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RAMSI management model and evaluation criteria for Nordic offshore wind asset

Risto Tiusanen | Jere Jännes | Jayantha P. Liyanage

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Risto Tiusanen & Jere Jännes

VTT Technical Research Centre of Finland

Prof. Jayantha P. Liyanage

Center for Industrial Asset Management (CIAM)
University of Stavanger

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Norwegian Centre for Offshore Wind Energy

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VTT
PB 1000 (Teknikvägen 4 A, Esbo)
FI-02044 VTT
Tfn +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax +358 20 722 7001

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Risto Tiusanen, Jere Jännes & Jayantha P. Liyanage. Espoo 2012. VTT Technology 47. 46 p.

Abstract

The offshore wind energy sector is in the early stages of development, but it is growing fast. Due to the European Union's renewable-energy and climate goals along with national legislation, the offshore wind sector will develop strongly over the coming years in Europe. In the offshore wind energy sector, there are many different wind-turbine designs ranging from traditional monopile structures to floating platforms, depending on the water depth. Today, most offshore turbines are based on onshore turbine designs, and turbine technology continues to develop incrementally. At the same time, there is strong demand in the market for new, innovative designs for offshore wind turbines whose main focus is reliability and cost efficiency.

For floating offshore wind turbine designs, there may be new types of uncertainty and system risks compared with onshore wind turbines. Wind turbines in cold climates, such as those experienced in the Nordic countries, may be exposed to extreme conditions, such as formation of ice or very low temperatures that are outside the design limits of standard wind turbines.

In the offshore wind energy sector, specification, implementation and verification of the so-called RAMS+I (Reliability, Availability, Maintainability, Safety and Inspectability) requirements during development work are important for companies delivering wind turbines, from the perspective of system integrity. Decisions made before the formal design phase strongly determine the costs and benefits gained during the whole lifecycle of a wind turbine. The benefits of implementing the RAMS+I program include support with investment decisions, cost management, improved management of resource requirements, systematic support with development & implementation of products, and integration of dependability and safety requirements.

This publication outlines a model for managing RAMS+I factors during the conceptual design phase of an offshore wind turbine. The model is based on the product development process, concurrent design principles and the Stage-Gate® model. The model concentrates mostly on technical decisions made in the early development phases. This publication also presents guidelines for comparing different offshore wind energy assets and their critical components from a system availability and safety viewpoint. The classification and evaluation criteria for RAMS+I factors are outlined and discussed, and a multi-factor risk-profiling (MFRP) method introduced.

Keywords RAMS, offshore, wind turbine, availability, safety, design, concepts

RAMSI- vaatimusten hallinnan malli ja evaluointikriteerit pohjoisten merialueiden tuulivoimaloissa

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Tiivistelmä

Tuulienergian tuotanto avomerellä on kehityskaarensa alkuvaiheessa. Uusiutuviin energiamuotoihin ja ilmastoon liittyvien Euroopan unionin tavoitteiden ja kansallisten lainsäädäntöjen ohjaamana tuulienergian tuotanto avomerellä tulee Euroopassa kehittymään voimakkaasti tulevina vuosina. Avomerikäyttöön on suunniteltu useita erilaisia turbiinikonsepteja meriveden syvyyden mukaan perinteisistä kiinteästi pohjaan perustetuista ”monopile”-rakenteista kelluville alustoille rakennettuihin turbiineihin. Tänä päivänä avomerelle rakennettavien tuuliturbiinien tekniset ratkaisut perustuvat pitkälti maalla käytettävien turbiinien hyviksi havaittuihin teknologioihin. Markkinoilla on kuitenkin voimakas kysyntä uusille innovatiivisille avomeriolosuhteisiin kehitetyille turbiinikonsepteille, joiden avulla keskeiset suunnittelukriteerit – luotettavuus ja kustannustehokkuus – saataisiin entistä kilpailukykyisemmiksi.

Avomerikäyttöön tarkoitettuihin kelluviin tuuliturbiinikonsepteihin liittyy aivan uudentyyppisiä epävarmuustekijöitä ja riskejä verrattuna maalla tai rannikolla käytettäviin tuuliturbiineihin. Pohjoisen arktisilla merialueilla tuuliturbiinit joutuvat lisäksi alttiiksi ääriolosuhteille, kuten jäänmuodostus, erittäin alhainen lämpötila, myrskytuulet ja korkea aallokko, jolloin suunnittelukriteerit poikkeavat nykyisistä tuuliturbiineille asetetuista vaatimustasoista. Tuuliturbiinijärjestelmän käyttövarmuus- ja turvallisuusvaatimusten ns. RAMS+I (Reliability, Availability, Maintainability, Safety and Inspectability) -vaatimusten määrittely, toteuttaminen, ja todentaminen kokonaisvaltaisesti kehitystyön aikana muodostuvat erityisen tärkeiksi toimitettaessa tuuliturbiineja näihin vaativiin avomeriolosuhteisiin.

Päätökset, jotka tehdään tuuliturbiinin konseptisuunnitteluvaiheessa, määrittelevät vahvasti niin tuuliturbiinin suorituskykyyn vaikuttavat ominaisuudet kuin sen elinkaarikustannuksiin vaikuttavat tekijät. RAMS+I-ohjelman systemaattinen toteuttaminen tukee investointipäätösten tekoa, tuotekehitystä ja järjestelmien toteutusta sekä erityisesti käyttövarmuus- ja turvallisuusvaatimusten integrointia ja implementointia.

Tässä julkaisussa kuvataan RAMS+I- vaatimusten hallinnan mallia ja sen soveltamista avomerikäyttöön tarkoitettujen tuuliturbiinien konseptisuunnitteluvaiheeseen. Kehitetty malli perustuu yleiseen teollisuustuotteiden tuotekehitysprosessiin, rinnakkaissuunnittelun periaatteisiin ja projektihallinnan ns. Stage-Gate®-malliin. RAMS+I- vaatimusten hallinnan kehitystyössä on keskitytty tuotekehityksen ensimmäisissä vaiheissa – konseptikehityksessä, vaatimusmäärittelyssä ja järjestelmäsuunnittelussa – tehtävän järjestelmäsuunnittelun päätöksenteon tukemiseen. Julkaisussa kuvataan myös menetelmä ”Multi Factor Risk Profiling method” (MFRP) ja arviointikriteerit, joiden avulla voidaan vertailla erilaisia avomerikäyttöön suunniteltuja tuuliturbiinikonsepteja niiden järjestelmätason käyttövarmuuden ja turvallisuuden näkökulmista. Tämä arviointimenetelmä perustuu yleisesti tunnettuun ”Multi-criteria decision analysis” (MCDA) -menetelmään.

Avainsanat RAMS, offshore, wind turbine, availability, safety, design, concepts

Preface

This is a publication for the bilateral research project “Integrity through Systems Engineering: Risk-based criteria” (INTECRITERIA) between the Center for Industrial Asset Management (CIAM) at the University of Stavanger and VTT Technical Research Centre of Finland.

This project has been funded partly by the Norwegian Centre for Offshore Wind Energy (NORCOWE) under grant 193821/S60 from the Research Council of Norway (RCN), and partly by VTT. NORCOWE is a consortium with partners from industry and science, hosted by Christian Michelsen Research http://www.norcowe.no/index.cfm. This project is specifically linked to the Asset Management Section of the WP3 on ‘Offshore Deployment and Operation’ at NORCOWE.

The core project team has comprised senior scientist Risto Tiusanen and scientist Jere Jännes from VTT. Project work has been guided by Professor Jayantha P. Liyanage from CIAM, docent Markku Reunanen from VTT and technology manager Helena Kortelainen from VTT.

Contact information in VTT in Finland and in CIAM in Norway concerning the research project and this publication is:

Risto Tiusanen
VTT Technical Research Centre of Finland
PL 1300, 33101 Tampere, Finland
Tel. +358 40 5066999, E-mail risto.tiusanen@vtt.fi

Prof. Jayantha P. Liyanage
Center for Industrial Asset Management (CIAM)
University of Stavanger, 4036 Stavanger, Norway
Tel. +47 481 07 343, E-mail j.p.liyanage@uis.no

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Authors

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1. Introduction

This publication is one outcome of the research work conducted at the Norwegian Centre for Offshore Wind Energy (NORCOWE). This research work has been carried out at VTT in close co-operation with the Center for Industrial Asset Management (CIAM) at the University of Stavanger during the period 2010–2012.

1.1 NORCOWE

NORCOWE, the Norwegian Centre for Offshore Wind Energy, is an interdisciplinary resource centre for exploitation of offshore wind energy as a natural sustainable energy source in Norway. The vision of NORCOWE is to combine Norwegian offshore technology and leading Danish and international communities on wind energy in order to provide innovative and cost efficient solutions and technology for large water depths and harsh offshore environments. NORCOWE aims to build strong offshore wind energy clusters in Norway by developing new knowledge and by providing skilled persons for the industry.

NORCOWE was established and the centre officially opened in 2009. Most of the work was focused on establishing the centre and getting it up and running. There are 15 partners in the centre: 9 partners from industry, and 6 scientific. The NORCOWE partners are located in Kristiansand, Grimstad, Stavanger, Bergen and Aalborg (Denmark). Christian Michelsen Research (CMR) is the host institution. There is a board with 12 members (7 from industry and 5 from science), with Hans-Roar Sørheim, CMR, as chair. (Guldbrandsen Frøysa, 2010)

The partners have been addressing a wide range of topics, and that is reflected in the five work packages (WP) within the centre. The work packages are:

- WP1 Wind and ocean conditions
- WP2 Offshore wind technology and innovative concepts
- WP3 Offshore deployment and operation
- WP4 Wind farm optimization
- WP5 Common themes: education, safety, environmental impact assessment and test facilities and infrastructure.

1.2 WP3 Offshore deployment and operation

The work package deals with challenges related to deployment and operation of wind turbines offshore in both shallow and deep waters. Moving wind farms offshore increases the cost of installation, operation and maintenance considerably compared with land-based wind farms, and there is a need for new cost-reducing technology to make offshore wind energy competitive without large subsidies. The work package is divided into the following four subtasks (Guldbrandsen Frøysa, 2010):

WP3.1 Asset management

This subtask deals with design strategies and maintenance strategies and methods that ensure the integrity of the offshore wind farm and at the same time reduce the life-cycle cost significantly. At present there is insufficient knowledge available to assess the condition of wind farms and to estimate how failures develop over time. This implies that a broad scope of new methods and techniques are required for management of offshore wind turbines. Ensuring technical integrity is an inherent design challenge for offshore wind turbines, and maintenance-related challenges contribute to a major part of the risk to which offshore wind turbines are exposed.

WP3.2 Single turbine control systems

The integrity of wind turbines and optimal use of wind resources require a well-designed control system. A floating turbine presents an even greater challenge for the control system due to the large movements of the floater. The activities within this subtask aim at developing more robust and fault-tolerant control systems than those in common use today.

WP3.3 Remote operation

Remote operation is necessary to ensure cost efficient operation of offshore wind turbines. The activities within this subtask deal with the necessary communication infrastructure, service- and data-integration platform, optimization of work processes and decision support system.

WP3.4 Marine operations

Marine operations related to installation, maintenance and decommissioning of offshore wind turbines are unreasonably expensive when using conventional state-of-the-art technology. There is therefore a need for new thinking to develop safe, but less costly technology and procedures for these operations. This subtask proposes and analyses alternative designs and new installation and maintenance methods that reduce these costs.

The following NORCOWE research and industry partners have activities within this work package.

- University of Agder (UiA): Condition-based Maintenance, Single Turbine Control Systems, Remote Operations, Marine Operations
- University of Stavanger (UiS): WP3 Management, Asset Management and Marine Operations
- Aalborg University (AAU):Single Turbine Control Systems, Reliability Analysis of Wind Turbines
- Christian Michelsen Research (CMR): Measurement Technology for Asset Management, Turbine Control, Origo Engineering: Remote Operation.

VTT in Finland has been acting as a subcontractor to the University of Stavanger. The work has been part of the research carried out on Asset management in the work package WP 3.1.

2. Scope and objectives

The scope of this work has been requirements specification and management in the early life-cycle phases of offshore wind turbine projects in the Northern context. The main objective of this research was an extended concept and methodology to systematically carry out specification of the RAMS+I (Reliability, Availability, Maintainability, Safety and Inspectability) requirements and support RAMS+I management decisions for all stages of the wind-turbine life-cycle. To achieve this challenging objective, the research work has been split into the following sub-goals:

- A review of system risks and a systematic risk-management framework that can be utilized in the wind farm design and deployment process under challenging Nordic conditions.
- A systematic approach for RAMS+I management and RAMS+I tasks specification in the early lifecycle phases for wind farms.
- Classification and evaluation criteria for different RAMS+I (Reliability, Availability, Maintainability, Safety and Inspectability) factors.
- Guidelines for comparing different offshore wind turbine concepts and their critical components from the viewpoint of system availability and safety.
- Multi-factor risk-profiling method based on the multi-criteria decision analysis (MCDA) for the evaluation of RAMS+I elements.

3. Research process and reporting

The research work started with a literature survey on both offshore wind industry trends and RAMS perspectives. The core competence of VTT's project team is in the industrial machinery sector where work on RAMS issues has been undertaken for years. Results and experiences from the industrial machinery sector were applied to the "machinery" in offshore wind industry. One of the main issues at the beginning of the project was to clarify the biggest differences between traditional industrial machinery and offshore wind technology.

The research and development work done to create an extended RAMS+I concept for the offshore wind turbine has been carried out via the following subtasks:

- Study of the general RAMS issues for complex machinery and specific offshore wind RAMS+I issues, and outlining of the RAMS+I model baseline.
- Study of system risks associated with offshore wind farms and wind-turbine development in Nordic conditions and an outline of the risk-management framework.
- Identification of RAMS+I factors in various wind turbine concepts.
- Development of a RAMS+I management model for offshore wind turbine designs.
- Outline of a multi-factor risk-profiling method for the evaluation of RAMS+I elements.

The overall picture of the progress with research work and the outcome of the project is illustrated in Figure 1. The research results are presented in four conference papers. The conference papers are published or are going to be published in the proceedings of the conference in question:

Tiusanen, R., Jännes, J., Reunanen, M. & Liyanage, J.P. (2011). RAMSI management – from single analyses to systematic approach. In: Proceedings of the 24th International Congress on Condition Monitoring and Diagnostics Engineering Management (COMADEM 2011). 30th May – 1st June 2011, Stavanger, Norway, pp. 1588–1596.

Tiusanen, R., Jännes, J. & Liyanage, J.P. (2011). Framework to assess system risks associated with offshore wind farms in Northern context. In: Proceedings of the 21st International Offshore (Ocean) and Polar Engineering Conference (ISOPE 2011). 19th – 25th June 2011, Maui, Hawaii, USA. pp. 540–547.

Tiusanen, R., Jännes, J. & Liyanage, J.P. (2011). From-design-to-operations risk mitigation in Nordic wind energy assets: a systematic RAMS+I management model. In: Proceedings of the Sixth World Congress on Engineering Asset Management (WCEAM 2011). October 2nd – 4th, 2011, Cincinnati, OH, USA. (Forthcoming)

Tiusanen, R., Jännes, J. & Liyanage, J.P. (2012). Identification and evaluation of RAMS+I factors affecting the value-added by different offshore wind turbine concepts in Nordic context. In: Proceedings of the 22nd International Ocean and Polar Engineering Conference (ISOPE 2012). 17th – 22nd June 2012, Rhodes, Greece. Pp 451–457.

Presentations in NORCOWE seminars have been published as internal Powerpoint documents in the NORCOWE WP3 project team.

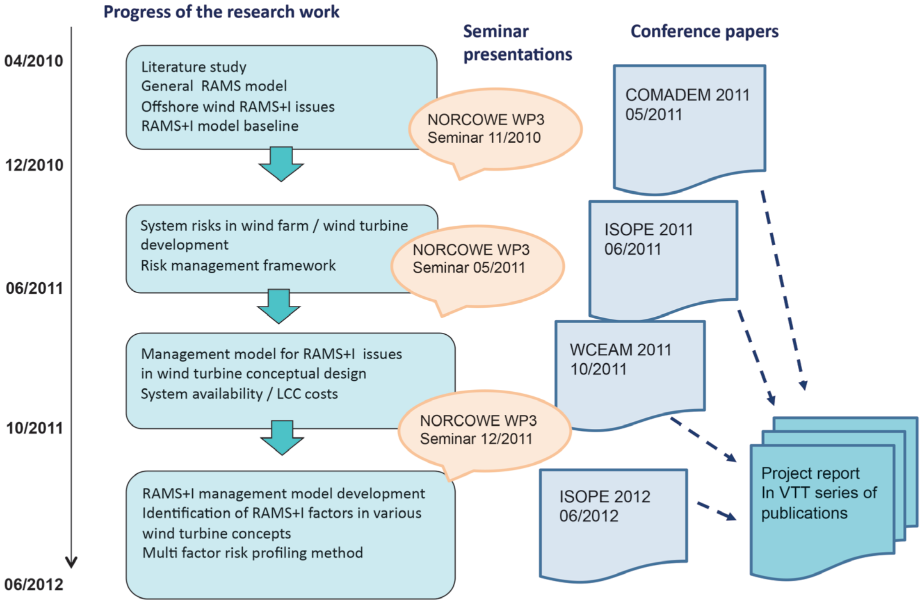


Figure 1. An overall picture of the research work and the outcomes.

This publication summarises the main results achieved at VTT and CIAM/UiS within the project. Background, state-of-the-art and the results are discussed more detailed in the aforementioned conference papers, which are referenced and cited in this publication.

4. Offshore wind energy

The Nordic countries have been working hard to adopt wind energy as the future energy solution for the region. As of 2010, there are 39 European offshore wind farms in waters off Belgium, Denmark, Finland, Germany, Ireland, the Netherlands, Norway, Sweden and the United Kingdom, possessing 3.16 GW of offshore wind power capacity between them. In the largest offshore wind farm, there are 100 individual wind turbines. Offshore projects generating more than 100 GW (or 100,000 MW) are proposed or under development in Europe. The European Wind Energy Association has set a target of 40 GW to be installed by 2020 and 150 GW by 2030. (EESI, 2010)

In the onshore sector, the size of wind turbines and turbine technology seems to have reached an optimum cost/benefit level, whereas offshore wind turbine technology is still developing strongly to fulfil the specific requirements of offshore operating conditions and the high demands for cost reduction required by the energy market. The trends in the offshore sector point towards larger offshore wind farms in the 200–300 MW range and beyond, using dedicated and standardized offshore turbines. According to EWEA, the main focus in the years ahead will be on standardizing the installation processes and developing dedicated offshore turbines from a dedicated supply chain, just as it was for onshore wind 15 years ago. (EWEA, 2009a)

Many of the technologies for offshore wind development have already been proven in the oil and gas industry. Many of the same issues that impact on oil and gas platforms will also influence the design of wind platforms, but the importance of each variable will be weighted differently. However, because platforms in the oil and gas industry are much larger and are unique applications, application of this experience to offshore wind will require technological innovations and new methods for manufacturing, logistics and maintenance that will be critical in lowering costs and extending the offshore wind farms to potential new areas. (Musial & Ram, 2010)

With regards to the future potential of current developments, the European Wind Energy Association names the following issues as key areas for wind energy research (EWEA, 2010)

- Improving the design and layout of wind farms
- Increasing the reliability, accessibility and efficiency of wind turbines

- Optimizing the maintenance, assembly and installation of offshore turbines and their structures
- Demonstrating large wind turbine prototypes and large, interconnected offshore wind farms
- New methods of grid management to allow high levels of wind power in the system
- Expansion of training schemes and better facilities for training.

Floating wind energy systems offer numerous advantages over existing onshore and shallow water systems. Winds are stronger and steadier offshore than onshore. Better wind conditions means more electricity produced per turbine and also less wear on the turbine components (Musial et al., 2006). Due to technical and operational challenges, and subsequent risks, some major issues must be addressed before full scale implementation of floating offshore wind farms can be a profitable, safe and competitive option for energy production. Notably, much can be learnt from other sectors in this context; for instance, various floating technologies have been used in the oil and gas industry for years, but in wind turbines they are still at the development stage.

5. Offshore wind turbine development

Current offshore turbines in shallow waters are mostly developed from onshore designs. According to EWEA's medium- and long-term scenarios, offshore wind turbine concepts will be changed from onshore-based constructions to turbine types specifically designed for the offshore environment. The main driver for offshore wind turbine development is efficiency, rather than generator size. The turbine size is specified by the wind farm operator in the preliminary wind farm design phase, based on site-specific characteristics and calculations. (EWEA, 2009b)

The market needs in offshore wind energy are contradictory when it comes to turbine development. To achieve large production volumes for the rapidly growing market, the manufacturers should focus on producing continual, incremental improvements to the current basic concepts to improve product reliability, to increase component lifetime and to develop preventive maintenance strategies. On the other hand, offshore project designers and wind farm operators are requesting completely new – robust, and easy to assemble, install and maintain – wind turbine concepts. New designs could be an opportunity to achieve significant reductions in the cost of energy. In practice, these two strategies will be developed in parallel.

Offshore wind turbines are complex machinery systems consisting of many multi-technology subsystems. Beginning with the underwater substructures, there are many different conceptual structures depending on the water depth, ranging from traditional mono-piles to new floating platforms. (Tiusanen et al., 2012) Implementations based on land-based designs are not optimum for offshore wind turbines, because of fundamental differences in the offshore operating environment and infrastructure. Offshore sites are far from harbours and support bases, construction costs are much higher, and operations are highly dependent on weather conditions, wave height and wind speed. Corrosive seawater exposure, wave loading, extreme wind and fatigue load combinations and other external conditions requiring special attention (e.g., ice and hurricanes) require different technological solutions for offshore structures and designs. Because of these differences, in future there may be significant divergences between offshore and land-based designs. (Musial & Ram, 2010)

5.1 Conceptual wind turbine design

In the conceptual design phase, the turbine manufacturer compares different concepts regarding how to manage the whole turbine-development process: design, manufacturing, assembly, transportation and installation. Examples of important aspects affecting conceptual design are nacelle concepts and structures, support structures, safe access and maintenance, and offshore logistics. Harsh offshore conditions create new challenges, but they also give the designers some freedom with regards to aesthetics and sound-emission levels. (EWEA, 2009a)

Wind turbines in cold climates, such as those experienced in Northern Europe, may be exposed to conditions outside the design limits of standard wind turbines. Issues specific to cold climates, such as accessibility, temperature, ice, snow, energy potential, technology, economic risk, public safety, infrastructure and labour safety, will require additional thought. (Baring-Gould et al., 2010)

System designers face the dilemma of maintenance-cost reduction in the concept-design phase – improved component reliability versus increased maintenance capability. Because of high reliability requirements and increasing cost-reduction demands in the offshore wind energy sector, many critical decisions and choices have to be made early in the turbine conceptual-design phase. Management of reliability, availability, maintainability and safety issues become essential as early as the system requirement specification phase at the beginning of the turbine conceptual-design phase. Decisions made before formal development are the most important, considering how successful the product will finally become. These decisions strongly determine the costs and benefits gained during the whole lifecycle of a product. (Tiusanen et al., 2011c)

Interest in floating wind turbine technology has accelerated over the last few years, and many technology demonstrations have been carried out. The main drivers for floating technology are said to be access to useful resource areas in a range of locations, varying from shallow to deep water. The developments indicate a growing potential for standard equipment that is relatively independent of water depth and seabed conditions, and enables easier installation and decommissioning; the developers have begun to look for possibility of system retrieval as a maintenance option. At the moment, the main obstacles to the realization of floating technologies appear to relate to effective design concepts and demonstration that takes into account different profit and cost profiles. (Tiusanen et al., 2012)

6. Added value from risk management

According to EWEA (2009b) wind farm design is a critical area for cost reduction and public acceptability, both onshore and offshore. As the wind industry gains experience in constructing projects in different conditions, the costs and other important issues are becoming better understood, and the risks should be no greater than in other civil-engineering or power-station projects of similar size.

Given the specific challenges in wind farm design and deployment in Northern areas, a system risk based approach can provide a good foundation in financial, operational and technical decision-making processes. The case with offshore constructions is even more demanding as comprehensive offshore wind farm data is not available for modelling, simulations and qualitative analysis to help support risk estimation, evaluation and assessment in the early conceptual phases of the system lifecycle. Moreover, risk analysis methods based on a systems approach become essential when identifying and analysing potential dependability and safety issues from technical and operational perspectives. (Tiusanen et al., 2011b)

Yet, if system risks related to new floating technologies and new operating principles are overlooked in the conceptual phase, there may be serious implications for the wind farm development and deployment efforts. The most important decisions concerning system safety and system dependability are made during the early phases of system design. In the literature, it is emphasized that up to 90% of the lifecycle costs of products are determined by the decisions made in the early phases of product design. (Tiusanen et al., 2011b)

In long-term projects such as offshore wind farm projects, there are obviously many more uncertainties than in incremental wind turbine development projects. Therefore, the techniques for managing these challenges must also be chosen differently. In the early phases of wind farm development, less detailed methods can be used. These should be refined as more information becomes available and more detailed analysis can be conducted. (Tiusanen et al., 2011b)

When designing totally new wind turbine concepts without any operational experience and quantitative data available, risk management can only be based on qualitative methods and assessment criteria. It is important to identify issues affecting the value added, which must be assessed in the conceptual design phase, and to understand their relation with and impact on the whole lifecycle of the wind farm. (Tiusanen et al. 2012)

According to Musial and Ram (2010), project risk can be broken down into the uncertainty surrounding regulatory and permit issues, the risks associated with construction and installation, and the operational risks that are associated with trouble free energy production and long-term reliability. Risk and uncertainty may decrease as the industry matures, but at the moment the industry is still immature.

6.1 System risks associated with offshore wind farms

System risk is not often seen as an integrated component in engineering projects. Certain elements of the overall system are mostly prioritized based on the business impact. This assumes that the owners or users of those solutions are prepared to accept some extra risks in respect of the savings or the expected margins. However, in those sectors that are exposed to limited margins, and particularly where slight changes in deployment and operating costs play a major role in the profitability formula, an approach based on system risk is effective. This is to allow the stakeholders a good insight into the explicit and implicit parameters that can make a difference to profits. This also facilitates measures required at the design stages from the perspective of lifecycle costs and lifecycle profit. (Tiusanen et al., 2011b)

"System" in this offshore wind farm context can be defined, following the EN 60300-3-9 (2000), as: "a composite entity, at any level of complexity, of personnel, procedures, materials, tools, equipment, facilities and software. The elements of this composite entity are used together in the intended operational or support environment to perform a given task or achieve a specific objective."

"System risk" can then be defined as a risk that is related to the whole wind turbine unit and the wind farm as a large "production plant". In this context, we consider system risks from the application perspective – not related to a single component, device or functionality. In this application-level perspective, the time frame for system risk analysis and assessment is also longer. System risk assessment follows the system lifecycle, identifying strengths and weaknesses in the development, operation and maintenance of the system. In general, in all industrial sectors there are different types of internal and external factors and uncertainties influencing how companies achieve their business objectives. These factors and uncertainties form a large variety of risks, external and internal, that should be considered in operational, financial and strategic decision-making. (Tiusanen et al., 2011b)

According to EWEA (2009b), offshore wind farm projects are significantly larger and more risky than most onshore projects, and there are different companies developing and constructing these projects, and the potential margins under the present conditions are limited. Special vessels and techniques for installing turbines have been developed, and the means of access to offshore turbines has emerged as a major issue, affecting cost, system availability and system safety.

System risks associated with offshore wind farms can be categorized into the following:

- External risks affecting wind farm projects
- Financial risks

- Infrastructure risks
- Technology development risks
- Health and safety risks
- Environmental risks
- Operation and maintenance risks. (EWEA, 2009b)

These risks have been discussed more in Tiusanen et al. (2011b).

In addition to the aforementioned risks, there are special risks that are related to Nordic weather conditions and the use of northern sea areas e.g. maritime traffic, shipping lanes and areas, and fishing grounds.

6.2 Special risks in the Nordic context

In northern sea areas, there are special conditions where financial, technological, weather and other risks play a prominent role in design and deployment decisions for wind energy production. In the current floating offshore wind turbine design concepts, system risks may vary due to the multiple influences of numerous risk factors. For instance, harsh weather conditions in northern sea areas (storms, waves, extremely low temperatures, ice, fog, etc.) and the remote location of an offshore wind farm may make it impossible to access the wind turbines during certain times of the year. (Tiusanen et al., 2011b)

Harsh weather conditions such as storm winds, waves and ice cause delays in installation schedules, leading to extra costs and loss of planned production. The same goes for maintenance operations. (Tiusanen et al., 2011b)

Ice formation in northern offshore conditions is predicted to be a much greater issue than onshore for many reasons. Humidity is much higher, causing more ice to accumulate on surfaces. A wind farm site may freeze over, posing a challenge for accessibility, and ice adds to the loads on structures. Also, the ice is generally mobile and may be quite unstable. It is reported that even lighthouses have been displaced by pack ice. In the Baltic Sea in particular, extensive ice formation takes place some winters. This impacts on access. For instance, access may be gained across the ice via ice roads assuming that the ice bed is straight and strong enough, or there may be access by hovercraft if the sea is frozen solid, or by using ice-breakers. (EWEA, 2009b)

Lightning has been more problematic offshore than expected. If systems are not appropriately protected, the consequences of lightning strikes can be severe. (EWEA, 2009b)

Various risks are related directly or indirectly to the location of the offshore wind farm in Northern sea areas. If shipping lanes are close to the wind farm, sea traffic (cruise ships, oil & gas tankers and other cargo ships) increase the risk of an accident due to a collision with a wind turbine. Similar risks occur when farms are located near fishing grounds or naval routes and their training areas. (Tiusanen et al., 2011b)

7. RAMS+I management

RAMS issues and RAMS management have been highlighted and studied in case studies, and availability, reliability, maintainability and safety issues have been discussed by many in the wind energy domain (e.g. van Bussel & Zaaijer, 2001; Walford, 2006; Echavarría, 2009). Various risk-based operation and maintenance concepts have also been published for offshore wind turbines and wind farms, but no systematic approach to the management of these issues throughout the entire lifecycle has so far been proposed.

Inspectability (I), on the other hand, has often been an integral component of maintenance and maintainability issues. However, over the last few years, inspection and testing have received increasing attention due to various incidents involving offshore installations. It is foreseeable that issues related to inspectability will also play an important role in large-scale wind farms, with the arrival of new standards and guidelines in the wind energy domain. (Tiusanen et al., 2011a) According to Sørensen (2008), collection of data and information and probabilistic modelling of this information are important steps in risk-based inspection & maintenance planning. The main sources of information are condition monitoring systems, inspections and indicators.

Experiences from other areas indicate, according to O'Connor (2002), that all well-managed reliability, maintainability and availability efforts pay off due to the fact that nearly every failure mode experienced in the R&D phase is worth discovering and correcting during development, owing to the very large cost disparity between corrective action taken during development and similar actions once the equipment is in service.

Offshore wind turbine designers are looking for the "optimal" solutions for the supporting platforms and turbine concepts that will achieve the best functionality and lowest cost. The solution is always a compromise that attempts to minimize the system costs by addressing each technical challenge. It is best to identify and assess issues affecting the value added, especially for new innovative technologies, in the early conceptual design phase. The added value achieved from successful RAMS+I management throughout the offshore wind asset lifecycle comes from, for instance: high system availability; motivated and committed personnel; no accidents and negative impacts on the marine natural environment; optimal utilisation of weather windows for marine operations and maximised turbine up-time and minimised down-time. (Tiusanen et al., 2012)

Offshore wind turbines face different conditions and challenges from those onshore. Therefore, the requirements for applications must be different. For example, due to access-related difficulties, reliability and maintenance issues cannot be addressed the same way as onshore (Echavarría, 2009). According to Frost & Sullivan (2009), the key factors affecting operating and maintenance costs and the impact on wind energy costs are the type of maintenance, the downtime due to weather conditions, design and component reliability, and enabling technologies (Table 1).

Table 1. Factors affecting operating and maintenance (O&M) costs and the impact on wind energy costs (adapted from Frost & Sullivan, 2009).

Factors affecting O&M costs	**Impact on offshore wind energy costs**
Type of maintenance	Preventive maintenance, remote condition monitoring, opportunity-based maintenance and risk-based maintenance are becoming more important, as harsh weather conditions and increasing distance from the coast will make corrective maintenance more expensive.
Downtime due to: weather conditions; delays in marine operations; logistics, etc.	Turbine downtime will be affected by weather conditions, marine operations, logistics, etc., if a turbine is located at a significant distance from the coast, and maintenance is done offshore only.
System design; systems and component reliability	R&D on offshore turbines is under way to make them easier to operate and maintain. Among other initiatives, blades are being designed to be more reliable, and new gear designs are being tested; structural changes have been made with other innovative design solutions.
Enabling means and technologies	For example, approaching an offshore wind turbine by barge or helicopter will help O&M activity. Helicopter as a support method can only be used if there is a landing platform. Other technologies involving remote operations, data management, work planning, etc. will also have significant impact on the costs.

One of the key issues for further improvements includes reliability aspects, where the reliability levels (2.2 failures/year) achieved onshore are said to be insufficient for offshore applications (van Bussel & Zaaijer, 2001). With the lack of reliability data for offshore wind turbines, and with the fact that onshore data is deemed misleading, a well-structured process to assess the criteria early in the concept phase is needed.

7.1 RAMS+I model

To be able to develop RAMSI+I management practices in wind energy projects, the concept of RAMS+I and its elements must be fully understood and defined. One of the results of this project is the structured model of RAMS+I.

According to our standard-based understanding (see e.g. EN 50126, IEC 60500(191), EN 60300-1 and EN 60300-2) the concept of RAMS+I comprises: Reliability, Availability, Maintainability, Safety and Inspectability. To understand the meaning and characteristics of RAMS+I, it is important to understand and specify the relationship between these RAMS+I elements and their characteristics. In addition, we have also paid specific attention to inspectability issues, which, in the RAMS+I context, are considered an inherent attribute in reliability and / or maintainability components. However, since inspectability has a significant impact on offshore context, and since effective standards and guidelines are available for inspection activities for offshore structures and platforms, this is considered to have an equally important role in the formula for risk management relating to offshore wind farms. Besides, in the northern context, offshore assets are subject to stricter regulations due to various levels of impacts, which again underlines the critical role of inspectability. (Tiusanen et al., 2011a)

In this research project we have outlined an extended RAMS model (RAMS+I) specifically for Nordic offshore wind energy purposes. The main elements of the RAMS+I model have been introduced and described. We have structured RAMS+I as shown in Figure 2. The RAMS+I model consists of two main sections: safety and availability. Safety and availability are divided into elements and further into RAMS+I factors. The system availability sector is divided into four elements, and the system safety sector into three elements. Each element consists of numerous factors. Elements of availability are as defined in the dependability management standard IEC 60300-1 (2003). System safety in this paper is seen from the viewpoint where the wind turbine itself causes hazards to people, the operational environment or nature. (Tiusanen et al., 2012)

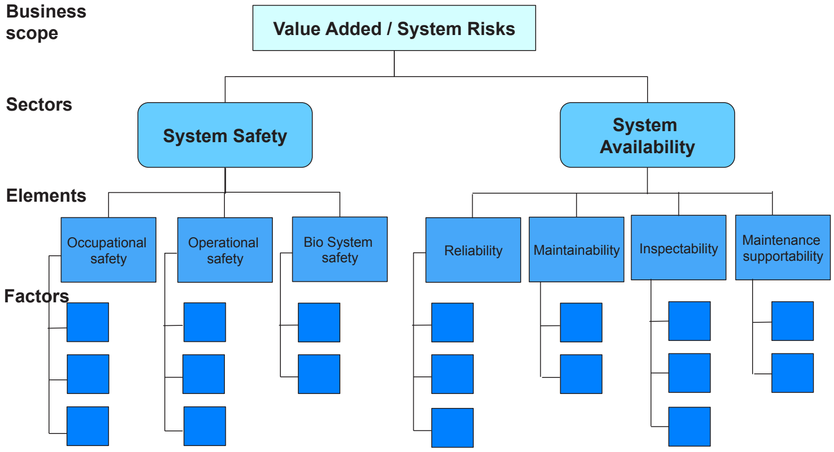


Figure 2. Elements related to added value and system risks in offshore wind assets in the Nordic context (Tiusanen et al., 2012).

7.1.1 System safety

Basic occupational safety aspects are relevant for wind turbines, not only in maintenance work at sea. There is a lot of manual work involved in the construction, installation, commissioning, testing, inspection, maintenance, repair and decommissioning phases of offshore wind farms. Examples of occupational safety risks are for instance: risks related to assembling and lifting large heavy components during installation on site; risks related to wind turbine access; risks related to working high in the nacelle; physiological and psychological effects when working in difficult Nordic weather conditions and when stressed due to time pressure (Figure 3). (Tiusanen et al., 2012)

In this study we have defined operational safety risks as risk affecting other operation at sea e.g. vessel traffic or fishing business near the wind farm site and aviation. Various risks are related directly or indirectly to the location of the offshore wind farm in Northern sea areas. Shipping lanes close to the wind farm, sea traffic (cruise ships, oil & gas tankers and other cargo ships) increase the risk of an accident due to a collision with a wind turbine. Similar risks occur when farms are located near to fishing grounds or naval routes and their training areas. (Tiusanen et al., 2011b)

An offshore wind farm can pose a risk to the surrounding biosystem. According to IUCN (International Union for Conservation of Nature), the potential impacts of offshore wind power development on the marine biosystem include disturbances from noise, electromagnetic fields, changed hydrodynamic conditions and water quality, and an altered habitat structure for benthic communities, fish, mammals and birds (Wilhelmsson et al., 2010).

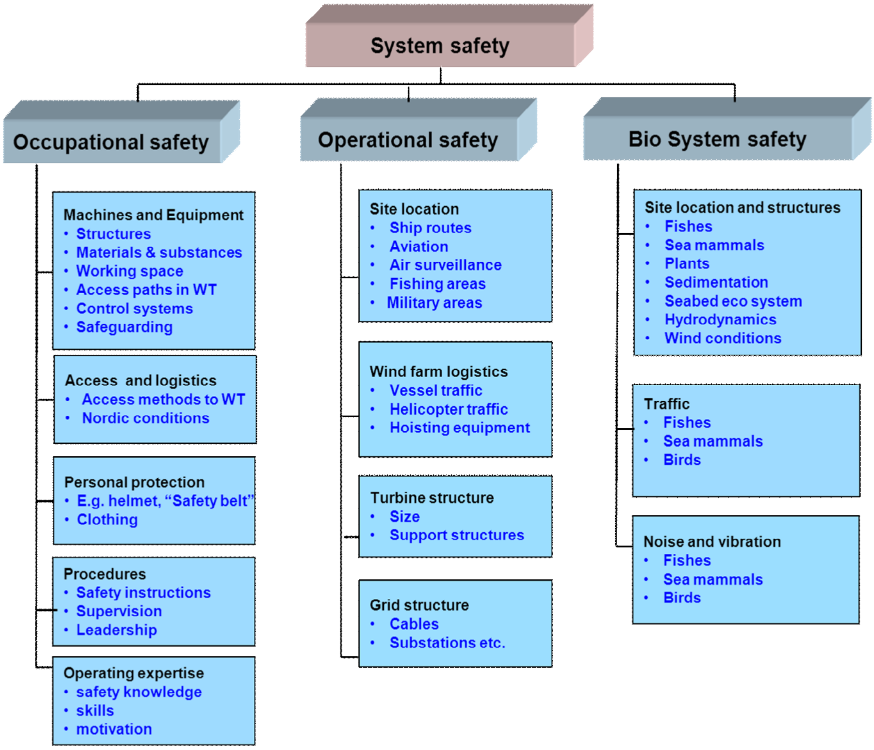


Figure 3. Factors affecting system safety in offshore wind assets in the Nordic context (Tiusanen et al., 2012).

7.1.2 System availability

As reliability is "the ability of a system to perform a required function under given conditions for a given time interval" (IEC 60050(191), 1999), it is very much determined during the development process. Our grouping of RAMS+I characteristics is based on the system perspective, and human actions are involved in the study. Therefore, operating expertise and accidents caused by external actors can also be seen as reliability factors.

"Maintainability (performance) is the ability of a system 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" (IEC 60050(191), 1999). Maintainability is therefore also a built-in characteristic determined during product development. In our RAMS+I model, we have classified Inspectability, which can be defined as the "ability to undergo visits and controls", as a separate entity. Classically, inspectability is seen as one of the characteristics of maintainability with a preventive objective (van Houtte et al., 2010).

“Maintenance supportability performance is the ability of a maintenance organization, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy” (IEC 60050(191), 1999). It comprises both external and internal maintenance contracts, number and skill-level of personnel, maintenance equipment, spare parts etc. In the offshore wind energy industry, special attention should be paid to the availability of suitable commissioning/maintenance/decommissioning equipment.

The factors presented in Figure 4 are chosen to illustrate both their variety and to highlight the importance of wide-scale consideration of different factors and their effects on the whole lifecycle of offshore wind turbines. (Tiusanen et al., 2012)

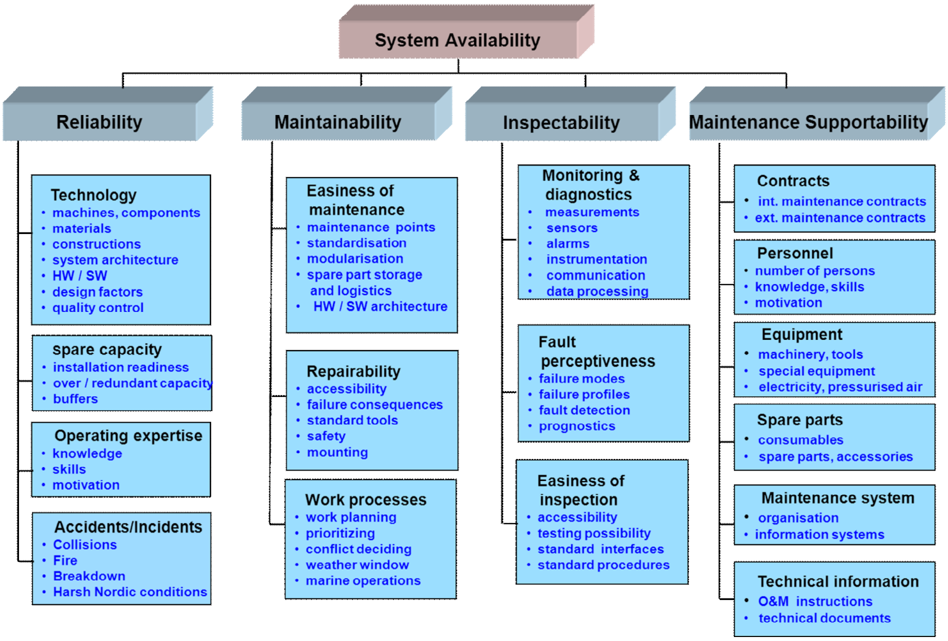


Figure 4. Factors affecting system availability in offshore wind assets in the Nordic context. (Tiusanen et al., 2012)

7.2 RAMS+I Management model for offshore wind turbine development

The main goals for wind farm design, as in all power-plant design, are to maximize energy production and ensure safe operation with minimum capital and operating costs. As the site-specific constraints and costs are all subject to some level of uncertainty, the optimization process during the design process obviously tries to minimize risks. (Tiusanen et al., 2011b)

Based on the general risk management framework described in Tiusanen et al. (2011b) and knowledge of system risks associated with offshore wind farm design and operation under challenging Nordic conditions, we have outlined a systematic risk management approach that can be utilized to support the wind farm design and deployment process. This system risk management approach is outlined in Figure 5.

The system risk analysis and assessment activities in this approach are divided into three levels. The first level aims to support wind farm project feasibility studies, support requirement specification and help find the appropriate criteria for the comparison of preliminary concepts. Risk analysis and assessment methods for this level have been developed to identify threats, problems, hazards and also opportunities. Methods can be used to evaluate benefits and disadvantages. The wind farm's external and internal context that is specified in the system requirement specification phase gives input and scope for the system definition and thus context for the forthcoming risk management activities. The second level aims to support wind farm layout design, key component selection, O&M strategy specifications and system design. Risk analysis and assessment methodology in this phase of the wind farm design are basically the same as in the former phase, but the analysis context is specified based on the decisions and choices made and specifications created in the project. When the system design is accepted and the project proceeds to the detailed design phase, the need for more detailed analysis and assessment methods becomes obvious. In the detailed design phase, there are several concurrent design branches such as offshore support structures design, wind farm and turbine electrical systems design, ICT & SCADA systems design, installation and commissioning planning, operation & maintenance concept design etc. The methodology and tools appropriate in this phase depend largely on the wind farm design tools and work methods in the project and in the subcontracting companies. System risk analysis and assessment support definition of design specifications, comparison of alternative design principles, design of system architectures and system integrity. Risk-based verification of designs is also essential. Tiusanen et al. (2011b)

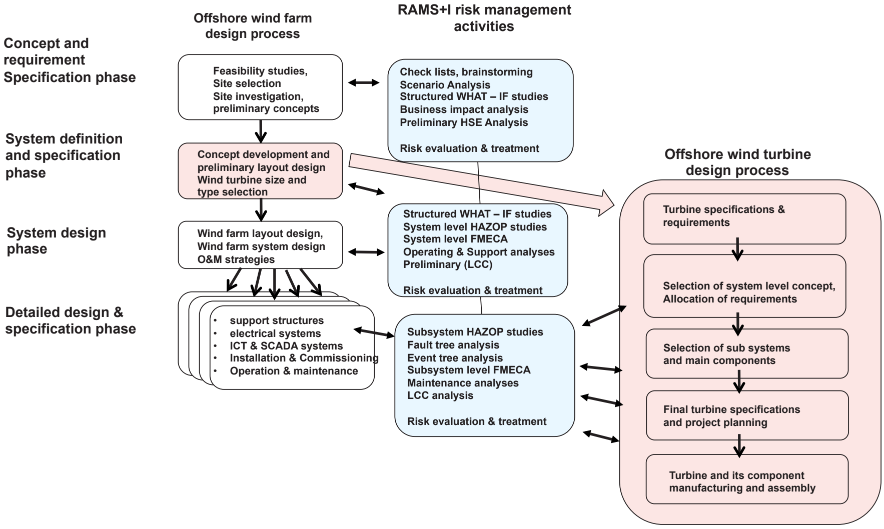


Figure 5. Design process and supporting RAMS+I risk management activities.

Figure 6 presents the front end phases that are related to the wind turbine design process. The model presented is developed according to different process models and is strongly influenced, for example, by Cooper’s Stage-Gate® model (see e.g. Cooper, 2005) and Ulrich and Eppinger’s product development description (see Ulrich & Eppinger, 2004). The main idea of the model is to divide the front end process into small and easily controllable phases and gates, where decisions concerning the future of the idea under development are made based on the criteria defined. Decisions that can be given for the idea on the gates are “go”, “hold” or “kill”. “Go” means that development of an idea can move to the next step or a stage for further development. A “kill” decision means that development of the idea stops. A “hold” decision is given to an idea that has potential but for some reason cannot be realized, for example because of a lack of the requisite technology. “Hold” can mean either waiting for better times or sending the idea back to a previous development stage, where it can be improved to meet the requirements of a gate. (Tiusanen et al., 2011c)

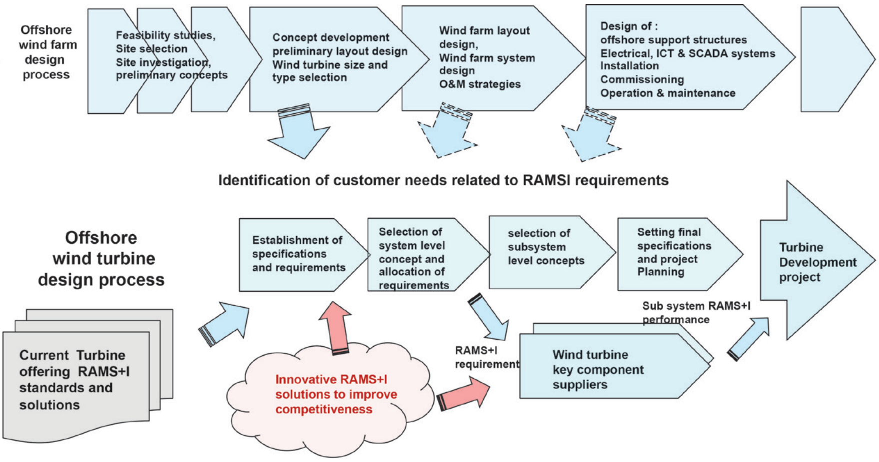


Figure 6. RAMS+I management in the early phases of wind turbine design (adopted from Tiusanen et al., 2011c).

7.3 Evaluation of RAMS+I factors

One aim of this research project has been to develop guidelines for comparing different offshore wind turbine concepts and their critical components from the viewpoint of system availability and safety. Classification and qualitative assessment of RAMS+I factors make it possible to create so-called comparable risk profiles for different concepts or combinations of components. (Tiusanen et al., 2012)

The Multi-Factor Risk-Profiling (MFRP) method that we have developed in this project is based on the well-known Multi-Criteria Decision Analysis (MCDA). The objective of multi-criteria decision analysis is to use a range of criteria to objectively and transparently assess the overall worthiness of a set of options. In general, the overall goal is to produce an order of preference between the available options. MCDA involves the development of a matrix of options and criteria, which are ranked and aggregated to provide an overall score for each option. (IEC 31010, 2009)

In contrast with the multi-criteria decision analysis method presented in the standard, we suggest that no single overall score or risk priority number (RPN) is calculated. Our opinion is that when the development process is still at its starting point and no reliable data is available, these kinds of overall ratings can hide some important findings. Nevertheless, the basic idea of comparing different options, in this case offshore wind-turbine concepts, based on multiple criteria remains. (Tiusanen et al., 2012)

The MFRP method is meant to be used at the very beginning of the development process. When the wind farm or wind turbine development process moves forward, MCDA can be used and the results of indicative risk profiling can also provide useful information for that purpose. The MFRP method uses the following the six step approach: definition of objectives; setting criteria for assessment categories; identification of relevant factors; evaluation of factors; specification of options for possible lower risk levels; evaluation of the results. (Figure 7.)

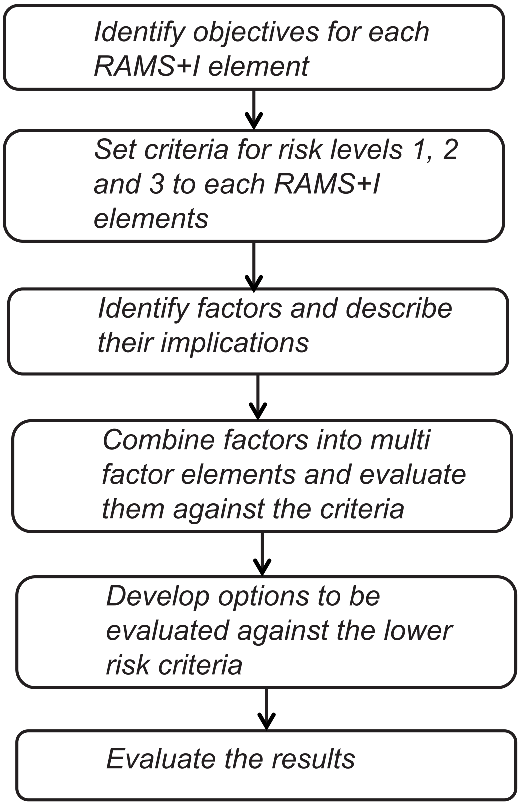


Figure 7. Multi-Factor Risk-Profiling process flow chart. (Tiusanen et al., 2012)

MFRP uses three risk levels for the assessment of RAMS+I elements. Three levels are enough to separate strong and weak values from each other. On the other hand, a small number of risk levels makes qualitative assessment more reliable because each assessment criterion can be clearly defined. Assessment criteria should be defined so that they highlight the main risks related to the group of factors identified under each element. Assessment criteria are presented as simplified expressions in Table 2. (Tiusanen et al., 2012)

Table 2. Simplified assessment criteria for RAMS+I elements. (Tiusanen et al., 2012)

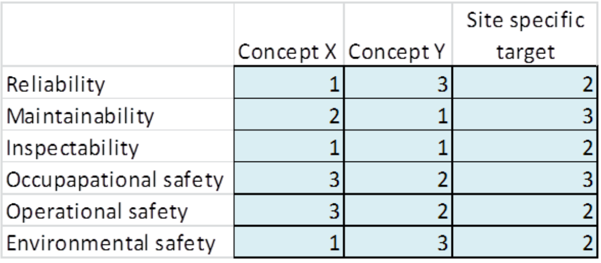
RAMS+I element	Assessment criteria
Reliability	MTTF estimation, comparison to onshore wind and oil & gas applications
Maintainability	Accessibility, required work effort and costs
Inspectability	Required technology, skills and costs
Occupational safety	Risk of accident, required safety measures and costs
Operational safety	Risk of accident or harm to business, severity of consequences
Biosystem safety	Risk of environmental effect, severity of consequences

The results of the evaluation are the numerical risk values 1, 2 or 3 for each of the RAMS+I elements of a case study. Such results can be visualized in many ways. Our proposition is to present this so-called risk profile in a simple radar graph. In our opinion, the radar graph is particularly good for visualizing the differences between different concepts and for comparing risk profiles with the objective pre-defined site-specific risk profile. The standard idea of showing MCDA results in a matrix of options is justified when the overall rating is calculated, but we believe that, in our approach, a radar or other illustration is more efficient and clear. Visualization examples are presented in Figure 8. (Tiusanen et al., 2012)

Risk-profiling results for the concepts revealed by the MFRP method can be used in many ways. For example, they can be used as a starting point when comparing different wind turbine concepts or their subsystems with each other, and with the site-specific requirements. A risk profile can also be used in more detailed wind turbine design phases to support resource allocation and risk management. In the MFRP method, each RAMS+I element is assessed against the criteria on a three-level scale. Level 1 represents high risk, level 2, medium risk and level 3, low risk. Because of the qualitative nature of the method and the available information in the conceptual design phase, the risk levels must have quite general verbal descriptions. An example of MFRP evaluation criteria is presented in Table 3. (Tiusanen et al., 2012)

Table 3. An example of evaluation criteria for three risk levels. (Tiusanen et al., 2012)

RAMS+I element	Risk level		
	1	**2**	**3**
Reliability	Technology maturity low, MTTF low compared to e.g. Oil&Gas / onshore WT levels	Technology maturity medium, MTTF medium compared to e.g. Oil&Gas / onshore WT levels	Technology maturity high, MTTF high compared to e.g. Oil&Gas / onshore WT levels
Maintainability	Maintenance takes a lot of effort and is time consuming. Accessing the target of maintenance requires considerable disassembly of structures. Special tools and expertise are needed.	Maintenance requires a typical level of effort and time. Performing maintenance tasks requires several years of experience but no special skills.	The unit is designed with maintenance in mind so that maintenance is easy and takes little time. The main maintenance task does not require major disassembly of structures. Tasks can be performed with basic tools by a person with typical skills.
Inspectability	Monitoring / diagnostics / inspection require extremely expensive technology and special skills.	Monitoring / diagnostics / inspection require expensive technology and special skills.	Monitoring / diagnostics / inspection require standard well-proven technology and special skills.
Occupational safety	High risks can be identified. Installation / maintenance / decommissioning is difficult to perform safely.	Medium risks can be identified. Installation / maintenance / decommissioning require special safety measures.	Low risks can be identified. Installation / maintenance / decommissioning require no special safety measures.
Operational safety	Has a serious negative impact on the operational environment.	Has minor negative impact on the operational environment.	Has no negative effect on the operational environment.
Biosystem safety	Has a serious negative impact on the environment and nature.	Has minor negative impact on the environment and nature.	Has no negative impact on the environment and nature.



	Concept X	Concept Y	Site specific target
Reliability	1	3	2
Maintainability	2	1	3
Inspectability	1	1	2
Occupapational safety	3	2	3
Operational safety	3	2	2
Environmental safety	1	3	2

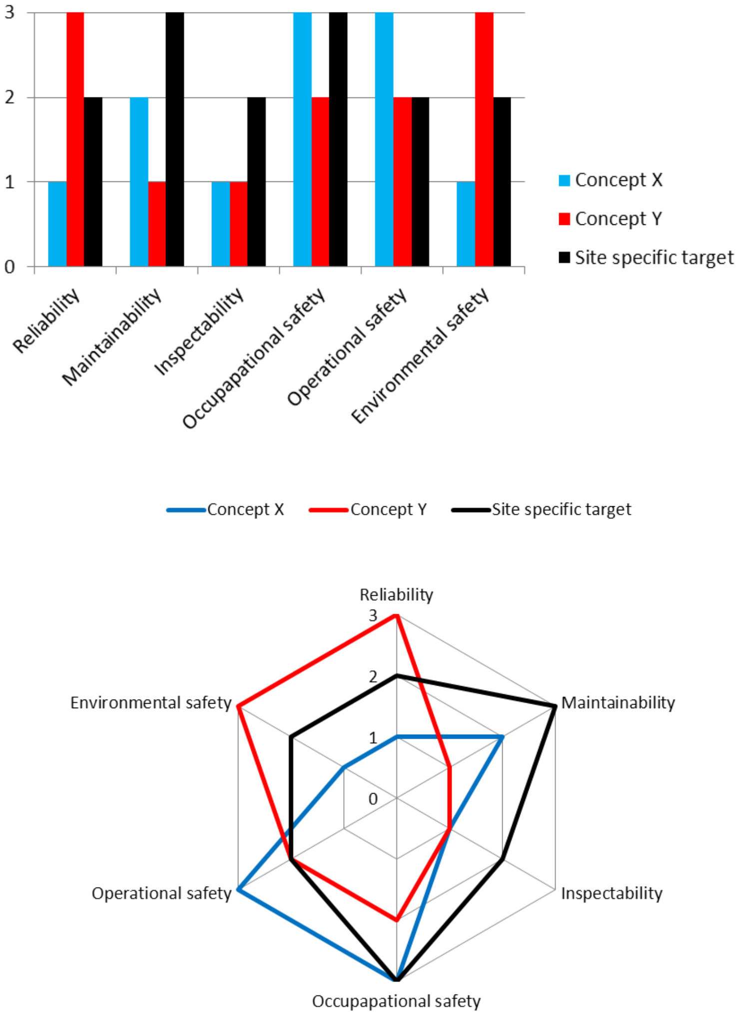


Figure 8. An example of an imaginary MFRP study. (Tiusanen et al., 2012)

The aforementioned MFRP criteria can be used to adapt more site-specific criteria. When the design process has proceeded further and more design data is available, a more detailed analysis, e.g. traditional FMECA, can be executed. Use of FMEA for wind turbines is presented for instance in Arabian-Hoseynabadi et al. (2010).

8. Discussion

The offshore wind energy sector is advancing very quickly. New wind turbine models, installation principles, and wind farm operating and maintenance concepts will be developed over the years to come. During this period of rapid growth and development, it is essential and beneficial to use experiences from other areas, such as the oil and gas industry, other energy-production sectors and the machinery manufacturing industry, for system risk management issues also. Frameworks and approaches are universal. Methodology and tools must be tailored to the needs of the application sector at hand. Because of the fast development of offshore technology and the introduction of new innovative turbine concepts, quantitative analysis methods cannot be used. Relevant data is not available. Conceptual design must be supported by qualitative risk analysis and reliability analysis methods.

The main goal of wind farm design is to maximize energy production and ensure safe operation with minimum capital and operating costs. As site-specific constraints and costs are always subject to uncertainties, the optimization process during the design process aims to minimize risks. Various risk types need to be considered in wind farm design and installation projects. This along with the complexity of the wind farm design process emphasise the need for a systematic risk management approach and framework. There is a need for appropriate and effective risk management measures from preliminary layout design to detailed turbine design and component selection.

Vinnem (2007) has stated that Quantified Risk Assessment (QRA) has become a key issue in the management of safety, health and environment in the oil and gas industries' offshore installations in the North Sea. QRA studies are somewhat specific in Northern Europe, and particularly in Norway. The use of these techniques is dominated by offshore applications, with the main emphasis on quantification of risk to personnel. The main hazards to offshore structures in the oil and gas industry are fire, explosion, collision and falling objects. Although the main challenge with subsea production facilities is demonstrably the reliability of the production function, due to the extensive costs and delays involved in maintaining subsea production facilities, according to Vinnem (2007), this aspect is not considered in QRA guidelines.

During the last two years, standardization in the industrial risk management field has moved on substantially. Internationally accepted and ratified ISO risk management standards and risk assessment standards have been updated, and the new guidelines give a good basis for the implementation of a system risk management framework in the offshore wind energy sector.

One result of this project is an outline of a risk management framework that can be applied to the wind energy sector and that is appropriate for large offshore wind farm projects to support system risk management and overall system integrity management. The system risk management approach outlined has been applied successfully in the last few years to several large-scale machinery system concepts in Finland (Tiusanen et al., 2008). The approach and methodology were developed to support complex remotely-controlled machinery systems in various industrial sectors such as the mining industry, paper industry and large-scale container handling applications in port terminals. The methodology has been implemented and tested in the conceptual design phase, the system design phase and the detailed design phase with various technological implementations.

Wind farm projects are carried out by large networks of wind farm operators and numerous subcontractors. For the successful implementation of the outlined framework for system risk management, it should be integrated into the wind farm project management process and as a tool of the wind farm design toolbox.

8.1 RAMS+I management model

The RAMS+I requirements are meant to guide the system development process in its various phases. The utilisation of a systematic RAMS+I program aims to identify, analyse and assess availability and safety issues and specify requirements in the most appropriate way. RAMS+I requirement management as an essential part of the general systems engineering approach, tries to help avoid situations where defects in availability and safety performance are not detected until the system is already operating. Corrective actions are then difficult and expensive to implement.

The high system availability and safety performance criteria concerning offshore wind turbines and offshore wind farms require a substantial effort in risk-conscious lifecycle management. Management of availability and safety requirements is an iterative and continuous process that follows the system lifecycle and overall quality assurance process of the company or project consortium. Successful management of RAMS+I requirements demands various activities such as analyses, assessments, and evaluations and a lot of documentation for various purposes during wind turbine and wind farm design, deployment and use. RAMS+I management can be seen as a characteristic of a wind farm’s long-term operation and is achieved via the application of proven engineering concepts, methods, tools and techniques throughout the whole lifecycle of the wind farm.

The benefits of implementing a RAMS+I program include support with investment decision-making, cost management, improved management of resource requirements, systematic support for development & implementation of products, and an integration of dependability and safety requirements. A systematic approach and the timeliness of the RAMS+I tasks make it possible to utilize the results from higher level analyses and decisions as specific requirements, design principles or potential solutions throughout different engineering project phases.

It is particularly important to recognise that a high integrity level of software-based systems, such as wind farm information systems, the wind mill and its subsystem control and monitoring systems, can only be achieved by following a systematic integrity assurance program where system availability, reliability, maintainability, inspectability and functional safety issues are managed throughout the system lifecycle. In software development projects especially, the system integrity level cannot be validated at the end of the project by testing the system in the factory or on site. System integrity must be built into the system by means of system requirement specifications, design specifications, design verification and testing, integration testing, system validation, etc. concurrently and with the right timing as part of the system development process.

The importance of system inspectability will increase as wind farms are situated in deep waters far from the coast. With well-designed online remote diagnostics and intelligent control applications, failures and deviations in planned functions can be detected early enough to minimize the consequences. Improving inspectability may increase development work, component costs and complexity of devices, but at the same time sophisticated diagnostics and monitoring systems will enable earlier detection of failures and support the planning of preventive maintenance. With the remote diagnostics developed, it will be possible to reduce the number of onsite inspection visits.

For offshore wind farm projects in northern areas, inspectability is even more important, as comprehensive offshore wind farm data is not available for modelling, simulations and qualitative analysis to help support risk estimation, evaluation and assessment in the early conceptual phase of the system lifecycle. Special risks related to the Nordic context, such as system availability, system reliability, accessibility and safety were described earlier in this paper. The implementation of the framework and methodology outlined will save time and money and resources thanks to better risk estimations and evaluation criteria for decision-making.

We have outlined the early stages of wind turbine design and RAMS+I management tasks related to these stages. The RAMS+I model presented is generic for the offshore wind sector, and it might not be applicable as it is for any company. Further research is needed for case-specific model implementation and verification. One main interest in RAMS+I management development is information transfer between different actors in the supply chain.

The models created were not tested in practice during this project. The models were constructed based on expert judgement, as no real-life data was available.

RAMS+I related lifecycle cost-benefit evaluations benefit both suppliers and customers. This message should be made clearer in both directions to avoid situations where the customer only looks at the purchase price. To avoid this, wind turbine manufacturers should be able to demonstrate the costs and benefits of the whole lifecycle of their product more clearly and precisely.

Designers are looking for the “optimal” solution for platform and turbine concepts that will achieve the best functionality and lowest cost. The solution is always a compromise that attempts to minimize the system costs by addressing each technical challenge. It is important to identify and assess issues affecting the value added, especially in new innovative technologies, in the conceptual design phase. The added value achieved from successful RAMS+I management throughout the offshore wind asset lifecycle comes from, for instance:

- high system availability
- motivated and committed personnel
- no accidents and negative impacts on the marine natural environment
- optimal utilisation of weather windows for marine operations
- maximised turbine up-time and minimised down-time.

Another factor that certainly has a strong impact on offshore wind farms' efficient and optimal energy production and costs is the system operation. Issues related to system operation or system operability do not fall within the scope of this study, but there is clearly a need for further research on these issues. As operation and maintenance strategies and concepts are developed simultaneously, issues adding value or creating system risks should be analysed and assessed together from both perspectives.

8.2 RAMS+I factors evaluation

The Multi-Factor Risk-Profiling (MFRP) method presented can offer support to the wind farm design team when selecting substructures and setting requirements for the wind turbines. Turbine manufacturers can use this method when comparing different turbine concepts and nacelle drivelines and components. The MFRP method could also be used for comparing operation concepts or assessing operability issues.

Risk profiles can be used to support the core decisions, for instance selection and specification of wind turbine maintenance strategy, including amongst other things, means of access to the nacelle, systems for handling components in the nacelle, etc. Such criteria and profiling help with strategic decision-making concerning whether the nacelle systems should be designed for long life and reliability based on integrated design, which poses challenges for local maintenance and partial removal of subsystems, or designed perhaps in a less cost-effective modular way for easy and safe access to components.

Butterfield et al. (2007) have used quite a similar assessment principle for offshore floating platform design challenge ratings and platform comparison. They also used a simple three-category rating method for design challenge assessment. Their aim was a framework for classification of floating wind turbine platforms on the basis of static stability criteria that can be used as a practical method for performing first-order economic analysis on a wide range of platform architectures.

The following can be considered strengths of the MFRP method:

- Supports qualitative assessment in early phases with limited information available

- Has a simple structure for efficient decision-making
- Can be used as a starting point for more detailed analysis
- Supports assessment of complex decision problems that are not amenable to cost/benefit analysis by splitting them into more manageable elements and factors
- Can help rationally consider problems where trade-offs need to be made.

Weaknesses of the MFRP are that it is heavily based on expert assessment and results can therefore be too subjective. Risk profiling can be affected by bias and poor selection of the decision criteria and the fact that most RAMS+I factors consist of many aspects that are difficult to combine together.

The MFRP method developed in this project is based on literature studies, experiences of risk management in VTT and co-operation in the NORCOWE research community. The next step should be a practical verification of the methodology and evaluation of assessment criteria in a real industry case.

9. Acknowledgement

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Title	**RAMSI management model and evaluation criteria for Nordic offshore wind assets**
Author(s)	Risto Tiusanen, Jere Jännes & Jayantha P. Liyanage
Abstract	The offshore wind energy sector is in the early stages of development, but it is growing fast. Due to the European Union's renewable-energy and climate goals along with national legislation, the offshore wind sector will develop strongly over the coming years in Europe. In the offshore wind energy sector, there are many different wind-turbine designs ranging from traditional monopile structures to floating platforms, depending on the water depth. Today, most offshore turbines are based on onshore turbine designs, and turbine technology continues to develop incrementally. At the same time, there is strong demand in the market for new, innovative designs for offshore wind turbines whose main focus is reliability and cost efficiency. For floating offshore wind turbine designs, there may be new types of uncertainty and system risks compared with onshore wind turbines. Wind turbines in cold climates, such as those experienced in the Nordic countries, may be exposed to extreme conditions, such as formation of ice or very low temperatures that are outside the design limits of standard wind turbines. In the offshore wind energy sector, specification, implementation and verification of the so-called RAMS+I (Reliability, Availability, Maintainability, Safety and Inspectability) requirements during development work are important for companies delivering wind turbines, from the perspective of system integrity. Decisions made before the formal design phase strongly determine the costs and benefits gained during the whole lifecycle of a wind turbine. The benefits of implementing the RAMS+I program include support with investment decisions, cost management, improved management of resource requirements, systematic support with development & implementation of products, and integration of dependability and safety requirements. This publication outlines a model for managing RAMS+I factors during the conceptual design phase of an offshore wind turbine. The model is based on the product development process, concurrent design principles and the Stage-Gate® model. The model concentrates mostly on technical decisions made in the early development phases. This publication also presents guidelines for comparing different offshore wind energy assets and their critical components from a system availability and safety viewpoint. The classification and evaluation criteria for RAMS+I factors are outlined and discussed, and a multi-factor risk-profiling (MFRP) method introduced.
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Nimeke	**RAMSI- vaatimusten hallinnan malli ja evaluointikriteerit pohjoisten merialueiden tuulivoimaloissa**
Tekijä(t)	Risto Tiusanen, Jere Jännes & Jayantha P. Liyanage
Tiivistelmä	Tuulienergian tuotanto avomerellä on kehityskaarensa alkuvaiheessa. Uusiutuviin energiamuotoihin ja ilmastoon liittyvien Euroopan unionin tavoitteiden ja kansallisten lainsäädäntöjen ohjaamana tuulienergian tuotanto avomerellä tulee Euroopassa kehittymään voimakkaasti tulevina vuosina. Avomerikäyttöön on suunniteltu useita erilaisia turbiinikonsepteja meriveden syvyyden mukaan perinteisistä kiinteästi pohjaan perustetuista ”monopile”-rakenteista kelluville alustoille rakennettuihin turbiineihin. Tänä päivänä avomerelle rakennettavien tuuliturbiinien tekniset ratkaisut perustuvat pitkälti maalla käytettävien turbiinien hyviksi havaittuihin teknologioihin. Markkinoilla on kuitenkin voimakas kysyntä uusille innovatiivisille avomeriolosuhteisiin kehitetyille turbiinikonsepteille, joiden avulla keskeiset suunnittelukriteerit – luotettavuus ja kustannustehokkuus – saataisiin entistä kilpailukykyisemmiksi. Avomerikäyttöön tarkoitettuihin kelluviin tuuliturbiinikonsepteihin liittyy aivan uudentyyppisiä epävarmuustekijöitä ja riskejä verrattuna maalla tai rannikolla käytettäviin tuuliturbiineihin. Pohjoisen arktisilla merialueilla tuuliturbiinit joutuvat lisäksi alttiiksi ääriolosuhteille, kuten jäänmuodostus, erittäin alhainen lämpötila, myrskytuulet ja korkea aallokko, jolloin suunnittelukriteerit poikkeavat nykyisistä tuuliturbiineille asetetuista vaatimustasoista. Tuuliturbiinijärjestelmän käyttövarmuus- ja turvallisuusvaatimusten ns. RAMS+I (Reliability, Availability, Maintainability, Safety and Inspectability) -vaatimusten määrittely, toteuttaminen ja todentaminen kokonaisvaltaisesti kehitystyön aikana muodostuvat erityisen tärkeiksi toimitettaessa tuuliturbiineja näihin vaativiin avomeriolosuhteisiin. Päätökset, jotka tehdään tuuliturbiinin konseptisuunnitteluvaiheessa, määrittelevät vahvasti niin tuuliturbiinin suorituskykyyn vaikuttavat ominaisuudet kuin sen elinkaarikustannuksiin vaikuttavat tekijät. RAMS+I-ohjelman systemaattinen toteuttaminen tukee investointipäätösten tekoa, tuotekehitystä ja järjestelmien toteutusta sekä erityisesti käyttövarmuus- ja turvallisuusvaatimusten integrointia ja implementointia. Tässä julkaisussa kuvataan RAMS+I- vaatimusten hallinnan mallia ja sen soveltamista avomerikäyttöön tarkoitettujen tuuliturbiinien konseptisuunnitteluvaiheeseen. Kehitetty malli perustuu yleiseen teollisuustuotteiden tuotekehitysprosessiin, rinnakkaissuunnittelun periaatteisiin ja projektihallinnan ns. Stage-Gate®- malliin. RAMS+I- vaatimusten hallinnan kehitystyössä on keskitytty tuotekehityksen ensimmäisissä vaiheissa – konseptikehityksessä, vaatimusmäärittelyssä ja järjestelmäsuunnittelussa – tehtävän järjestelmäsuunnittelun päätöksenteon tukemiseen. Julkaisussa kuvataan myös menetelmä ”Multi Factor Risk Profiling method” (MFRP) ja arviointikriteerit, joiden avulla voidaan vertailla erilaisia avomerikäyttöön suunniteltuja tuuliturbiinikonsepteja niiden järjestelmätason käyttövarmuuden ja turvallisuuden näkökulmista. Tämä arviointimenetelmä perustuu yleisesti tunnettuun ”Multi-criteria decision analysis” (MCDA) -menetelmään.
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