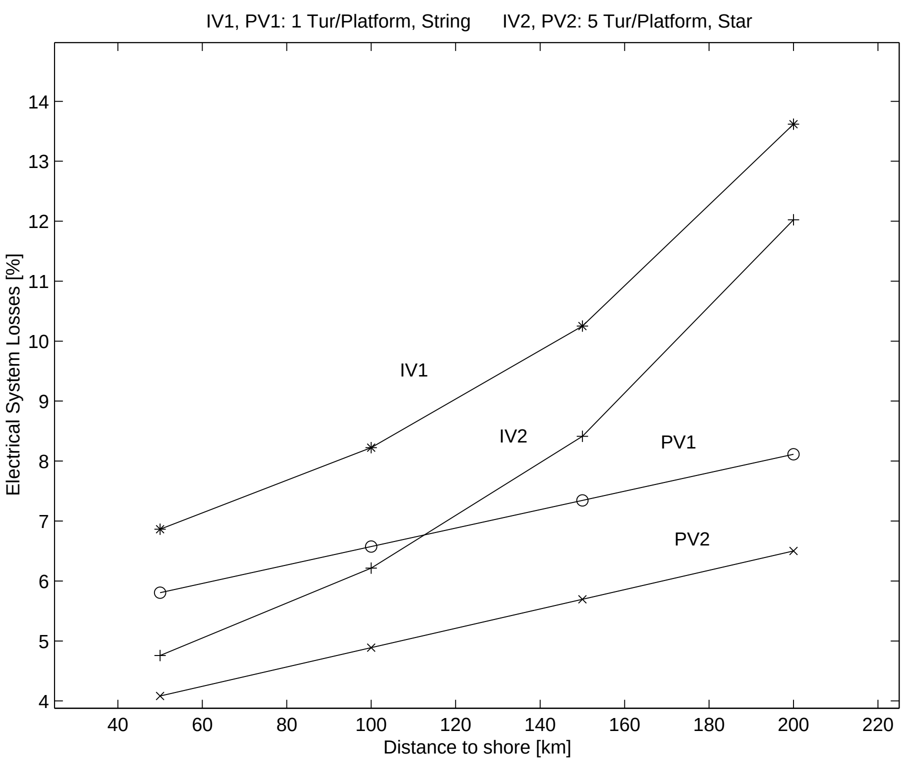

Figure 13 Electrical system losses ERAO turbine

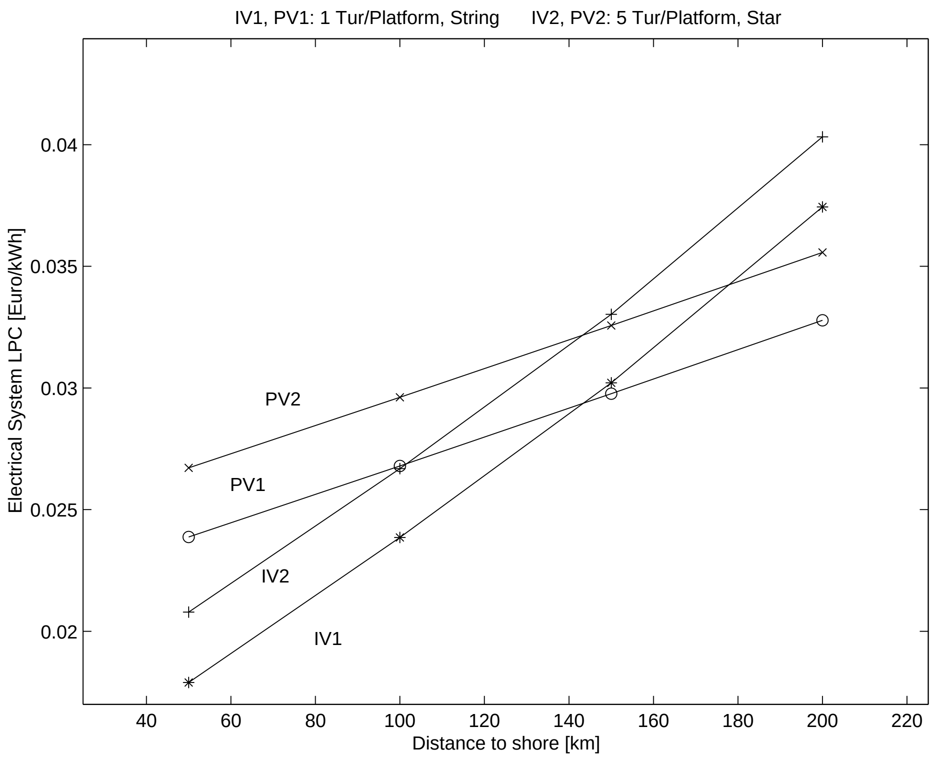

Figure 14 Electrical system LPC ERAO turbine

The losses in the star configurations turned out to be slightly lower than in the string configurations (see figures 11 and 13). This is surprising, since the medium voltage cables are longer in the star than in the string layouts. However, there is a factor which can counteracts this completely: the power to be transported by a cable section. In the star configuration the power is constant over the length of the cable and equal to 5 times the turbine power. In the string configurations the power increases linearly from 1 times the turbine power to 10 times the turbine power. Since the influence of the power on the losses is quadratic, the star configuration wins in this particular case.

The cables and the cable laying represent a major part of the cost of the electrical infrastructure. Since the power level is too high for a single three phase AC cable system at 150 kV, the con-nection to shore for the IV concepts is made by three parallel three phase cables. It is assumed that each cable system will be layed separately. This is a deviation from the assumptions in the ERAO study. For the DC cable to shore, the situation is better: a double bipolar cable system is required to transport the full 500 MW at 141 kV. This implies two laying operations. This partly explain why the prices and costs per kWh are more favourable for the DC system than in the ERAO study. This effect is amplified at longer distance to shore. The second major contribution to the electrical system price are the converters. The results show that a single converter of 500 MW operating at 141 kVdc is much more expensive than 100 converters of 5 MW operating at 7 kVdc.

8.5 CONCLUSIONS AND REMARKS

8.5.1 Conclusions

1. Two electrical system types, Individual Variable speed (IV) and Park Variable speed (PV), have been investigated for the connection of a 500 MW floating wind farm to the high voltage grid. Based on the assumptions in this study (see chapter 4), the individual variable speed system with 150 V AC connection has the lowest price for a distance less than 160 km. Above this distance, the park variable speed system with a 141 kV DC connection is cheaper.

2. The load flow calculations showed that it is possible to transport the full park power over a distance of 200 km with an AC cable without intermediate shunts.

3. For a distance of 200 km the electrical losses of an AC connection are relatively high. For the conditions in this studie an AC connection will loose 14-20% of the total park energy at 200 km. A DC connection dissipates 7-12% at the same distance.

4. For the contribution of the electrical system to price of the produced energy (Levelized Production Cost, LPC), the break even point for the two system types IV and PV is found at about 140 km distance. The difference in losses moves the break even point by 20 km in favour of the system with DC connection.

5. Two platform options were compared: a single turbine platform and a five turbine plat-form. The differences in price are caused by a wider spacing of the five turbine platform, induced by the star layout. The spacing in the star layouts can be reduced, bringing the five turbine platform results close to the single turbine cases.

6. Electrical system choice: Based on economics only, the best choice for the Drijfwind 500 MW wind farm will be the Individual Variable speed system for distances below 140 km and the Park Variable speed system for distance above 140 km. Differences in controllability and stability of the two options may influence the choice, but has not been investigated (see remark 2).

8.5.2 Remarks

1. Floating platforms tend to move up and down and possibly also sideways. Electrical cables are not designed for such conditions. A short list with questions was sent to two cable manufacturers to investigate the issue. No answer was received by the time of completion of this report. It is believed however that this matter should be investigated in the Drijfwind feasibility study.
2. This study has investigated the steady state electrical behaviour of the most promising electrical concepts for the Drijfwind project: individual variable speed and park variable speed. However, this is only part of the required information. A second major aspect in the choice of an electrical system is

its controllability and behaviour with respect to the (high voltage) grid. Studies on offshore wind farms in Denmark already have shown that control and stability aspects will play an important role in the final system choice. In order to be able to get more solid data on the control and stability of the different electrical options, dynamic turbine and park models are required, as well as measurement data to validate these models. The second phase of the ERAO project and IEA Annex 21 deal with these aspects.

8.6 REFERENCES

[1] B.H. Bulder. Feasibility study floating offshore wind energy: Terms of reference. Techni-cal Report ECN-CX-02-0??, ECN, 2002.

[2] J.T.G. Pierik, M.E.C. Damen, P. Bauer, and S.W.H. Damen. Electrical and control aspects of offshore wind farms, phase 1: Steady state electrical design and economic modeling, vol. 1: Project results. Technical Report ECN-CX-01-083, ECN Wind Energy, 2001.

8.7 ECONOMIC PARAMETERS IN ERAO AND DRIJFWIND EEFARM CALCULATIONS

The economic parameters are:

- operation and maintenance cost as percentage of the investment: 5%;
- nominal interest rate: 7%;
- rate of inflation: 2%;
- economic life time of the wind farm: 12 years;

an effective availability of 90%.

8.8 EEFARM PROGRAM

The *EEFARM* computer program has been written in MATLAB. It consists of the following modules:

EeFarm	main program successively loads component and general data for each specified configurations calls cluster for all wind speeds in P(V) curve calls loss evaluation module calls Levelized Production Cost module
Makestruct	transfers component data into clusterdata structure, included components depend on the configuration
EeData	component database, component data stored in structs Part 1: electrical components Part 2: P(V) curves
Parkconf	definition of configurations: loads individual components in system structure
Park	calls string, star, octo calls MV and HV components adds losses and costs of these components adds price of components
String	calls LV components in a string configuration adds losses and costs of these components adds currents of strings adds price of components
Star	calls LV components in a star configuration adds losses and costs of these components adds currents in star adds price of components
TurGen	current and voltage phasor at turbine generator terminals, frequency
B2b	output current and voltage phasor of back-to-back converter losses
Trafo	output current and voltage phasor of transformer losses
Rectifier	output current and voltage of rectifier losses
StepUp	output current and voltage of step up chopper losses
CableAC	output current and voltage phasor of AC cable losses
CableDC	output current and voltage of DC cable losses
Inverter	output current and voltage phasor of inverter losses
Eloss	average yearly electrical losses
EraoLPC	Levelized Production Costs of the electrical system

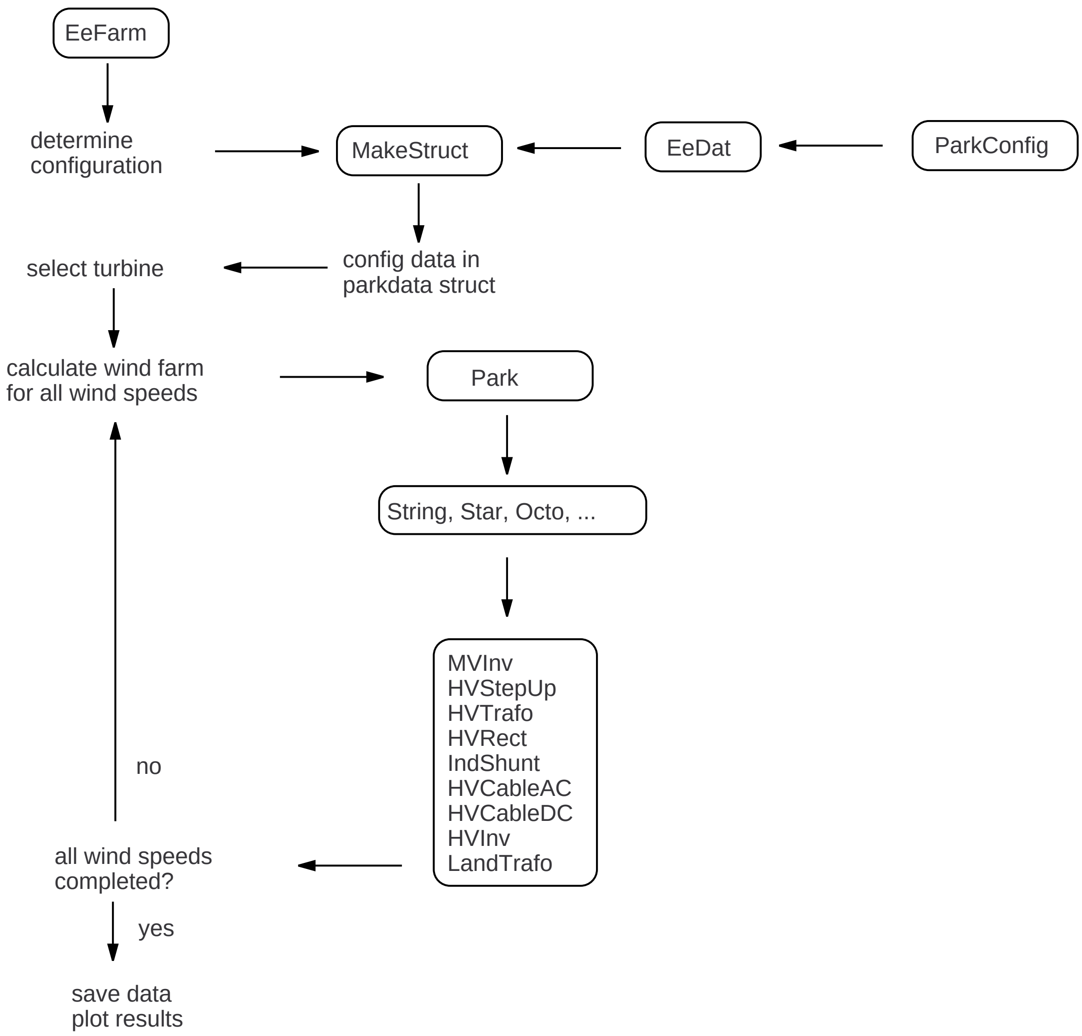

Figure 15 **EeFarm program structure**

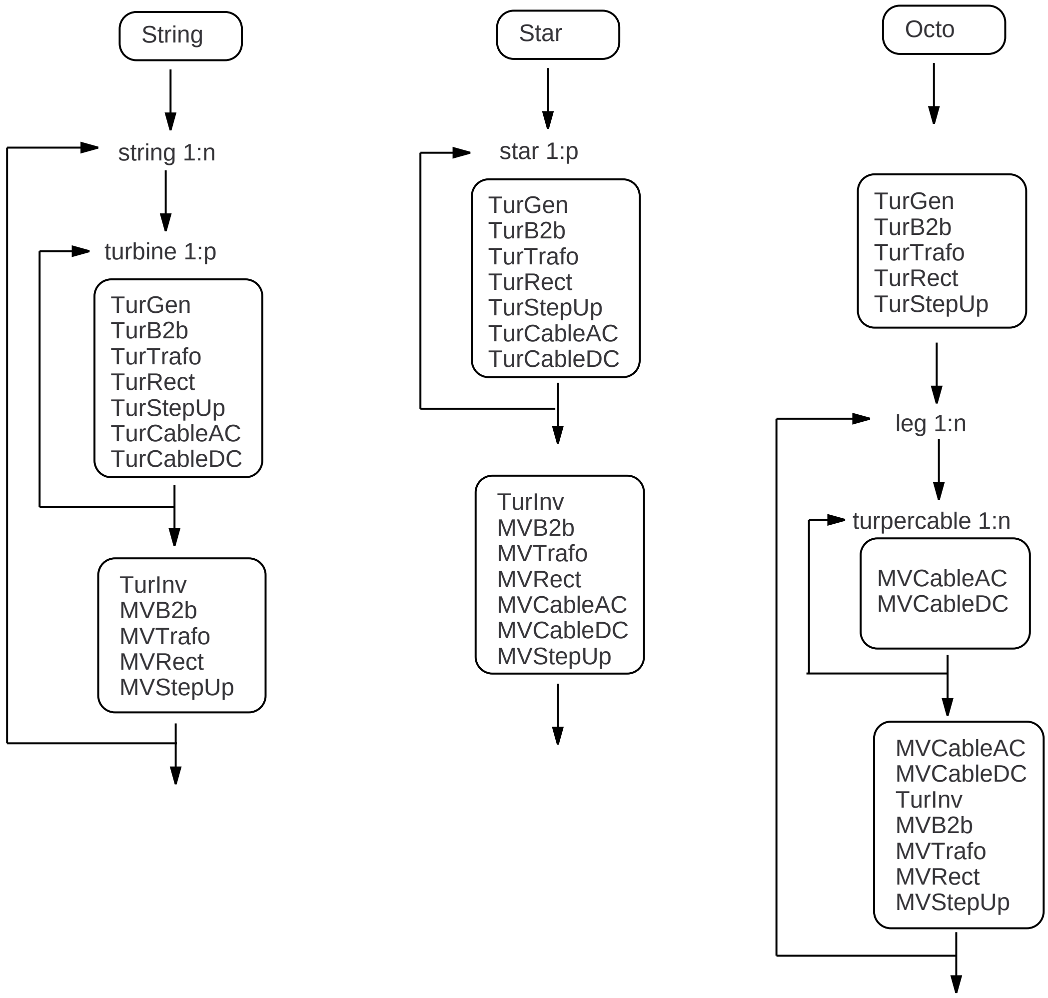

Figure 16 EeFarm program structure (continued)

8.9 QUESTIONS TO CABLE MANUFACTURERS

A consortium of industrial parties and research institutes is currently investigating the feasi-bility of a floating wind power plant. To give an idea of the scope, a paper prepared by A. Henderson, who is also involved in the current project, is included. One of the important issues in the investigation is the connection of the power cable to such a platform. The floating plat-forms are moored, chains and anchors keep the platform at its location but leave some freedom for motion, leading to movement of the cable and possibly twisting. To give an idea of the platform motion, it is expected that vertical oscillating movements of the platform of 5 m during a period of 12 seconds (the period of a wave) are possible. Depending on the wave spectrum of a given location, movements may contribute to degradation of the lifetime of a cable.

It would be of much help to us if you could give an idea with regard to the following questions:

1. which maximum motions and stresses are allowed in the cables you recommend for a submarine connection?

2. will fatigue limit the cable lifetime and can you give an indication of the allowed fatigue spectrum?

3. how could these cables be attached to the platforms to prevent any wear at the connection point?

The following answer was received:

```
Subject:
Request for submarine cable information
Date:
Mon, 8 Apr 2002 09:02:24 +0200
From:
leo.pols@nl.abb.com
To:
pierik@ecn.nl
Jan Pierik

Finally we have some comments to your old question for this issue.
1. The motions and stresses that are actual in a certain situation
are
input for the design of a dynamic submarine cable. The design is
made in
such a way that, amongst others, the eigenfrequencies of the cable
hanging from the floating platform are such that no stress or strain
limits
are exceeded. The maximum occuring strains and stresses have to be
judged for every part of the cable.
Therefor, no simple answer can be given and the issue has to be
studied.

2. The answer is more or less like under question 1. Fatigue will
always
limit a device, whether it is a cable or another object subjected to
mechanical stresses. The design has to be made such that the
fatigue limits will be met well after the guaranteed life-time of
the
object.

3. Special hang-off constructions, specially designed and used by
the oil
platform industry, are to be used.
```

Due to the strong mechanical forces of dynamic character involved, no lead-sheath is used for dynamic cables. Though the lead-sheath is a very well proven technique giving an abolute watertight barrier, it may become brittle after continuous mechanical stresses of the dynamic type. As this leads to a reduction of the watertightness and could lead to local reduction of the mechanical properties of the cable, leadsheaths are not used for dynamic cables.

The static part of the connections make preferably use of common lead-sheath technique.

Thrusting that we have served you herewith we remain
Kind Regards

Leo van der Pols
Sales engineer projects

	Date: Februari 2002	**Report No.:** ECN-CX- -02-025
Title	Drijfwind: Electrical System	
Author	J.T.G. Pierik	
Principal(s)	Novem/Lagerwey	
ECN project number **Principal's order number**	7.4139	
Programmes		

Abstract

An important aspect in the determination of the feasibility of an offshore wind farm is the choice of the electrical system, necessary to collect the power in the farm and transport it to shore. This report describes how this choice was made for the Drijfwind concept. Based on the results of the ERAO project the two most promising system types for Drijfwind have been chosen: individual variable speed and park variable speed. For these options, two park layouts based on platforms with 1 and 5 turbines have been investigated. These layouts correspond to different cable layouts inside the park: string and star. The second parameter investigated is the distance between the wind farm and the shore. The *EEFARM* computer program has used to calculate the electrical and economic performance of these options. Based on economics only, the best choice for the Drijfwind 500 MW wind farm will be the Individual Variable speed system for distances below 140 km and the Park Variable speed system for distance above 140 km. Differences in controllability and stability of the two options may influence the choice, but has not been investigated.

Keywords

offshore wind energy, electrical models, economic models, power performance

Authorization	**Name**	**Signature**	**Date**
Checked	B. Bulder		
Approved	L. Rademakers		
Authorised	H.J.M. Beurskens		

9 Operation and Maintenance

Summary

On behalf of a feasibility study for remote offshore wind platforms, which have a distance to shore in the range of 50 km and up, the maintenance costs in order to safeguard the availability of these systems has been estimated.
An issue that is of particular interest in this study, is the question to what extent it is profitable to perform “on site” maintenance in comparison with “on shore” maintenance for which the floating platform needs to be shipped.The factor that towing of a platform is subjected to a weather window leads to the result that “on site” maintenance is favourable for practically all failure mechanisms, since this weather window is supposed to present a clear barrier.
Specific “on shore” activities such as recovering of the platform or clustered activities within a “substantial overhaul” have been assumed to be unnecessary due to a maintenance free platform and the use of reliable components.

The cost calculations assume the availability of exchange parts, the costs of which are managed by using renewed cost-intensive components that have failed. Efficiency measures such as opportunity based maintenance or implementation of clustered corrective maintenance actions, have not been incorporated in the model since the failure rates are limited. This factor therefore determines the maintenance costs only to a limited portion of the accuracy of estimation.

Uncertainties with respect to the maintenance demand, resulting from the fact that no detailed design is present, are to be controlled by incorporating a RAM specification and assessment within the design phase of the final construction. In a RAM assessment the final design is evaluated with respect to its maintainability (with function loss during a specific time) and the resulting availability (capability to produce), by using the reliability performance data of the specific components.

The reliability data that are applicable for supposedly “maintenance free” components in order to safeguard the assumptions made within this study, are determined by a failure rate of ultimately $4*10^{-4}$ (yr^{-1}). This guideline in combination with availability criteria is applicable during the actual design phase.

The maintenance costs for a platform are estimated to 2,2 % of the investment costs (offshore position: 100 km).
This implies a reduction of 35 % of the actual “capital production” to be expected during a year.
In this calculation the capital effects of the realised CO_2 reduction have been omitted.

Contents

9.1 Introduction

Interest for Wind Energy Conversion systems increases due to the growing demand for durable energy sources and the improved reliability and profitability of the technology.
In order to meet environmental requirements, the use of offshore wind energy conversion systems is increasing. At larger offshore distances, due to the larger water depths, floating systems could provide economic advantages.
In order to envisage advantages and profits as well as bottlenecks and costs, a study “Studie naar haalbaarheid van en randvoorwaarden voor drijvende offshore windturbines” has been implemented in order to reveal the typical characteristics of a floating offshore energy plant.
Besides production as well as constructional aspects, the requirements presented due to the maintenance demand of the system during the operational phase, have to be listed as well.
This part of the project is dedicated to the phase during which the energy conversion plant is producing.
The next aspects have been defined as deliverables of this study and are hence elaborated in the scope of this report:

- A ± 50% estimation of the total maintenance costs, in dependence to "on site" maintenance or "off-site" maintenance
- Assessment of the availability of units, resulting from the maintenance demands of the unit.
- Effects of the implementation of various maintenance approaches imaginable; maintenance “on shore” or “off-shore”.

- The influence of the distance with respect to the maintenance planning (100 km offshore is the reference distance)
  a) Which decision criterion should be used in order to plan repairs?
  b) What are the consequences for the availability and the maintenance costs for this type of energy plant in comparison with onshore wind energy plants?
- In order to assess this planning, two configurations will be elaborated, incorporating, if possible, turning points or categorisation for the offshore distance.
- The risks of lightning for the performance of the wind park (this is considered to present a major risk by the manufacturer Lagerwey). The way by which this risk needs to be managed or banned is to be assessed.
- The requirements to be formulated in order to be able to exclude the risks of fatigue of the electricity connection cable as a source of failure (fatigue is considered to present a potential problem; the approach to be followed in order to tackle this risk is not yet clear).

- Identification during the operational phase of critical factors that are related to maintenance management, which should be addressed during the design phase in order to safeguard a reliable production unit.
- Determination of the effects of the location in terms of limitations with respect to the maintainability as resulting in repair time.
- A maintenance program implemented in Excel spreadsheet format with a detail limit to "sub-system level". In this program the next issues will be addressed:

  a) The yearly inspection and maintenance activities,

b) A list of repair tasks with respect to critical components, discriminated to "on site" and "off site" tasks.
c) A cost model with which the costs for a temporary transferral of the turbine unit to a harbour can be estimated.
d) The costs of operational management for a complete plant; off shore & on shore.

9.2 Definitions

Availability (Ref. 1 & NEN-EN 13306): The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided, expressed as the probability that a system will be in a condition to perform its intended function(s) when required.
Basic Maintenance Schedule: An overview of component and related preventive maintenance tasks in combination with the ultimate maintenance intervals per task and the clustered intervals as defined on the basis of efficiency purposes.
Corrective maintenance: Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.
Failure: The termination of the ability of an item to perform a required function.
Note 1: After failure the item has a fault
Note 2: “Failure” is an event, as distinguished form “ fault”, which is a state.
Maintainability (Ref. 1): The ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources, expressed as the probability that a system will be retained in, or restored to, a condition where it can perform its intended function(s), within a specified time.
OWEC - Offshore wind energy converter: single unit of the OWECS comprising wind turbine and support structure.
OWECS - Offshore wind energy conversion system: Entire system, comprising (usually) several wind energy converter units, for conversion of wind energy into electric power including the wind turbines, the support structures, the grid connection to the power delivery point and operation and maintenance aspects.
Note that the environment, i.e. air, water and soil as well as the utility grid, are not considered as a part of the OWECS.
Operation and maintenance aspects: auxiliary facilities, equipment and strategy required for operation, maintenance, control and administration of an OWECS.
Preventive maintenance: Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.
Primary failure: A failure of an item not caused either directly or indirectly by a failure or a fault of another item.
Reliability (Ref. 1): The probability that a system will perform its intended function(s), within the stated conditions, at a certain time, for a given time interval.
Secondary failure: Failure of an item caused either directly or indirectly by a failure or a fault of another item.
Surveyor: A surveyor is a professional person with the academic qualifications and technical expertise to practice the science of measurement; to assemble and assess land and geographic related information; to use that information for the purpose of planning and implementing the efficient administration of the land, the sea and structures thereon; and to instigate the advancement and development of such practices (definition Table 9.1 Ref. # 1). In this report the surveyor represents a person that decides which circumstances are allowed during transport in order to exclude risks in accordance with the requirements of the insurance companies involved.
Wave Height Hs: the “significant wave height” Hs is 4 x the square root of the total energy of the wave spectrum. Empirically it matches the average wave height of the one

third of waves measured during a representative period. Hence it doesn't represent the highest wave height that can be expected.

Weather Window: That period of time, which can be hours or days, during which weather elements are appropriate for a specific, selected transit, having considered the vessel and crew's capabilities and other constraints.

Wind Strength: the intensity of the wind expressed in Beaufort or metres per second.

Wind turbine (WT): Component of an offshore wind energy converter that transforms wind energy into electric power on generator voltage or AC-rectifier voltage, comprising rotor, nacelle with entire interior, control and safety system and electrical turbine system.

Support structure (bottom-mounted): Structure that supports the wind turbine and transfers the loading into the soil. Hence, the support structure comprises both the tower and the foundation.

Grid connection and wind farm layout: This comprises two main parts that are considered for convenience as one subsystem.

Firstly, electrical system that takes the power provided at the turbine connection points and collects it at the wind farm collection point(s) and successively transmits it to the onshore connection point with the public grid.

Secondly, the physical arrangement of the OWEC units.

9.3 Model structure

In this section the next issues will be discussed:
- The model used in order to structure the maintenance demand and related costs
- The object hierarchy used in order to identify different parts.

9.3.1 Information model

The model used in order to calculate the costs of maintenance is structured by discerning in the data input the next aspects:
Scenario, Task Breakdown and Failure mechanism.
Failure mechanisms are discriminated by means of the mechanism (e.g. lightning damage), impact on repair procedure (standard tools adequate or additional means necessary –e.g. crane) and the extent of the repair (repair of part or exchange of component).
The data output is structured by means of accumulating the results on the next properties: maintenance costs and availability.

9.3.1.1 Scenario

The model used in order to calculate the costs of maintenance makes use of maintenance scenario's. Scenario's are defined by discriminating both the maintenance situations (depending on the component it can fail due to a varying extent) as well as weather situations and various causes. The last detail has only been incorporated if that appears to have a clear effect (more than 10% of the result of that scenario) in the cost calculation or the availability.
Since all the situations result in effects that are separated in time as well as in space, the various scenario's with the accompanying corrective maintenance tasks can be summed in order to yield the overall effect.

9.3.1.2 Failure mechanisms

The failure mechanisms that determine the maintenance demand during the year, can be discerned by their principal character as denoted within the **r**eliability-**c**entered **m**aintenance RCM2 methodology (Ref. 5). Since the behaviour of a mechanism is essential when implementing maintenance management and identification of the deterioration process is essential when implementing control measures, the possibility for identification has been integrated in the model.
When detailed info about the mechanism was present, this has been elaborated in the model by linking it to a specific scenario. With the data present for failure due to lighting, this has been elaborated for those cases that meet the accuracy criterion for the model. The failure rates contributed to lightning, have been subtracted from the "averaged component failure rates" that had been obtained from other sources.
In this manner the effect of protective measures for lightning could be evaluated as well.
Details about the data used in the implementation can be found in § 9.5.3.

9.3.1.3 Strategy

For a specific failure scenario then, if effective, various maintenance strategies can be elaborated. A strategy is that Maintenance can be performed on site or off-site. In the last case the complete system has to be transferred to harbour facilities, where

maintenance can be performed thus reducing the influences of wind and waves and the need for additional hoisting barges.
The "off-site" strategy is only evaluated when it is likely that earnings due to increased maintenance cost efficiency will compensate the additional costs for transport of the platform. Items such as transmitters or electronic parts that are replaceable with comparable effort "on site" as "off-site" have therefore no "off-site" cost evaluation as denoted in the cost calculation model (spreadsheet appendix C).
The costs of harbour facilities have only been implemented in the model when that might yield a clear difference.
The "on site" strategy is elaborated by determination of the type of vessel needed in order to perform the maintenance task, and subsequently determining the delay involved with the use of this vessel by using the scheme of figure 1.
Since the type of vessels involved have no requirements with respect to the weather window during travel, the right side of the scheme has been omitted in the model (appendix C).

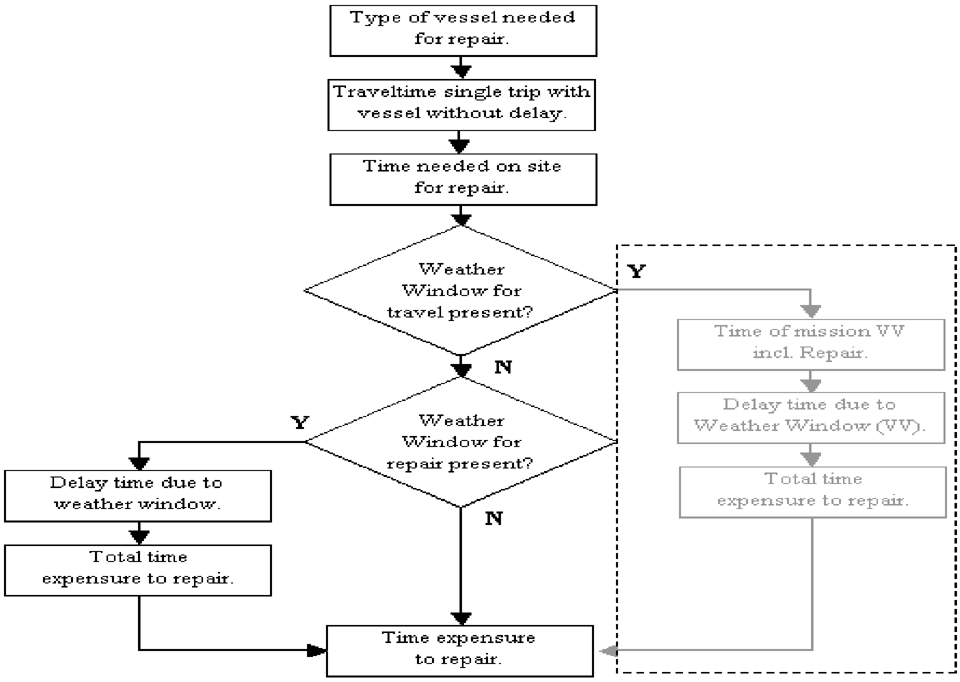

Figure 1: decision scheme for determining the mission time and the time to repair.

9.3.1.4 Task Breakdown

The maintenance tasks have been differentiated in order to reflect the fact that in a major number of failures of the system, a limited task can correct the failure.
A major corrective action for a component always means that the component needs to be replaced as a whole. If practise has shown that in 80% of the cases the failed component can be repaired with time, the resulting reduction of the costs of the component to be replaced has been incorporated in order to reflect this effect. This procedure is common for capital parts whose repair is labour intensive.
The task break down has been limited to the level that is necessary in order to identify the object subjected to a maintenance task and the equipment needed therefore.

9.3.1.5 Maintenance costs

The costs of parts have been accumulated using multiple information sources.
As a first step the data presented in Ref. 3 Annex B have been taken as a point of reference. This report presents the ultimate costs that might arise due to failure of a specific component as a percentage of the total investment costs.
The assumption (that can be deduced from the data presented) that a complete exchange of a part might cost 120% times the costs of a part as installed, has been adopted in the model calculation. One should realise that costs can increase due to costs of stock and loss of quantity effects that play a role during the investment phase.
As a second step for those parts that, when displaying a catastrophic failure, are apt for an exchange with "renewed parts", part costs amounting to 45% of the "part costs as installed" are incorporated (65% without exchange using "renewed parts" in stead of "new"; 20% remaining value for the failed part).
As a third step the accuracy has been enhanced by incorporating those part-costs that are known with more detail.

For Lagerwey parts, the costs have been derived from the costs –when known- of the 1,5 MW LW 70/1500 turbine, by extrapolating the component costs from 1,5 MW tot 5 MW using the historical formulae for extrapolation of investment costs in relation to generator power and assuming no increment of time expenditures for maintenance tasks.

The costs for transport equipment have been determined by using information gathered for earlier projects and comparison of this info with specific info gathered for this situation, taking into account the specific requirements as height and transport force needed for this type of platforms. For the costs the assumption has been made that contracts with firms for transport vessels have been made. In the offshore spot market (day to day business) prices can vary over the year with a factor 10 dependent on the seasonal requirements, which can be controlled by using contracts based on long-term services and a regular demand for this service.

9.3.1.6 Decommisioning costs

The costs for decommissioning have been studied in Ref. 12 fig. 16 and appear to account for 2,5 % of the total energy costs for a bottom mounted offshore energy platform.
When comparing the decommissioning costs for a floating platform with those for a fixed platform, the next statements apply:

a) the investment costs for a floating structure are higher due to the platform costs
b) the labour costs for decommissioning and equipment are lower due to less expensive handling on-site
c) the remaining value after 20 years are higher since a complete system can be traded,

Due to these factors the costs of decommissioning can be maximised on this 2,5%.
For the scope of this study with the required accuracy, these costs are neglected.

9.3.2 Object identification

The whole system that may contain 100 generators, contains the following system break down that is used in order to identify the system parts:

Offshore wind farm, or Offshore Wind Energy System (OWECS)

- Offshore Wind Energy Converter (OWEC= Wind Turbine)
  - Rotor- nacelle assembly
    - Rotor
    - Drive train
      - Generator
      - Shaft
    - Nacelle
    - Electrical power system
    - Control system(s)
  - Support structure
    - Tower
    - Floating platform
    - Fixture
- Infrastructure facilities
  - Maintenance facilities
  - Control, safety, administrative facilities
- Transmission system
  - Power collection
  - Power transmission

This object break down is reflected in the sheets (appendices B and C).

9.3.3 Specific situations

In Ref. 2 a visit of twice a year with more visits during the “demanding first year” is specified. Since the scope of this report extends over 20 years lifetime and the basic maintenance schedule clearly shows that a MTBM of **one** year is adequate, this intensity of standard once a year preventive maintenance visits is considered adequate.

9.4 Reference design

The reference design (Ref. 2) that has been incorporated, contains the next description:

Location		North Sea	
Water depth		more than 50 m	
Distance to shore		more than 25 km	
Weibull wind speed parameters @ 10 m height		V_{ave} = 9 m/s k = 2	
Wind shear profile		determined from a roughness height of 0.005 m	
Turbulence (IEC description)	I_{15} A	0.12 3	
wind rose		- (see Ref. 2; Draft)	
Wind farm turbine spacing		Approx. 8 Diameters apart.	
Wind farm array efficiency		95%	
Turbine data	General	Rated Power	5 MW
		Diameter	115 m
		Hub Height [1]	>80 m
		# blades	3
	Electrical system	Direct Drive generator	
Floater/Submersible		single wind turbine	
		3-5 wind turbines	
mooring?			
yawing?			
Water conditions		- (see Ref. 2; Draft; defined by Marin)	
Soil conditions(for anchoring)		Sand	
Economic parameters	Real Interest rate inflation rate economic lifetime	5 0 20	

The preliminary design for the floating system, as supplied by MSN, contains the following characteristics:

Number of support columns in base: Specific column data:		3	
Height per column	30 m	Distance between platforms:	0,8 km.
Column material	Carbon steel		
Wall thickness	10 mm		

The design for the electrical systems meets the following requirements (Ref. 3):

1. Turbine rated power: 5 MW
2. P(V) curve according to Terms of Reference (Ref. 2)
3. Platform rated power: 5 and 25 MW (1 and 5 turbines per platform)
4. Park size: 100 and 20 platforms (total rated power: 500 MW)
5. Star configuration (all platform cables connect to one central platform)
6. Distance between platforms: about 8D: 1 and 3 km
7. Distance to shore: 100 and 200 km
9. Average Annual Energy Production: 95% of single turbine

[1] Minimum height determined by rotor radius, maximum wave height and splash

With the platform design as shown in figure 1, the electrical systems options elaborated by ECN (Ref. 4) are delimited to two "string" configurations (10 turbines in line) with a "park variable speed" in PV-1 and the "individual variable speed" IV-1.

The costs of this electrical system have been approximated on the basis of the least square fit to the data presented for the range 50-200 Km.
The costs of a choice for a layout vary less then 20% to the average at a specific distance to shore.
The least square fit approximates the average within 2%. The accuracy of this cost-estimate is hence adequate within the scope of this study.
The maintenance demand of the PV-1 and the IV-1 layout and the consequences of a failure can differ due to the next main differences:

Figure 2: Drawing of the floating foundation construction; design by MSC – Marine Structure Consultants).

Concept:	**Type of connection to shore:**	**No. of separate lines to shore**	**No of converters**
IV-1	AC	3	100 (5MW)
PV-1	DC	2	1 (500 MW)

The functional loss of an essential component in a serial system leads to loss of the whole system. Due to the fact that in this phase of the design no specific component parts are known and hence generic failure rates need to be used, the IV-1 system provides more redundancy and is hence less vulnerable for incidents.
The chance of loss of a transport cable due to damage caused by a vessel's anchorage system (responsible for 53% of all cable failures according to Ref. 8) might be below acceptance limits since it is difficult to predict (depends on location, burial depth, presence and type of protecting stone layer). Nevertheless, the effects can be that large (loss of 50% of the capacity in PV-1 when one connection is lost) that the IV-1 option is assumed.
In Ref. 8 failure rates for cables of 0,32 failures per year per 100 km are given in combination with the remark that this represents old date that are likely to present an overestimate.
Since it is clear that due to the wide variation of the factors determining the failure rate can only be managed by setting quality standards, in this report it is assumed that the failure rate of the system can be neglected with respect to the other factors involved.
This implies that the risk of failure for the connection to shore is less than 2k€/yr (see § 9.5.2). The consequence of this figure for the probability of failure of the connection can be determined by assessing the effect of a cable failure. This effect can be estimated using engineering judgments as:

- loss of (part of) production capacity during 80 days due to 5 days repair time (cable has to be uncovered which presents a rather precise job), and a resulting average of 75 days delay in repair due to a weather window 6 (wave height below 1 mtr, wind strength below 6 m/s),

- estimating the production loss, with an average of 0,25 (§ 9.9 # 2) for the effective production capacity over the year and a loss of 1/3 of the capacity due to 3 redundant lines (IV-1 layout), to an amount of 0,08(€/kWh)*80*24*500MW*1000*0,25/3= 6,4 M€.
- additional costs for repair amounting to a fraction of the production loss which are hence not considered here.

In order to manage the risk of the loss below a 2k€/yr acceptance limit, the probability of failure for one of the cables in the whole system should be below $3*10^{-4}$ (yr^{-1}).
Hence the risk for an individual connection should be below 10^{-4}, which represents a clear challenge considering the length of the lines. For comparison a rather rough figure for the overall failure rate for power cables as 3 per million hours can be found in Ref. 9, what amounts to a failure rate $2,6*10^{-2}$ (yr^{-1}).

Within this study, the assumption is made that for the electrical systems this risk acceptance criterion is met and safeguarded by means of the requisitions imposed upon the manufacturers.

9.5 Input and selection criteria

The next data have been used as general input for the costs calculation:

		Parameters:		Note:
		Distance to shore:	100 km	1,852 ning intensity/yr/km2: 0,291 /(yr*k
	Towing platform to shore:	Type of boat:	Towboat 100 Tons &	Towboat for stability
		TransportSpeed (during towing):	4 knots/hour	or 7,4 km/hour implying at least 13,4 hrs
		Speed tugboat without tug (speed for normal repair):	12 knots/hour	or 22,2 km/hour implying at least 4,4 hrs
		Hourrate of tug boats:	0,6 k€/hr	
		Mobilisation costs tug-boats (start rate):	7,5 k€	=> total costs: 36,6 k€ (Go and retu
		Ultimate wind strength (not allowed during operations):	8 Bf	See Tab Winddata Costs and tr
		Travel time of single boat(s) to platform for repair :	4,5 hrs	
		Travel time: Tug OWEC to shore:	13,5 hrs	
	Transferring people to platform:	Type of boat:	Tender ship	
		TransportSpeed:	26 knots/hour	or 48,1 km/hour implying at least 2 hrs t
		Hourrate of boat:	0,4 k€/hr	
		Mobilisation costs boat (start rate):	1,5 k€	
		Ultimate wind strength (not allowed during operations):	6 Bf	See Tab Winddata
		Maintenance personel costs per hour (2 persons due to requirements):	160 €/hr	
	Transferring hoisting crane to platform:	TransportSpeed:	5 knots/hour	
	OWEC typicals:			
		Ultimate Height (m) in "straight up position"	138 m	=> coll. area: 0,53 km^2
		Energy price (per kWh):	0,08 €	Range: ± 0,02 € ; info HJT Kooiman ECI
		Turbine costs based on land based calculation:		
		Power:	5.000 kw	Yielding 400 Euro per hour when perforr
financial production yield/hr:	**100 € / hour**	Average production efficiency:	25,0%	Yielding average 1250 kWhour and 100
		Investment costs	850 €/kw	4.250.000 € Investement
		Floating platform costs:	3.000.000 €	Guestimation by telephone: Sanders -M
		Anchoring system:	1.000.000 €	Guestimation by telephone: Sanders -M
		Electrical infrastructure/OWEC:	2.820.000 €	=Average value for system IV-1 and PV-
		Total investment costs:	11.070.000 €	Investment costs for a fixed construct d.d.
	OWES System typicals:			
		Number of OWECS in system:	100	=> total capacity: 500 MW.

9.5.1 Detail needed during object decomposition

The extent of detail that has to be implemented in the model, is determined by the accuracy criterion stated that has been limited to 50%. This result should be valid under "normal" circumstances. This implies the validity criterion that the chance that the actual situation reveals results that differ more than 50% of the results calculated over lifetime should be less than 5 %.

Since various minor failure causes with relatively large effects could lead to relatively large impact, neither solely the repair costs nor the cost of neither a component nor the amount of labour can be used as a criterion for delimitation. The only criterion that can be applied in this case can be derived from the validity criterion.

For parts that lead to complete loss of production, and that exist in multiplicity within one OWEC, failures that meet the following criteria are judged to be negligible in the cost calculation:

- The resulting damage of one failure doesn't override 10% of the total maintenance costs as spent per year (TMC)
- The probability of failure of a component has less than 5% chance of appearing during the lifetime (20 years) for a single OWEC [2].

The average costs of such a component over the lifetime can be maximised to costs per year as 0,05/20*0,1*TMC, or $2{,}5*10^{-4}$*TMC.

Since even an amount of 100 comparable components within one OWEC, which is obviously rather rare, would produce over a year only a minor effect of 2,5%*TMC this criterion can be regarded as safe.

The TMC for a land based Lagerwey wind energy converter can be derived from the costs of an integral maintenance contract as specified for an all-in contract of 17 k€/yr for the LW72/2000 (Ref. 19); this covers the integral maintenance and profit but does not involve the loss of production. Assume 20 k€/yr as TMC for a 5 MW land unit.

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[2] Note that with this figure it is to be expected that within the whole system of 100 OWECs the failure will show up during the lifetime since the chance that not any failure will show up is $(0{,}95)^{100}$= 0,5%.

Referring to the land situation, failures with a risk delimited to 5 € (!) per OWEC per year are negligible; it is obvious that this limit is very low what leads to a large detail.
This risk criterion can be extrapolated in that sense that all damages that don't exceed this limit can be neglected.
Hence the design in combination with the O&M applied to the floating platform, should be such that the risk of chance of complete loss by a "fatal failure" of an OWEC unit over the lifetime should be below the risk limit for the offshore situation.

If the risk acceptance limit for an OWEC for single essential components is set at the component level to 2k€/yr, and the total investment is estimated to up to 11 M€ per unit (§ 9.9 # 4) and this figure is considered the maximal loss, the probability of fatal failures (yr^{-1}) resulting in complete loss of the platform (e.g. burn out) should be below $2*10^{-4}$. This implies high quality standards for critical parts such as the floating platform, the incorporation of early warning systems in order to tackle critical failures by means of the O&M program and the implementation of protection system in order to mitigate the effects of incidents to this acceptance level.

9.5.2 Accuracy of data needed

The requirements with respect to the accuracy of the determination of costs is the result of a process that contains the subsequent steps A) failure rate determination B) failure effect determination; cost effect calculation C) corrective action; cost calculation.
Since step A) multiplies with the steps B) + C), and since it is clear that variations within each step can accumulate, the variations in each step should be limited clearly below 50% for those cost factors, that contribute significantly to the overall result.
Within this calculation the target is set to 50% accuracy for the overall process, hence the accuracy of the failure rate calculation should be within 35% considering a 2 step process ($50 / \sqrt{2}$).

9.5.3 Failure due to lightning

The risk of failure due to lightning has been elaborated in Ref. 6 (model structure) and Ref. 7 (elaboration of cases). This study shows by means of calculated characteristics for a number of wind turbines in the range 1,5- 6 MW and offshore locations varying between 0 – 300 km that:

- The number of flashes per year per km^2 (NF(d)) decreases with the distance d to the coast.
- The size of the windfarm, the orientation and the size of the turbines has impact on this figure; the variation is limited to 11% around the middle value.
- The collection area (A; km^2) of an elevated object with height H (m) is given by $A = 28*10\text{-}6*H^2$ with a radius R=2,98*H. If the collection area's overlap this is to be corrected. The collection area depends on the blade position and may vary with 20% (§ 9.9 # 5) below the maximum of A which is obtained for the "straight up" position.
- A lightning strike results in a distribution of effects over various components (Appendix A).

From the data presented it can be concluded that:

- At a certain distance to shore, the variation due to differing orientation and size of the plants with respect to the middle value is maximal 11%.

- The middle values for the number of flashes NF(d) can be approached within 7% by the expression NF(d)= 0,25*(23+d)/(5,5+d). Since this 7% variation lies between the 11% this expression can be handled as adequate within the 11% variation of the data calculated. This accuracy is sufficient referring to § 9.5.2 for the cost calculation, assuming the data in Ref. 6 present the actual situation reliably (measured data are used in combination with assumptions for the 300km offshore site).
- The maximum collection area A for one floating OWEC is given by: Height H= hub height + diameter/2= 80 + 115/2= 138 meter. Hence A= 0,53 km^2 and R= 411 metres. On the basis of the reference design in chapter 9.4 the distance between two towers = 800 metres. With this data the overlap can be calculated to be less than 1% meaning that within the scope of this study the overlap can be neglected.
- The "hit rate" per year for one OWEC at a distance d is then given by: 0,53*0,25*(23+d)/(5,5+d). The assumption has been made that each hit results in damage unless a protection system is present with a specific distribution that (Appendix A).

9.5.3.1 Component costs

The costs of components have been derived from Ref. 6 annex B, where costs for components during replacement can be retrieved assuming that their investment costs can be categorized by 0.5%, 10% or 18% of the total investment costs. These costs are used as default costs.
More specific information with respect to the costs of components has been used if available, thus overriding the default values.
For the costs of the major complex components being the generator, the hub and the drive train, it has been assumed that in case of a major failure the repair will always take place by using a (renewed) exchange unit in order to save repair time. The costs of this approach have been estimated to 45% of the parts costs [3], incorporating the rest value of the failed component.
Parts costs have been estimated to be 20% higher than the costs of the item when obtained as part of the OWECS during purchase. This implies that the addition of all default costs amount to 120% of the investment costs.
The component costs have been linked to two repair categories:

Category 1 = repair or replacement that needs special equipment that requires rental and planning.

Category 2= repair or replacement enabled using common equipment.

Repair and replacement have been combined in this categorization, since in many cases repairable parts will be replaced in order to save time (repair may be delegated to specialised firms that calculate standard prices); the failed part may be repaired later and used as stock for future changes. Since this approach deviates from the categorization made in Ref. 6, the two categories discerned there are combined here and the costs averaged.

9.5.3.2 Equipment costs

Due to the large distance to shore what necessitates navigation permits outside the 30 miles zone and the lack of a helicopter platform, the transport equipment for

[3] For failure rates that accumulate to the exchange rate of 1 capital part over 1 year (for single components per OWEC and 100 OWECS in a production field, implying a failure rate exceeding 0,01/yr), the development of a dedicated exchange and revision spare part strategy may reduce the exchange costs of those components with a factor 2-4.

small repairs that can be applied within this study is limited to transport by means of a Tender vessel or a Tugboat.
A tender vessel lacks overnight facilities but is twice as fast as a tugboat.
Due to the lack of overnight facilities its use implies a daily go-return trip.
With 26 knots speed, travelling time for a 100 km OWECS will take minimal 4 hours.
On the basis of this figure, it is clear that the use of a Tender Vessel is only effective for short tasks like inspection visits, reset actions and limited repairs.
A tugboat offers advantages for more time consuming repairs or multiple actions that are clustered within one visit since it provides overnight facilities.
Due to clustering of activities, it can be expected that in practise a tugboat will be used in order to perform corrective as well as preventive actions on multiple platforms. One should realise that the costs made for one visit are at least 5 k€ and this implies that every occasion for opportunity based maintenance should be used.
In the calculation therefore the use of a tugboat, even for small repairs, has been incorporated.
The delay in repair time in comparison with a tender boat lies in the range of 2 hrs amounting to 200 € (using § 9.9 # 3) at time-average production. This is the possible error that has been introduced by this assumption for every limited task.

9.5.3.3 Labour costs

For the costs of maintenance personnel, an hour rate of 80 € has been assumed.
For every task on the vessel, two persons are needed due to regulations.
They can perform different tasks within one OWEC; working on separate platforms is not allowed (since in case of an accident immediate action should be guaranteed).
In the cost calculation the repair time involves the time needed by the team; the hour costs involve two man.

9.6 Results

For one OWEC, the total costs for maintenance of a system, without protection for lightning, amounts to 298 k€ per year. With a total estimated investment for an OWEC of 11,07 M€, this amounts to 2,7% of the total investment. This represents 38% of the averaged year "capital production" as estimated in this situation. With lightning protection this amounts to 277 k€/yr or 35% of the estimated capital production. These figures assume that the platform as well as the anchorage system has been built as maintenance free.
The availability of one OWEC is limited by 35 days production loss (including two days planned for preventive maintenance) due to failures and maintenance, hence resulting on an availability of 91%.
This availability exceeds the limits set within the requirements.

The waiting time for transport vessels has been assumed to be negligible; the prices used for the transport calculation have been assumed to be fixed on an acceptable level as set by means of contracts.
Since in practise the availability of transport means will be limited at specific times the actual performance of an OWEC might tend to become even less (ship owners strive for maximal activity and hence minimal availability on request). Since an availability of transport equipment that doesn't meet requirements can be tackled by adequate measures (e.g. dedicated boat) and clustered actions can improve performance, the accuracy of the prediction can be considered adequate.

The calculations show that the use of a lighting protective system with 90% effectivity, results in 22 k€ reduction of the maintenance costs. The loss of availability remains to a level of 33 days.

The costs for a protective system have been estimated to the order of 27 k€ (Ref. 7; 3 MW turbine). Hence the costs of a protection can be estimated to a pay-out time of less than two years, implying the need for such a system.

Towing a OWEC to shore for corrective maintenance tasks appears in general not to be cost effective, due to the next fact findings:

- the transport speed of the current platform design is estimated to be limited to 4 knots an hour, due to the fact that the height of the platform in combination with the depth of the substructure yield an direction insensitive type of vessel that might heave when torn with forces above 25 ton bollard pull. For a tug process to shore this implies a time of minimal 13 hrs for a 100 km offshore position.
- The weather window, which will be set by a surveyor in practise, is estimated to 1 metre wave height and 6 m/s wind strength. The delay in maintenance efficiency this presents (up to several weeks during wintertime – go/ return - for the more time consuming maintenance tasks for which towing forms a consideration), doesn't compensate for the possible gain in efficiency on the shore.

A "pareto" presentation of the "top 4 costdrivers" presents (100 km to shore; lightning protection "switched on") yields the next list:

1	Rotor Blades,	62 k€/yr	and	137 hrs unavailability
2	Yaw system,	50 k€/yr	and	75 hrs unavailability
3	Inverter,	45 k€/yr	and	347 hrs unavailability
4	Pich mechanism,	34 k€/yr	and	94 hrs unavailability

9.7 Recommendations

The maintenance demand for corrective maintenance should be reduced to a level that is acceptable from a costs and availability perspective. The fastest improvements can be accomplished by reducing the failure rate of those processes that appear to contribute heavily due to the characteristics of the repair scenario (repair time, delay due to weather window and repair time needed). Focus is provided by the list of cost drivers.

As suggested in Ref. 20 a reliability approach in which target levels for availability and maintenance costs are set will provide the certainty for the return on investment.
A number of standards are available (Ref. 15, Ref. 16, Ref. 17 and Ref. 18) that provide the means in order to define the specifications in terms of a RAM-spec that are to be used in communications with suppliers.
Estimations of the costs of a RAM-spec of a part have yielded an amount of 5-10% of the equipment costs. The costs for registration of maintenance data with the detail needed, can be estimated to 10% of the maintenance costs. These costs can be equalised to 2300 Hrs (96 days) production loss for a single unit.
The merits of such an approach lie in an increasing efficiency of maintenance (that can be estimated to at least 10%, compensating for the investment) and a reduction of the unavailability with 25% over the lifetime, what amounts to 8 days per year.

It is recommended to use a RAM-spec during the design phase since the balance can be expected to be cost-effective within 1 yr for ten turbines already. With the multiplicity presented by 100 OWECS the positive effect of such an approach is obvious.

9.8 References

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9.9 Data reference list

Data used in this report that are not straightforward and hence require arguments, are presented in this section in order to provide traceability.

Table 9.1

Ref. ID #	Term or Parameter	Property	Argument
1	Surveyor	Task; definition	International organisation of surveyors FIG; http://www.ddl.org/figtree/general/definition.htm
2	Average effective production rate	Value; 25%	Reasonable value based on published rates for offshore sites Fjaldene (23,2 %) and Tunø (32,3%) (Ref. 21), estimation of 43% in Ref. 20 and the onshore site Moerdijk (24%; Ref. 22).
3	Time averaged production yield per generator	Value; 100 €/hr	Value obtained by combining Ref. ID # 2 with design generator power times 0,08 €/kWhr (error 25%), info H.J. Kooiman ECN (8 july 2002).
4	Investment costs per platform	11,07 M€	Assumed 100 generators; division of costs for electrical infrastructure over 100.
5	Variation in lightning collection area	20%	Table A.1 in Ref. 6 assessed the variation in the collection area of a turbine depending on the position of the blade.

Data and value generated within the scope of this study.

A Lightning damage fault distribution

The distribution of faults for wind turbines without a protection system (Ref. 7) combined with the reduction in failures when using standard lightning protection is as follows:

	component Fault Type Class (FTC)			
	1	**2**	**3**	Total
control system	21,0%	9,0%		30,0%
electric	10,5%	13,2%	2,6%	26,3%
rotor blades	8,0%		11,9%	19,9%
sensors	12,8%			12,8%
generator	2,1%	0,6%	0,3%	3,0%
hub	1,6%	0,4%	0,2%	2,2%
hydraulic system	0,3%	1,4%		1,7%
yaw system	0,2%	1,0%		1,2%
gear box	0,2%	0,7%	0,1%	1,0%
mechanical brake	0,2%	0,7%		0,9%
drive train	0,1%	0,4%	0,1%	0,6%
structural parts	0,1%	0,1%	0,3%	0,5%
Distribution FTC:	57,1%	27,5%	15,5%	

component Fault Type Class (FTC)		
1	**2**	**3**
90,0%	90,0%	90,0%
90,0%	90,0%	90,0%
0,0%	90,0%	90,0%
90,0%	90,0%	90,0%

Table 2.3.1: Efficiency of standard protection system.

The efficiency of the protection system has been incorporated in the model. Enabling a protection system changes the failure rates for those items, that are influenced by lightning damage and that get protected.
These items subjected to lightning incidents have been marked by a red checkmark in appendix C, column “failure type class”.

B Preventive maintenance program

The draft preventive program as set-up by Lagerwey for the LW-70-1500 has been analysed and transposed to a basic maintenance schedule for a 5 MW floating turbine.
The result is displayed here.

Item Part to be maintened Reference to Lagerwey document LW-C1-345-00-R0 version 27-6-02	Discipline E= Electrical I = Instrumental S/R= Static/ Rotating	Task_ID Denomination of the clustered task which contains the subsequent taskts denoted.	Maintenance_task_type Preventive Condition assessment, Preventive Maintenance, Description of task	Cause The reason why this task has to be performed. Options are: -L- Legal requirement and/or requirement of authority; -N- Safeguarding reliability by caring actions or Y/N test -Q- Safeguarding reliability by Calibration (Quality assessment).	Shut_ Down Mark Y/N if shut down is required for task.	Soll_Interval Ultimate maintenance interval by reason of Pfail and legal requirements. (Year).	Kann_Interval Applicable maintenance interval by reason of clustering, logistic or production reasons. (Year)	Remark	Time_expenditure Time needed in order to perform this task within the Total Task ID as denoted in the column "Maintenance_task_type". (Hours)
6.1 Foundation	S/R	Routine O&M	C; Visual	N	Y	12	1		12/16
6.4 Tower and platforms	S/R	Routine O&M	C; Visual	N	Y	12	1		12/16
Cables	E	Routine O&M	C; Visual	L;N	Y	12	1	NEN 50110, NEN 3140 & NEN 3840.	3/16
TL-Armatures and emergency lighting	E	Routine O&M	C; Visual	L;N	Y	12	1	NEN 50110, NEN 3140	3/16
Elevator	E	Routine O&M	C; Visual	N	Y	12	1	NEN 50110, NEN 3140	3/16
Earth connections	E	Routine O&M	C; Visual	L;Q	Y	12	1	NEN 50110, NEN 3140	12/16
6.5 TOWER TOP FLOOR									
6.5.1 Cable work	E	Routine O&M	C; Visual	Q	Y	12	1		3/16
6.5.2 Yaw pinion	S/R	Routine O&M	C; Visual and Clearance measurement	Q	Y	1	1		3/16
6.5.3 Yaw bearing	S/R	Routine O&M	C; Visual	Q	Y	1	1		3/16
6.5.4 Yaw brakes	S/R	Routine O&M	C; Thickness Measurement	Q	Y	1	1	Interval extendable by changing criteria.	12/16
6.5.5 Cable twist sensor	I	Routine O&M	C; Visual, Y/N test and Calibration	N;Q	Y	1	1		3
6.5.6 Cleaning	S/R	Routine O&M	M; Cleaning	N	Y	Infinite	1		4/16
6.6.1 First aid box	S/R	Routine O&M	C; Visual	L	Y	12	1	Arbo (?)	4/16
6.6.2 Fire-extinguisher	S/R	Routine O&M	C; Visual	L	Y	1	1	According to NEN 2559 this should be controlled by a REOB certified maintenance man	4/16
6.6.3 Grease lubrication system	S/R	Routine O&M	C; Visual	Q	Y	1	1	Interval extendable by extending reservoir-size.	4/16
6.6.6 Connecting laptop	I	Routine O&M	C; Paramater check	Q	Y	12	1	Interval extendable by proving extended reliability of system.	1 8/16
6.6.7 Cable work	E	Routine O&M	C; Visual	L; N	Y	12	1	NEN 50110, NEN 3140	4/16
6.6.8 Connections	W	Routine O&M	C; Visual	N	Y	12	1		4/16
6.6.9 Lubrication of the yaw bearing	S/R	Routine O&M	C; Visual	Q	Y	1	1	Interval extendable by extending reservoir-size.	12/16
6.6.10 Lubrication of the yaw motors	S/R	Routine O&M	M; Greasing	N	Y	1	1	Interval extendable by extending reservoir-size.	12/16
6.6.11 Lighting and emergency lighting	E	Routine O&M	C; Function test	L	Y	12	1	Arbo	4/16
6.6.12 Nacelle control box	E	Routine O&M	C; Visual and function test	N	Y	12	1		12/16
6.6.12.1 Acceleration sensor	I	Routine O&M	C; Function test	Q	Y	3	1	Extendable by using proven reliable components and redundancy.	1 8/16
6.6.12.2 Analog input signals	I	Routine O&M	C; Calibration	Q	Y	3	1	Extendable by using proven reliable components and redundancy.	3
6.6.12.3 Glas fibre cables	I	Routine O&M	C; Visual	N	Y	12	1		4/16
6.6.12.4 Automatics	I	Routine O&M	C; Function test	N	Y	3	1	Extendable by using proven reliable components and redundancy.	12/16
6.6.12.5 Windsensor	I	Routine O&M	C; Function test	N	Y	1	1		12/16
6.6.12.6 PLC	I	Routine O&M	C; Function test	N	Y	1	1	Extendable by using proven reliable system with redundancy.	12/16
6.6.12.7 Yaw motors	I	Routine O&M	C; Function test	N	Y	3	1	Extendable by using proven reliable components and redundancy.	12/16
6.6.12.8 Hydraulic unit	I;S/R	Routine O&M	C;M; Function test and filter exchange.	Q	Y	3	1	Extendable by using proven reliable components and redundancy.	3
6.7 Generator									
6.7.1 Lubrication of the main bearing	S/R	Routine O&M	C; Visual	N	Y	3	1	Interval extendable by extending reservoir-size.	12/16
6.7.2 Generator windings and coil / isolation	E	Routine O&M	C; Function test	Q	Y	6	1		12/16
6.7.3 Temperature sensor PT100	I	Routine O&M	C; Function test	Q	Y	3	1	Extendable by using proven reliable components and redundancy.	1 8/16
6.8 Maintenance of the rotor and rotor blades									
6.8.1 Cable work	S/R	Routine O&M	C; Visual	N	Y	6	1	Either immediate renewal or condition should allow use till next maintenance visit.	4/16
6.8.2 Bolt connections	S/R	Routine O&M	C; Visual	N	Y	6	1		12/16
6.8.3 Pitch unit	S/R	Routine O&M	C; Visual	N	Y	3	1		4/16
6.8.4 Lubrication pitch unit	S/R	Routine O&M	M; Lubrication	N	Y	1	1	Interval extendable by extending reservoir-size.	12/16
6.8.5 Pitch gear greasing	S/R	Routine O&M	M; Greasing	N	Y	1	1	Interval extendable by changing oil-type and grease system.	12/16
6.8.6 Overspeed sensor	I	Routine O&M	C; Function test	N	Y	3	1	Extendable by using proven reliable components and redundancy.	12/16
6.8.6.1 Dynamical test for 1,5 MW	I	Routine O&M	C; Function test	Q	Y	3	1		3
6.8.7 Lightning protection	E	Routine O&M	C; Function test	Q	Y	6	1	Reliability of test procedure not clear.	1 8/16
6.8.8 Slipringset	E	Routine O&M	C; Visual	N	Y	6	1		8/16
6.8.9 Rotor control box									
6.8.9.1 Cable work	E	Routine O&M	C; Visual	N	Y	6	1		4/16
6.8.9.2 Components	E	Routine O&M	C; Visual	N	Y	6	1		4/16
6.8.9.3 Batteries chargers	E	Routine O&M	C; Function test	Q	Y	6	1		1 8/16
6.8.9.4 Adjusting Maxi Meastro	I	Routine O&M	C; Visual	Q	Y	3	1		4/16
6.8.9.5 Batteriespack	E	Routine O&M	C; Function test	Q	Y	1	1	Extendable by using proven reliable components and redundancy.	1 8/16
6.8.9.5.1 Replacement of the batteriespack	E	Routine O&M	M; Replacement	N	Y	3	1	Opportunity based exchange is combined with redundancy philosophy.	4/16
	Total time expenditure		Hour rate:						
	E	9	€ 80,00						
	I	17 1/2	€ 80,00						
Note: Total no.: of hours calculated = 35	S/R	8 1/2	€ 80,00	Remark:					
Manhour Costs (travelling excluded):			€ 2.834,40	N.b.: referentie #16: 40 hr/jr.					
Travelling time (go/return):			8	N.b.: go-return on two days.					
No.: of persons:			3						
Total no.: of km's:			500	= 160 Euro	0,32 €				
Travelling costs:			€ 2.080,00						
Subtotal:			€ 4.914,40						
Logistics / planning / management / additional expenses (material):			10%						
this amounts to:			€ 491,44						
Total:			€ 5.405,84	Amount for LW-72-2000 Land location is specified to 5407 Euro according to E-mail Dersjant (manager customer relations) dated 16 jul 2002.					

The total costs for preventive maintenance can be estimated to **17,5 k€**. 5,5k€ for labour costs, 13,4 k€ for travel assuming the use of a Tugboat (€ 6000/day) at 12 knots/hr. (so 100 km in 9 hrs with 9*2*80 € travel expenses or 1,4 k€ –at least 2 persons perform maintenance) in order to be able to make one overnight stay for 2 day’s labour

C Corrective maintenance program

The corrective tasks to be expected, are presented in the next table and explained on the next page:

Specification of failure causes and failure effects (FMECA).

Fault type class: **FTC1** Repair, Cleaning, Reset
FTC2/3 Replacement

This column to be implemented **manually** on the basis of column N and O

Average T_delay towing OWEC to shore: (hours - go return-) **338 hrs** or 14,1day

Yellow Fields in this column concern "Good Engineering Judgments - WsG-".

Data mentioned in this column have been transferred from ref. Sheet.

Scenario: Situations that impose the need for a different approach are separated in different row's.

FailForm: - Bath-tub - Monotonous limited by Wear-out - Gradual Increasing - Incubated - Monotonous - Gradual Decreasing - Childs desease

Repair Type Class: C1= repair needs special equipment that requires rental and planning. C2= repair enabled using common equipment.

Component:	Comment:	Lightning damage	Wear process	Aging (corrosion; embrittlement)	Other (see remark under specs)	FailureChance	FailForm	Repair Type Class:	Reference	M_Component	Values: 0,5 / 1 / 2 / NR Limit_Wave	Values: 6 / 12 / 15 / NR Limit_Wind.	Weather Window:	(hours) T_Repair_NoTravel	Equip_Req	T_Delay_Equip	(hours) T_Delay_Seazon	T_Travel	Costs_Material (kEuro)	(Euro) Costs_Equip	(Euro) Costs_People	Total Costs Failure Offshore (including costs due to lack of production):	Unavailability (hrs):	Dock_Repair_Feasible	Costs_Dock_Equip	TimeToRepair incl T_delay (-go return-) towing OWEC to shore incl (single trip) travel time tugboat to OWEC:	(incl. Production loss) Total Costs Dock Repair (kEuro)
Rotor blades						0,1253	M	C1	DOWEC-2	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	133 k€	238.674 €	11.136 €	61,6 k€	137 hrs	Y		418 hrs	27 k€
	All seazon; disc	X				0,0035	M	C1	ECN-3	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	133 k€	238.674 €	11.136 €	1,7 k€	4 hrs	Y		418 hrs	1 k€
Hub or Shaft						0,0188	M	C1	DOWEC-2	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	344 k€	238.674 €	11.136 €	13,2 k€	21 hrs	Y		418 hrs	8 k€
	All seazon; disc	X				0,0006	M	C1	ECN-3	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	344 k€	238.674 €	11.136 €	0,4 k€	1 hrs	Y		418 hrs	0,3 k€
	All seazon; disc	X				0,0058	M	C2	ECN-3	Part	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	15 k€	21.450 €	9.120 €	0,5 k€	2 hrs	N			
Bearings	Hub + Bearings has been spli					0,02	M	C1	DOWEC-2	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	60 k€	238.674 €	11.136 €	8,4 k€	22 hrs	Y		418 hrs	3 k€
Generator						0,00913	M	C1	DOWEC-2	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	344 k€	238.674 €	11.136 €	6,4 k€	10 hrs	Y		418 hrs	4 k€
	All seazon; disc	X				0,00087	M	C1	ECN-3	-	1	6	6	48 hrs	Crane	0	1.033 hrs	10,8 hrs	344 k€	238.674 €	11.136 €	0,6 k€	1 hrs	Y		418 hrs	0 k€
						0,0321	M	C2	DOWEC-2	Part	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	15 k€	21.450 €	9.120 €	2,5 k€	11 hrs	N			
	All seazon; disc	X				0,0079	M	C2	ECN-3	Part	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	15 k€	21.450 €	9.120 €	0,6 k€	3 hrs	N			
Hydraulic system	Is present within the LW 70/1					0,115	M	C2	Drijfwind		2	12	10	24 hrs	Tugboat	0	35 hrs	4,5 hrs	9 k€	13.050 €	5.280 €	3,8 k€	7 hrs	N			
	All seazon; disc	X				0,00495	M	C2	ECN-3	Part	2	12	10	24 hrs	Tugboat	0	35 hrs	4,5 hrs	9 k€	13.050 €	5.280 €	0,2 k€	0 hrs	N			
Blade tips						0,2567	M	C2	DOWEC-2	-	1	6	6	12 hrs	Tugboat	0	93 hrs	4,5 hrs	3 k€	8.850 €	3.360 €	6,6 k€	28 hrs	N			
	All seazon; disc	X				0,0233	M	C2	ECN-3	-	1	6	6	12 hrs	Tugboat	0	93 hrs	4,5 hrs	3 k€	8.850 €	3.360 €	0,6 k€	3 hrs	N			
Yaw system						0,22	M	C2	DOWEC-2	-	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	159 k€	21.450 €	9.120 €	50,1 k€	75 hrs	N			
	All seazon; disc	X				0,0058	M	C2	ECN-3	Part	2	12	10	8 hrs	Tugboat	0	16 hrs	4,5 hrs	9 k€	7.450 €	2.720 €	0,1 k€	0 hrs	N			
Pitch mechanism						0,28	M	C2	DOWEC-2	-	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	60 k€	21.450 €	9.120 €	34,7 k€	94 hrs	N????			
Nacelle						0	M				1	6	6			0				?	#VALUE!	#VALUE!	#VALUE!	N			
Mechanical brake						0,04738	M	C2	DOWEC-2	-	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	15 k€	21.450 €	9.120 €	3,8 k€	16 hrs	N			
	All seazon; disc	X				0,00262	M	C2	ECN-3	Part	2	12	10	8 hrs	Tugboat	0	16 hrs	4,5 hrs	0,4 k€	7.450 €	2.720 €	0,0 k€	0 hrs	N			
Parking brake						0,05	M	C2	DOWEC-2	-	2	12	10	24 hrs	Tugboat	0	35 hrs	4,5 hrs		13.050 €	5.280 €	1,2 k€	3 hrs	N			
Tower						0	M	C1	PersComm		1	6	6			0		10,8 hrs		?	3.456 €	#VALUE!	0 hrs	N			
Structural parts	All seazon; disc	X				0,0006	M	C2	ECN-3	Part	2	12	10	8 hrs	Tugboat	0	16 hrs	4,5 hrs	5 k€	7.450 €	2.720 €	0,0 k€	0 hrs	N			
	All seazon; disc	X				0,0009	M	C2	ECN-3	-	2	12	10	72 hrs	Tugboat	0	282 hrs	4,5 hrs	344 k€	29.850 €	12.960 €	0,4 k€					
Converter/ Electric						0,0569	M	C2	DOWEC-2	Part	2	12	10	4 hrs	Tugboat	0	16 hrs	4,5 hrs	9 k€	6.050 €	2.080 €	1,1 k€	1 hrs	N			
						0,0064	M	C2	DOWEC-2	Complete sys	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	425 k€	21.450 €	9.120 €	3,1 k€	2 hrs	N			
	All seazon; disc	X				0,0069	M	C2	ECN-3	Part	2	12	10	4 hrs	Tugboat	0	16 hrs	4,5 hrs	9 k€	6.050 €	2.080 €	0,1 k€	0 hrs	N			
		X				0,0008	M	C2	ECN-3	Complete sys	2	12	10	48 hrs	Tugboat	0	282 hrs	4,5 hrs	425 k€	21.450 €	9.120 €	0,4 k€	0 hrs	N			
Inverter						0,32	M	C2	DOWEC-2	-	1	6	6	48 hrs	Tugboat	0	1.033 hrs	4,5 hrs		21.450 €	9.120 €	44,5 k€	347 hrs	N			
Hardware						0,25	M	C2	DOWEC-2	-	2	12	10	24 hrs	Tugboat	0	35 hrs	4,5 hrs	0,4 k€	13.050 €	5.280 €	6,3 k€	16 hrs	N			
						0	M	C1					--			0		10,8 hrs	20 k€	?	3.456 €	#VALUE!	0 hrs				
	Spring	X				0,0000	M	C2	ECN-3	Control sys	2	12	10	8 hrs	Tugboat	0	12 hrs	4,5 hrs		7.450 €	2.720 €	0,0 k€	0 hrs	Y		332 hrs	0 k€
		X				0,0005	M	C2	ECN-3	Part of Control sys	2	12	10	2 hrs	Tugboat	0	12 hrs	4,5 hrs		5.350 €	1.760 €	0,0 k€	0 hrs	Y		326 hrs	0 k€
	Summer	X				0,0000	M	C2	ECN-3	Control sys	2	12	10	8 hrs	Tugboat	0	2 hrs	4,5 hrs		7.450 €	2.720 €	0,0 k€	0 hrs	Y		272 hrs	0 k€
		X				0,0047	M	C2	ECN-3	Part of Control sys	2	12	10	2 hrs	Tugboat	0	2 hrs	4,5 hrs		5.350 €	1.760 €	0,0 k€	0 hrs	Y		266 hrs	0 k€
	Autumn	X				0,0000	M	C2	ECN-3	Control sys	2	12	10	8 hrs	Tugboat	0	14 hrs	4,5 hrs		7.450 €	2.720 €	0,0 k€	0 hrs	Y		347 hrs	0 k€
		X				0,0030	M	C2	ECN-3	Part of Control sys	2	12	10	2 hrs	Tugboat	0	14 hrs	4,5 hrs		5.350 €	1.760 €	0,0 k€	0 hrs	Y		341 hrs	0 k€
	Winter	X				0,0000	M	C2	ECN-3	Control sys	2	12	10	8 hrs	Tugboat	0	37 hrs	4,5 hrs		7.450 €	2.720 €	0,0 k€	0 hrs	Y		561 hrs	0 k€
		X				0,0005	M	C2	ECN-3	Part of Control sys	2	12	10	2 hrs	Tugboat	0	37 hrs	4,5 hrs		5.350 €	1.760 €	0,0 k€	0 hrs	Y		555 hrs	0 k€
Software							M				1	12	11			0				?	#VALUE!	#VALUE!	#VALUE!	N			
Sensors	All seazon; disc	X				0,0037	M	C2	ECN-3	Part	2	12	10	4 hrs	Tugboat	0	16 hrs	4,5 hrs	0,1 k€	6.050 €	2.080 €	0,0 k€	0 hrs	N			
Floating Base	Failure chance is that low res					0	M	C1	PersComm				--			0		10,8 hrs	3.600 k€	?	3.456 €	#VALUE!	0 hrs	Y		370 hrs	0 k€
Anchoring system	Failure chance is that low res					0	M	C1	PersComm				--			0		10,8 hrs	1.200 k€	?	3.456 €	#VALUE!	0 hrs				
Remaining							M						--														
						0,0087																					

Note:

the maximum failure rate present is 0,32
atforms 100 this implies for "single parts" 32 failures per year ultimately
he MTTF is comparable to the average MTTR (incorporation delay-time)
system displays a relatively high failure rate with relatively large MTTR.

This classification is different from the one use by ECN
C1 corresponds with FTC3 (repairable with standard means, if spares present direct action)
C2 corresponds with FTC1 +FTC2 (repairable with standard means, if adequate spareposition direct action)
Assumption: a repair of type C2 introduces part costs of 0,02 times the single part costs (which is 1,2 times the costs of a part; system price)

Total loss due to unplanned maintenance:	**253 k€**	or representing 2,2% percent of total investment
Time spent with preventive maintenance program:	2 days	& transport: 18 k€
Total unavailability (Days):	33 days	or 9% of the year
Total costs for unplanned and planned maintenance:	277 k€	
Total cash-production expected:	796 k€	
Hence percentual loss of cash due to investment in maintenance:	35%	

The meaning of the various columns incorporated in the model is as follows:

Component: is the component as discerned in the system brake down (§ 9.3.2).

Comment explains why discrimination in different failure, repair or seasonal scenario's is needed in order to implement the corrective maintenance plan.

FTC columns identify the principal cause that introduces the failure mechanism observed. If this mechanism is not known, a grey bar is displayed.

Failure chance: the probability of occurrence of a failure, when using the data mentioned in the source referred in the column "**reference**".
When detailed information about specific failure mechanisms is provided, this info is introduced in the next lines while subtracting the additional data from the overall figure used before.

Failform: This property indentifies the type of failure pattern present and is indicative for the type of mechanism that introduces the chance of failure. In case of improvement of the reliability of a particular component, it is necessary to discern the failure pattern present. The default value that is also used for lack of information is "M" (monotonous failure pattern).

Repair type class: this column identifies whether the repair can be performed with the standard means for transport and repair (C2) or special means for repair like a crane, jack-up platform etc.

M_component: this column identifies the specific part of the component that shows a need for maintenance. This is of specific use when it is efficient to simply exchange a part (for instance repair of circuit boards). If no part is mentioned the whole component is subjected to the maintenance action.

The columns **Limit_Wave** and **Limit_Wind** identify the weather limitations that are present in order to enable repair procedures.

The **weather window** is the specific window as resulting from Limit_Wave and Limit_Wind.

T_repair_NoTravel: this column contains the time needed in order to perform the maintenance task, assuming that all requirements are met and available at the windgenerator.

Equip_Req defines the specific part needed in order to perform the maintenance task. It can be a "Crane" but also a "Crane with welding generator". The choices implemented here are linked to costs by means of a formula in column Costs_Equip.

Costs_Equip determines the costs for the equipment needed, using repair time and transport time vice versa to the platform times the average hourrate, added with the startup costs present. These costs are assumed to be managed by using contracts with suppliers present (when not, excessive costs can result due to the character of the offshore service market).

Costs_People identifies the costs for maintenance personel, based on 2 persons times the total travel time and repair time (note that delay due to the weather window does not influence this factor). An increment of people for specific tasks can be implemented by adjusting the formula (not implemented for this report).

Total Costs Failure Offshore identifies the product of a) the cost for equipment, people and equipment needed, added with the costs of production loss (identified by delay times average capital production per hour) times b) the failure rate.

Unavailability identifies the product of a) the mean time to repair (repair time + single trip travel time + delay) times b) the failure rate.

Dock_Repair_Feasible identifies whether the maintenance inquiry present, may be performed more efficiently after transfer of the OWEC to shore.

Costs_Dock_Equip provides the possibility to incorporate docking costs, like 0,5 € per ton weight/week and 125 € for a pilot to the dock. This accumulates to the order of 1 k€ which is neglected considering the total maintenance costs.

TimeToRepair incl T_delay presents the time needed for towing the platform to shore and repairing it there (using the time for the maintenance task T_repair_NoTravel) including the average delay to be expected over the seasons considering the distance to shore and the travel speed during towing (it is during that time that the requirements of the weather window have to be met). When the failure mechanism shows clear seasonal dependences, a specific formula has been used (for instance for hardware failure due to lightning).

Total Costs Dock Repair presents the product of a) the costs of towing vessels (transport time multiplied with hour rates added with start-up costs), the costs of the component and the costs due to loss of production during repair and due to delay, times b) the probability of failure.

Assuming that all maintenance is done "on site"; the costs (for 1 OWEC) at various distances to shore are displayed in the next table:

Distance to shore (km):	50	100	200
Total maintenance costs/yr:	243 k€	253 k€	275 k€
Total unavailability:	33 days	33 days	34 days

One should notice that the probability of failure due to lightning, are dependent on the distance to shore as implemented in the model (specific formula in cell failure rate; for details see § 9.5.3). In this table lightning protection is assumed to be effective.

When lightning protection is switched "off", the table looks as follows:

Distance to shore (km):	50	100	200
Total maintenance costs:	265 k€	274 k€	297 k€
Total unavailability:	35 days	35 days	35 days

It can clearly be seen that lightning protection pays out with about 20 k€ per year.

The model shows that only the costs due to failure of rotor blades, as caused by indefinite sources, can be reduced with maximal 30 K€/yr by performing this maintenance "off site" (50 and 100 km distance to shore; at 200 km the difference decreases to about 10 k€/yr). Since the design of the wind platform and its depth may require special harbour facilities the most adequate solution to tackle this cost aspect seems to be to reduce the failure frequency.

Zooming into detail in order to determine the additional costs for harbour facilities has not been done. The effect of this extra detail provides no yield since the effect (reducing the saving foreseen at ultimately 30 k€/yr) on the overall cost figure is limited with respect to the estimation margins.

10 Levelised production cost Tri-floater wind farm

As given in chapter 3, the simplified method for the levelised production cost will be used, which means that the following equation has to be evaluated

$$LPC = I/(a \cdot AUE) + TOM / AUE$$

In which

I Initial investment;
a annuity factor, depending on discount rate and economic lifetime ;
AUE Annual utilised energy;
TOM Total Levelised annual "downline cost", i.e. Operations and maintenance, insurance, retrofit cost, and salvage cost.

In the following table, the calculation of the levelised production cost is given. Variation is made between the distance to shore, the electrical system and the place of production of the floater

	200 km to coast pv1, Europe	100 km to coast iv1, Europe	200 km to coast pv1, Asia	100 km to coast iv 1, Asia
Kosten floater + installation	€ 4,500,000.00	€ 4,500,000.00	€ 3,500,000.00	€ 3,500,000.00
Mooring costs	€ 2,500,000.00	€ 2,500,000.00	€ 2,500,000.00	€ 2,500,000.00
Turbine costs (575 Euro/kW)	€ 2,875,000.00	€ 2,875,000.00	€ 2,875,000.00	€ 2,875,000.00
Electr. Infrastructure costs	€ 3,710,000.00	€ 2,710,000.00	€ 3,710,000.00	€ 2,710,000.00
Total Capital Investment	€ 13,585,000.00	€ 12,585,000.00	€ 12,585,000.00	€ 11,585,000.00
Costs per year maintenance	€ 299,000.00	€ 277,000.00	€ 299,000.00	€ 277,000.00
Insurance Cost assumed 1% of the total investment	€ 135,850.00	€ 125,850.00	€ 125,850.00	€ 115,850.00
Total Levelised annual "downline cost"	€ 434,850.00	€ 402,850.00	€ 424,850.00	€ 392,850.00
Gain Wh gross	2.4600E+10	2.4600E+10	2.4600E+10	2.4600E+10
Wind Farm Efficiency	95.00%	95.00%	95.00%	95.00%
Electrical transport efficiency	88.500%	88.30%	88.500%	88.30%
Yield Netto in Wh	2.0682E+10	2.0636E+10	2.0682E+10	2.0636E+10
Interest	5.00%	5.00%	5.00%	5.00%
Economic Life Time [years]	20	20	20	20
annuity factor	12.462	12.462	12.462	12.462
Levelized Production Cost	€ 0.074	€ 0.068	€ 0.069	€ 0.064

[1]575 Euro/kW

Uncertainty in LPC

The costs for the electrical infrastructure are based on budget prices for existing components. However, the prices can still vary within ± 10% due to competition etc.
The costs for the construction of the floater are the construction costs in 2002 of offshore constructions based on experience of MSC. The prices can vary within ± 10%.
The total maintenance costs are a ± 50% estimation.

11 Conclusions and recommendations

11.1 Conclusions

- A literature study has been carried out and relevant literature has been gathered on a cd-rom.
- The literature study is the basis for the boundary conditions and references for the floating turbine.
- All the references, data, equations etc., are brought together in the knowledge based system Quaestor .
- Quaestor has been used to analyse different floater concepts in a quick and easy manner.
- The Quaestor analysis showed that the tri-floater concept looks feasible.
- Motion response calculations for the tri-floater concept showed that the concept is technical feasible regarding motions.
- A more thorough design of the tri-floater has been made. The strength, production and installation costs and mooring of the tri-floater are calculated.
- The total investment costs of the tri-floater are approximately 5 million Euro. This is excluding the electrical system and maintenance costs.
- Based on economics only, the Individual Variable Speed system is the best choice for distances below 140 km and the Park Variable Speed system for distances above 140 km.
- The maintenance costs are calculated to be about 277 kEUR/ year per 5 MWatt turbine. The availability is 91 %.
- It appears not to be cost effective to tow the floating turbine to shore for corrective maintenance.
- The levelised production costs for a wind turbine 200 km of the coast build in Asia is 0.069 EUR, build in Europe 0.074 EUR
- The levelised production costs for a wind turbine 100 km of the coast build in Asia is 0.064 EUR, build in Europe 0.068 EUR

11.2 Recommendations

- The tri-floater has been designed for water depths of 50 m and more. However, it can also be used in water depths of 40-45 m. This increases the area of the Netherlands continental shelf, which can be used for offshore wind energy, to at least 14 %. (See figure 3 chapter 4).
- In order to select/ optimise the presented concepts in terms of both economical and technical aspects, it is absolutely necessary to improve the Quaestor application by adding more data and equations.
- For the choice of the electrical system, a second major aspect is the controllability and behaviour with respect to the (high voltage) grid. This should be done for a final decision.
- It is recommended to use a RAM-spec during the design phase, which reduces the maintenance costs within 1 year for ten turbines already.
- Reducing the maintenance costs can be achieved in the fastest way by reducing the failure rate of those processes that appear to contribute heavily due to the characteristics of the repair scenario (repair time, delay due to weather window and repair time needed).