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A review of reliability-based methods for risk analysis and their application in the offshore wind industry

Mareike Leimeister[a,b,*], Athanasios Kolios[b]

[a] Fraunhofer Institute for Wind Energy Systems (IWES), Am Luneort 100, 27572 Bremerhaven, Germany
[b] Cranfield University, Energy and Power, Whittle Building, Bedfordshire MK43 0AL, United Kingdom

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ABSTRACT

Offshore and marine renewable energy applications are governed by a number of uncertainties relevant to the design process and operational management of assets. Risk and reliability analysis methods can allow for systematic assessment of these uncertainties, supporting decisions integrating associated consequences in case of unexpected events. This paper focuses on the review and classification of such methods applied specifically within the offshore wind industry. The quite broad differentiation between qualitative and quantitative methods, as well as some which could belong to both groups depending on the way in which they are used, is further differentiated, based on the most commonly applied theories. Besides the traditional qualitative failure mode, tree, diagrammatic, and hazard analyses, more sophisticated and novel techniques, such as correlation failure mode analysis, threat matrix, or dynamic fault tree analysis, are coming to the fore. Similarly, the well-practised quantitative approaches of an analytical nature, such as the concept of limit states and first or second order reliability methods, and of a stochastic nature, such as Monte Carlo simulation, response surface, or importance sampling methods, are still common practice. Further, Bayesian approaches, reliability-based design optimisation tools, multivariate analyses, fuzzy set theory, and data pooling strategies are finding more and more use within the reliability assessment of offshore and marine renewable energy assets.

1. Introduction and outline

Offshore wind turbines are exposed to severe environmental conditions. Occurring failures could have environmental impacts, but definitely would lead to considerable financial losses. This is not only due to the lost production output because of the failure, but is especially amplified by the limited accessibility of offshore assets, located some distance from the coast and sometimes even in quite remote areas. Transport of offshore engineers and work on the asset can only be performed in acceptably safe sea states and at medium wind speeds. These prescribed working weather windows imply quite long delays sometimes, until the asset can operate in normal mode again. This moves the point of focus towards risk management and reliability assessment of offshore wind turbines.

According to BS ISO 31000, risk is the “effect of uncertainty on objectives…[and] is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood…of occurrence” [1], p. 1. The latter can be influenced by the level of reliability. Reliability itself is defined, based on BS 4778 [2], as “the ability of a component or a system to perform its required functions without failure during a specified time interval” [3], p. 12, but “can also be denoted as a probability or as a success ratio” [4], p. xxvi. Several different techniques for obtaining qualitative or quantitative measures of reliability exist; however, not every method is

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Abbreviation: AHP, Analytic Hierarchy Process; ALARP, As Low As Reasonably Practicable; ANP, Analytic Network Process; ATF, Artificial Transfer Function; B(B)N, Bayesian (Belief) Network; BT(A/D), Bow-Tie (Analysis/Diagram); CPN, Cost Priority Number; DO, Deterministic Optimisation; ET(A/D), Event Tree (Analysis/Diagram); FM, Failure Mode; FMEA, Failure Mode and Effects Analysis; FMECA, Failure Mode Effects and Criticality Analysis; FMMA, Failure Mode and Maintenance Analysis; FORM, First Order Reliability Method; FST, Fuzzy Set Theory; FT(A/D), Fault Tree (Analysis/Diagram); HAZID, Hazard Identification; HAZOP, Hazard and Operability Studies; HL, Hasofer and Lind; IS(R)M, Importance Sampling (Reduction) Method; LHS, Latin Hypercube Sampling; LS(F), Limit State (Function); MA, Markov Analysis; MADM, Multi-Attribute Decision Making; MCDA, Multi-Criteria Decision Analysis; MCS, Monte Carlo Simulation; NPI, Non-Parametric Predictive Inference; OREDA, Offshore Reliability Data; PDMP, Piecewise Deterministic Markov Process; PNET, Probability Network Evaluation Technique; PoF, Probability of Failure; RA, Reliability Analysis; RAMS, Reliability, Availability, Maintainability, and Safety; RBD, Reliability Block Diagram; RBDO, Reliability-Based Design Optimisation; RI, Reliability Index; RIF, Risk Influencing Factor; RIV, Reliability Index Vector; RPN, Risk Priority Number; RS(M), Response Surface (Method); SORM, Second Order Reliability Method; SRSM, Stochastic Response Surface Method; SWIFT, Structured What-If Technique; SWOT, Strengths, Weaknesses, Opportunities, and Threats; TOPSIS, Technique for Order Preference by Similarity to Ideal Solution

[*] Corresponding author at: Fraunhofer Institute for Wind Energy Systems (IWES), Am Luneort 100, 27572 Bremerhaven, Germany
E-mail address: mareike.leimeister@iwes.fraunhofer.de (M. Leimeister).

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suitable to be applied to the assessment of offshore energy systems. Some may be more useful than others, and some have to be adjusted or combined to obtain valuable results.

The aim of this paper is to classify reliability methods used in the offshore and marine renewable energy industry. Other objectives are the analysis of these methods with respect to their applicability to offshore wind turbine systems, their benefits and limitations, as well as the elaboration of existing trends and further approaches required to overcome those limits still remaining. The paper is structured in such a way that first a classification of common reliability methods is given in Section 2. After this general overview, qualitative and quantitative reliability assessment procedures, specifically applied within the offshore wind and marine renewable energy industry, are presented and categorised (Sections 3 and 4). This is based on a systematic literature review, which primarily used the specific words “reliability” and “offshore”, focused on the latest research work done, preferably from 2010 onwards, and aimed to concentrate on offshore wind turbines; however, some examples of other offshore industries and structures were also included due to the still low information density on offshore renewable energy devices. In total, more than 100 papers have been reviewed and further information was taken from recent conferences, as well as industrial experiences. Section 5 points out how offshore wind turbine systems challenge common reliability assessment methods, in which way and how far the presented techniques are already able to cope with this, as well as which limits are still existing and which theories will potentially develop further. Finally, a conclusion is provided in Section 6.

2. Classification of reliability methods

Reliability analyses (RAs) can be performed for different systems and components, such as mechanical, electronic, or software, as well as at various stages of the engineering process, for example design or manufacture [4]. Due to the broad application of reliability, attempts at categorisation are being made. Stapelberg [5] for example focuses on reliability in engineering design and distinguishes between reliability prediction, assessment, and evaluation, depending on the design stage conceptual, preliminary/schematic, or detailed, respectively. Furthermore, two different levels at which reliability can be applied are defined: component and system level. These already introduce the bottom-up and top-down approaches, which can be found in some reliability methods as well.

Considering the different reliability methods themselves, there are two main categories into which they can be grouped: qualitative methods and quantitative methods, depending on the availability and quality of data [5]. However, a comparison of different literature, such as O'Connor et al. [4] or Rausand and Høyland [6], shows some discrepancies in the assignment of certain reliability methods and indicates the need for a third intermediate category for such semi-quantitative reliability methods. The methods covered in the following, as well as the chosen categorisation, are visualised in the form of a Venn diagram, presented in Fig. 1. The abbreviations used will be explained in the following sections and are listed at the beginning of the paper.

Furthermore, it has to be noted that some of the presented methods are rather risk assessment tools than reliability methods. However, these risk assessment techniques are still included, as the awareness of the existing risks is the decisive basis for RAs. In the following, it is just stated whether the tool is strictly speaking used for risk or reliability. A detailed list of risk assessment methods can be found in BS EN 31010 [7].

2.1. *Qualitative reliability methods*

Missing or insufficient data does not allow for quantitative assessment of reliability. Nevertheless, relations within the system, covering hazards, failure causes, events, failure modes, faults, effects, and consequences, can be shown and this way an estimate of reliability, failure probability, and consequence can still be obtained by using qualitative methods.

Before performing any qualitative RA, first the system structure and functions have to be identified and classified [6]. On this basis, a qualitative reliability assessment can be carried out. Some of the most common methods are briefly explained in the following, grouped into sheet-based, table-based, and diagrammatic techniques.

2.1.1. *Sheet-based qualitative reliability methods*

Typical sheet-based qualitative methods are checklists; they are used to assist engineers [6] in determining and examining influencing factors, and thus identifying risks, for design operation, maintainability, reliability, safety, and availability. Thus, for each stage there are different question sets, on which basis the contributing parameters can be studied [5].

2.1.2. *Table-based qualitative reliability methods*

The table-based qualitative methods focus either on hazards or failure modes (FMs).

The aim of hazard identification (HAZID) analysis is to determine potential hazards, as well as their causes and consequences. This risk identification method should be applied as early as possible, so that changes and adaptions, which may avoid the hazard or at least reduce the effects to the system, can be integrated in the early system design. A typical HAZID worksheet starts by naming the investigated component or area, followed by the potential incident. Then, the potential causes and consequences are determined and the severity of the latter is categorised. Finally, recommendations for corrections or precautions are given [5].

A hazard and operability (HAZOP) study, another risk assessment tool, is also used for the identification of hazards, their potential causes and effects; however, this analysis rather focuses on deviations from the normal operation mode as initiating event. Special guide words, such as NO or NOT, MORE, LESS, LATE, or BEFORE, are used for describing these deviations. The HAZOP procedure itself could either start with the guide word or the considered element. A HAZOP worksheet contains, besides the guide word and element, the explicit meaning of the deviation, the potential causes and consequences, already existing safeguards, as well as recommended necessary actions and further comments [8].

More adaptable tools for identifying risks are the what-if analysis or structured what-if technique (SWIFT). The SWIFT starts with collecting potential hazards and uses in addition a checklist, containing typical errors and failures that could also make up hazards. The hazards are then organised in a worksheet, comprising the hazard itself, mentioned in the column headed What-if?, its potential causes and effects, as well as presenting safeguards and giving recommendations, similarly to HAZID and HAZOP [9].

Not only focusing on hazards, the failure mode and effects analysis (FMEA) aims to identify FMs in the system function or equipment, their potential impacts and causes, as well as determining existing controls and precautions. Thus, while being originally a risk assessment tool, FMEA can also be used for RA. Three different types of FMEA exist: concept/functional FMEA, design/interface FMEA, and detailed/updated FMEA, implying that FMEA can be used throughout the entire life cycle of an asset [6].

2.1.3. *Diagrammatic qualitative reliability methods*

Qualitative reliability methods in the form of a diagram can be structured from the top down or the bottom up. Such a top-down approach is used in the cause and effect diagram, which is also called the fish-bone diagram due to its shape. The top event, a failure or incident, makes up the head of the fish on the right side. Different cause categories, containing several specific factors, are then added in form of fish-bones to the diagram, allowing a structured risk assessment [6].