RiaSoR

RELIABILITY IN A SEA OF RISK

Reliability Guidance for Marine Energy Converters

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Editor: Pär Johannesson

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Contributors:

Pär Johannesson, Thomas Svensson, Fabio Santandrea

Chong Ng, Chunjiang Jia

Elaine Buck, Andy Shanks

SP Technical Research Institute of Sweden

Offshore Renewable Energy Catapult

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Project Partners

EMEC ORKNEY THE EUROPEAN MARINE ENERGY CENTRE LTD	The European Marine Energy Centre Old Academy Business Centre Stromness, Orkney, KW16 3AW, UK http://www.emec.org.uk
CATAPULT Offshore Renewable Energy Development Services Ltd	Offshore Renewable Energy Catapult National Renewable Energy Centre Offshore House, Albert Street, Blyth, Northumberland, NE24 1LZ, UK https://ore.catapult.org.uk
SP your Science Partner / PART OF RISE	SP Technical Research Institute of Sweden Gibraltargatan 35 400 22 Göteborg, Sweden http://www.sp.se

Summary

The Reliability in a Sea of Risk project (RiaSoR) addresses the strategic need for the ocean energy industry to focus on the key engineering challenges that underpin the reliability and survivability of this emerging technology. The project will reduce these risks by developing industry approved reliability methodologies and testing practices which will be applied through the leading ocean energy testing houses to ensure consistency and robustness by which reliability is demonstrated across all wave and tidal technologies. This process will be used to de-risk the uncertainty of failures in the structural, electrical and connection elements of wave and tidal devices and allow more accurate predictions on the load variations they encounter. This reliability methodology is ultimately aimed at reducing Health Safety and Environmental (HSE) risks, technological risks, Operations and Maintenance (O&M) costs which will lower the Levelised Cost of Energy (LCoE) for the sector.

In today's uncertain investment environment, the perception of technical risk is dependent on how confident the investors are that the ocean energy devices will perform reliably and produce the expected output for their devices. As the industry is approaching a pre-commercial stage, in sea testing and demonstration at various scales will be a primary focus for the sector over the next three to five years. This places a key role on the test houses to put in place a rigorous testing programme whereby the reliability of this emerging technology can be tested and independently verified before these systems move onto large scale array deployments.

A methodology is presented for working with reliability and robustness when developing Ocean Energy Devices, based on the Variation Mode and Effect Analysis (VMEA) methodology. For studying reliability regarding mechanical failure, the concept of load-strength interaction is useful. This means that the problem can be separated into studying a) the outer load acting on the structure to be designed and b) the strength, or resistance, of the structure. The aim is to design the structure to assure, with sufficient confidence, that the strength exceeds the load for future usage. Statistical methods provide useful tools for describing and quantifying the variability in load and strength. For this purpose the concept of VMEA will be used, which is a method aimed at guiding engineers to find critical areas in terms of the effects of unwanted variation. The VMEA method can be used as a reliability tool throughout the product development process. In the early design stage when only vague knowledge about the variation is available, the basic VMEA is used to compare different design concepts. Further in the design process, when better judgements of the sources of uncertainties are available, the enhanced VMEA is used, which is further developed into the probabilistic VMEA in the later design stages where more detailed information becomes available, and the goal is to verify the reliability targets and derive safety factors.

When using a life evaluation model, the uncertainty in the calculated life can thus be quantified using the VMEA method. The factors that cause the most uncertainty can be identified, thus guiding the design improvements to reduce the critical uncertainty, which will lead to more robust and optimized products. Further, it also allows proper safety factors to be established with regard to a required service life or strength. In operation of devices, the VMEA can be updated by condition monitoring data and can thus be a tool used in maintenance planning.

This reliability guidance transfers the experience of reliability and application of VMEA from automotive and aerospace industries to the ocean energy sector. The presented reliability methodology is described in view of the design criteria for marine energy converters, and the different phases of the VMEA methodology are explained in great detail. Further, the application of VMEA is detailed for structural, electrical and mooring/foundation elements of devices, each one exemplified by a case study.

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Preface

Reliability has been identified as a key issue for the development and success of the *Marine Energy* sector. The *RiaSoR (Reliability in a Sea of Risk)* project addresses this strategic industrial need for guidance in reliability design. The primary task of the RiaSoR project has been to address this industrial need for reliability design methodologies by implementing and adapting the VMEA (Variation Mode and Effect Analysis) methodology, that is used in automotive and aerospace industries, to the ocean energy application. A fundamental basis of the VMEA methodology is to view reliability design in terms of insensitivity to random variation and other sources of uncertainties. Thus, reliability improvements in the design stage should be focused on reducing uncertainties and/or diminishing the sensitivities to uncertainties.

This *Reliability Guidance* is a main result of the RiaSoR project, where SP has been responsible for implementing and adapting the VMEA methodology to the ocean energy setting, with input and contributions from EMEC and ORE Catapult, within *WP 2 Reliability Methodology Framework* of the RiaSoR project. The reliability framework is tailored for different types of components/systems within, namely

- *WP3 Structural Methodology Analysis*, where SP has been the responsible partner, with contributions from EMEC and ORE Catapult.
- *WP4 Electrical power conversion systems Methodology Analysis*, where ORE Catapult has been the responsible partner, with methodological support from SP and contributions for EMEC.
- *WP5 Moorings/Foundations Methodology Analysis*, where EMEC has been the responsible partner, with methodological support from SP and contributions for ORE Catapult.

An educational workshop was organized within the RiaSoR project at Technology & Innovation Centre in Glasgow, November 30 to December 1, 2016, with participation of engineers from both wave and tidal energy technology companies. This Reliability Guidance and other material from the RiaSoR project, including training material from the educational workshop, is available on the RiaSoR webpage:

www.riasor.eu

Pär Johannesson, editor

December 2016

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This Guideline is a result of the project RiaSoR (Reliability in a Sea of Risk) produced in collaboration with the European Marine Energy Centre (EMEC), The Offshore Renewable Energy Catapult (ORE Catapult), and SP Technical Research Institute of Sweden (part of RISE Research Institutes of Sweden). Further guidance and review of the document was in collaboration with the National Renewable Energy Laboratory (NREL) in the United States of America, and EDF Renewable Energy in France.

The project was funded by the Ocean Energy ERA-NET and co-ordinated by Scottish Enterprise, the Regional Economic Development Agency for lowlands Scotland. Ocean Energy ERA-NET is comprised of a consortium of partners of which Innovate UK, Swedish Energy Agency including Scottish Enterprise are funding partners for RiaSoR project.

The Ocean Energy ERA-NET was set up to address the research and innovation challenges in ocean energy and how this sector will contribute to future renewable energy targets, economic growth and job creation.

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Reliability guidance methodology and editorial oversight

Editorial contributions from Pär Johannesson (editor), Thomas Svensson, Fabio Santandrea with SP, Elaine Buck and Andy Shanks with EMEC, Chong Ng and Chunjiang Jia with ORE Catapult.

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1 Reliability and the VMEA Concept

The overall goal of engineering design is to make a robust and reliable product that meets the demands of the customers, see (Bergman & Klefsjö, 2010). In order to achieve this goal, it is important not only to predict the life of a product, but also to investigate and take into account the sources of variability and their influence on life prediction. This topic is addressed in Reliability and Robust Design Methodologies, see e.g. (Bergman et al., 2009), (Johannesson et al., 2013) and (O'Connor, 2002), and also in related methodologies like Design for Six Sigma, (Creveling et al., 2003), Design for Variation, (Reinman et al., 2012) and Failure Mode Avoidance, (Davis, 2006). The challenges in reliability design are similar in all industry sectors, thus these general documents are also valid for wave and tidal technologies.

There are of course documents that more specific address wave and tidal technologies. Reliability is identified as a key aspect in "Guidelines on design and operation of wave energy converters", (DNV, 2005), in the development of wave energy devices. However, guidance on how to deal with reliability is only given on a very generic level. Several methods are suggested to help reliability assessment, such as Life Cycle Costing (LCC), Fault Tree Analysis (FTA), Reliability Block Diagram, Failure Modes and Effects and Criticality Analysis (FMECA) and Reliability Centered Maintenance (RCM), (EMEC, 2009b). A more specific, yet still general, framework is given in "State of the Art Descriptions and Tasks for Structural Design of Wave Energy Devices", (SWED, 2010).

In this guidance the components of a wave energy device are divided into two groups with regards to reliability assessment:

1. Electrical and mechanical components where the reliability and failure rates are estimated using classical reliability models such as Weibull distribution models.
2. Structural components where a ***limit state*** equation can be formulated defining failure or unacceptable behaviour. The parameters are then modelled by random variables and the reliability is estimated using Structural Reliability Methods, see e.g. (Ditlevsen & Madsen, 1996).

As mentioned above, an important goal of engineering design is to get a reliable system, structure or component. In industry, the method of Failure Mode and Effect Analysis (FMEA) is often used for reliability assessments, where the aim is to identify possible failure modes and evaluate their effect. This is primarily a qualitative method which points out weaknesses in design, but without giving measures of the resulting reliability. Studies of FMEA have indicated that the failure modes are in most cases triggered by unwanted variation, (Lönnqvist, 2009), variation that may be quantified.

Further, a general design philosophy within reliability and robust design methodology, is to make designs that avoid failure modes as much as possible, see e.g. (Davis, 2006), and (Bergman et al., 2009). Thus, it is important that the design is robust against different sources of unavoidable variation.

Therefore, a tool for addressing robustness against variation was developed, namely the so-called Variation Mode and Effect Analysis (VMEA) that was first presented by (Chakhunashvili et al., 2004), (Johansson et al., 2006) and further developed in e.g. (Chakhunashvili et al., 2009) (Johannesson et al., 2009) and (Svensson et al., 2009). A more general presentation of the methodology is found in (Bergman et al., 2009), (Johannesson et al., 2013) and (Svensson & Johannesson, 2013). The VMEA concept takes the quantitative measures of failure causes into account and the method is based on ideas from statistics, reliability and robust design.

The reliability target for the ocean energy sector is a design that can withstand existing environmental conditions during the 20-25 year lifespan of an array. There are mainly two quantities influencing the life, namely the load the construction is exposed to, and the structural strength of the construction. Statistical methods provide useful tools for describing and quantifying the variability in load and strength. Here we will use the concept of Variation Mode and Effect Analysis (VMEA) to guide engineers to find critical areas in terms of the effects of unwanted variation.

Assessing the uncertainty using VMEA allows proper safety factors to be established with regard to a required service life or strength, (Svensson & Johannesson, 2013). The factors that cause the most uncertainty can also be identified giving opportunity to reduce the uncertainty, which can lead to more efficient and optimized WEC and TEC devices. The VMEA method has been successfully implemented for fatigue design and maintenance in vehicle and aeronautic industries, see e.g. (Svensson et al., 2009) and (Johannesson et al., 2009). These experiences will be used to enable efficient knowledge transfer to the ocean energy sector, as demonstrated in the pre-study (Svensson & Sandström, 2014).

Modern engineering relies heavily on simulations with methods like FEM, CFD etc. These can shorten and improve testing. Design for variation with the VMEA method is fully usable together with simulation analysis. When the most current design methods used in the ocean energy industry are combined with the proposed reliability analysis based on VMEA, new and more accurate reliability methods will be available. The ocean energy companies will then have new tools to both increase service life and lower overall costs. This new capability can be a significant step towards commerciality of the ocean energy concept.

1.1 Principles of Reliability and Robustness

Variation and uncertainty have become important parts of our current world view. In an industrial setting, concepts like Six Sigma and Design for Six Sigma have become important, see (Creveling et al., 2003) and (Hasenkamp, 2010). The quality movement initiated by Walter A Shewhart was based on an understanding of variation. W. E. Deming in (Deming, 1986) suggested that “Understanding variation” should be one of the basic building blocks of what he called “Profound Knowledge” – necessary for management in order to lead a dramatic improvement of organizational capability as described in his 14 points for management, (Deming, 1993). An important aspect on variation introduced by (Shewhart, 1931) was the distinction between what he called chance causes and assignable causes of variation. The first kind arose from the activities of many not identifiable sources of variation none of which dominated while the second kind gave rise to clearly distinguishable (assignable) changes in the process under study. As emphasized by Shewhart, only chance causes may be modelled by probability models – thus giving an opportunity to probabilistic predictability – Shewhart called processes with only chance causes of variation “in statistical control” and “predictable within limits”. In manufacturing the goal is creation of processes under statistical control – however, in companies without a systematic improvement program few processes are under statistical control. Despite that, the outcomes of the processes are modelled utilizing probabilistic models assuming that the underlying statistical processes are under some sort of statistical control, i.e. predictable.

As mentioned above, a general design philosophy is failure mode avoidance, (Davis, 2006). Another important principle is parsimony, which is the idea of making things as simple as possible (but not simpler). Together with VMEA, the parsimony principle can be used in order to achieve a balanced model complexity. Further, according to (Clausing, 1994) and (Davis, 2006), causes of failures can be divided into two categories. The first category is called “lack of robustness” and the second category is labelled “mistakes”. Thus, minimizing the possibilities for making mistakes are

also important in the design process.

1.1.1 Uncertainty – Variation and Lack of Knowledge

We want to emphasize the importance of understanding variation in order to create reliable products. In fact, we will widen the perspective and also discuss other uncertainties that may be present when assessing the reliability of a product. The first kind of uncertainty is due to random variation, while the second kind is due to our lack of knowledge, for example when modelling the fatigue life of moorings or when estimating parameters in, say, in a simulation model for the motion of a buoy.

1.1.2 Sources of Variation

Random variations are the main reason why the demand on designs and the capacity of designs vary. Consequently, variations are the cause of failure of many designs. Unfortunately, variations are often expensive or even impossible to control under operating conditions. Thus their possible influence has to be dealt with by other means. There are two kinds of variations – those which create the loading conditions on the device and those affecting its strength to withstand the loading conditions, (Davis, 2006) and (Hasenkamp et al., 2009). Major uncertainty sources on the load side are due to:

- *customer usage*, which is the variation in operation of the product among the customer population,
- *external environment conditions*, which can be wave climate, currents, wind speed, temperature, humidity, marine growth, etc.,
- *internal environment conditions*, which is the interaction between neighbouring sub-systems, e.g. through transmitted heat or vibrations,

and on the strength side we have

- *unit to unit variation* due to production conditions
  - material variation,
  - manufacturing process variation,
- *changes over time* due to field operation, i.e. long-term deterioration due to effects from the usage of the product and its environment, e.g. wear, corrosion or reduced fatigue resistance.

Unit to unit variation could, in the case of a well controlled production process, usually be described as coming from a process which is predictable within limits. However, on the load side this is more complicated. In general, there is a variation in the marine load environment which is not predictable in the same sense as the manufacturing process. Once a product is in use by a specific customer the reliability of this unit is to a large extent determined by the load conditions at the very site of that customer. The overall reliability of a device is then the average of the reliability of the unit of each customer. Then the reliability of the device can very well be high, although the unit at a specific customer fails to meet the demand of that particular customer and does not comply with the expectation. Reliability as a design criterion in this context is hard to work with. Instead we advocate a robust design methodology and its design criteria as a way to handle reliability in the product development process.

1.1.3 Uncertainty due to Lack of Knowledge

When predicting the properties of a product, not only random variation comes in, but also other sources of uncertainty, such as model errors, parameter uncertainties, and human mistakes. There are various ways in which the types of uncertainties may be classified, see especially (Melchers, 1999), but also (Ditlevsen & Madsen, 1996). The first way is to distinguish between aleatory uncertainties and epistemic uncertainties. The first one refers to the underlying, intrinsic uncertainties, e.g. the scatter in life and the load variation within a population of customers. The latter one refers to the uncertainties due to lack of knowledge, which can be reduced by means of additional data or information, better modelling and better parameter estimation methods.

In (Melchers, 1999) a detailed breakdown of different kinds of uncertainties is presented. In the statistical modelling we will focus on the three kinds of uncertainties, also mentioned by (Ditlevsen & Madsen, 1996) , and denote them by

- *Random variation* or physical uncertainty, which is uncertainty identified with the inherent random nature of the phenomenon, e.g. the variation in strength between different components. Sometimes it is also called scatter, randomness or noise. Note that a noise factor is a source of random variation.
- *Statistical uncertainty*, which is uncertainty due to statistical estimation of model parameters based on available data, e.g. the estimation uncertainty of parameters in a regression model describing the life as a function of the load level. Generally the observations of the variable do not represent it perfectly and as a result there may be bias in the data as recorded. In addition, different sample data sets will usually produce different statistical estimates. This causes statistical uncertainty.
- *Model uncertainty*, which is uncertainty associated with the use of one (or more) simplified relationship to represent the 'real' relationship or phenomenon of interest, e.g. a finite element model used for calculating stresses, is only a model for the 'real' stress state. Modelling uncertainty is often due to lack of knowledge, and can be reduced with research or increased availability of data.

The first type of uncertainty, random variation, is clearly an aleatory uncertainty, whereas the others should be regarded as epistemic uncertainties, as they can be reduced through better knowledge.

Another important kind of uncertainty is the uncertainties due to human factors. These are the uncertainties resulting from human involvement in the design, system, use, etc., and may be considered to be due to the effects of human errors, and human intervention. It must be controlled by other means than statistical considerations. Failures caused by misuse, gross errors and human mistakes are primarily subjects to quality management. However, the human uncertainties can also be treated by means of creating inherent robustness through system design changes or by using an extra safety factor.

1.1.4 The Load-strength Concept

In order to make products that are safe, engineering prediction methods are often chosen to be on the safe side. Thus, material strength specifications are given as, say, a 5% or 1% quantile in its distribution, external load are exaggerated to more severe than expected and models and parameters are chosen to give conservative predictions. For instance, traditional fatigue design is based on a comparison between "the most severe customer" and "the weakest product". Such comparisons are, of course, quite vague and strongly dependent on subjective judgements. In consequence, the actual risk of failure is difficult to quantify and it often leads to components being overdesigned with respect to their required performance.

The VMEA and other similar robust design methodologies differs a lot from these engineering customs. Firstly, it is based on a prediction of the ***expected*** performance, meaning that material specifications and external loads are chosen as their expected values and that models and parameters are chosen as the best choices for a result close to reality. Secondly, it transforms all possible sources of uncertainty and variation to a final total uncertainty measure for the expected performance. Based on this uncertainty, a proper statistical safety factor is calculated. For the final reliability of the device, the "controlled" statistical safety factor is completed by an extra safety factor, based on engineering judgement about balancing safety and cost.

As mentioned above there are uncertainties in both load and strength. The load-strength concept postulates that a failure will occur if the load placed on the device exceeds its strength. For robustness and reliability analysis we will use the load-strength concept together with VMEA, see Figure 1.1. The basic VMEA is suggested to be used for assessing which sub-systems and/or components that are most critical in terms of uncertainty, and thus need to be studied in more detail. The most critical components may then be studied using the enhanced and probabilistic VMEA in order to derive adequate safety factors for design.

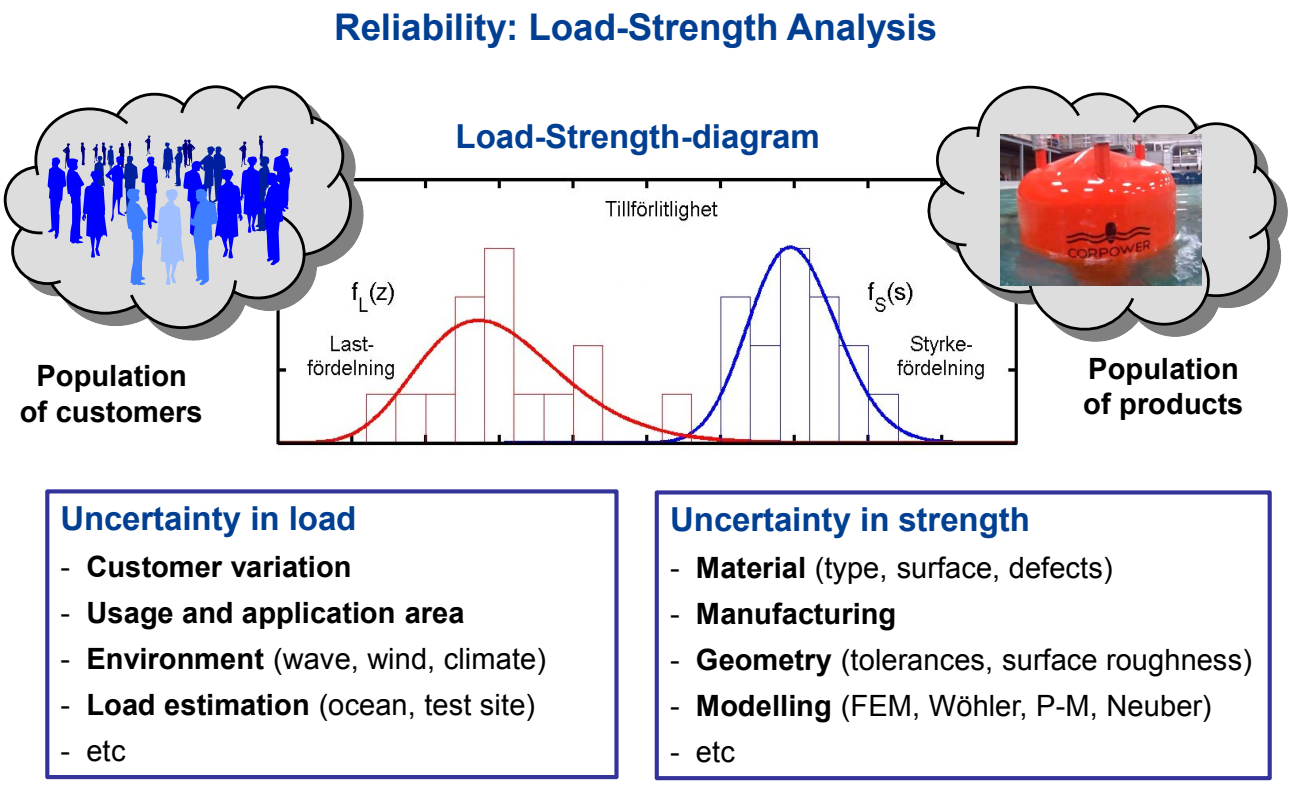


Figure 1.1: Load-strength concept.

The uncertainties in load and strength are assessed by components testing, measuring of load conditions, numerical evaluations, as well as data and knowledge from literature and engineering experience. The different kinds of uncertainties, e.g. scatter, statistical uncertainties and model errors, are combined into a resulting uncertainty for the life prediction. The result of the probabilistic VMEA will give the safety margin of the design, but also indicate where it is most cost effective to reduce the uncertainty and thus improve the reliability of the component.

1.2 Risk Analysis, Failure Modes and Uncertainties

1.2.1 NREL Risk Management Framework

The large-scale implementation of marine energy converters is undermined by a number of technical and economic challenges, which currently limit their deployment to a tiny fraction of the capacity of other renewable energy technologies such as wind and solar power systems. Industrial development of the marine energy sector crucially depends on the possibility to rapidly transform promising concepts and prototypes at the laboratory scale into economically viable products on the global market. Besides the short time from lab to market, a successful industrial implementation of marine energy technology requires also robustness against technological and environmental risks, intended as uncertain events and conditions which might lead to critical consequences in terms of performance, safety and costs of the final product.

A systematic approach to risk mitigation for industrial projects in the marine energy sector has been proposed by the U.S. Department of Energy (DOE) and the National Renewable Energy Laboratory (NREL) with the Marine and Hydrokinetics Risk Management Framework (Snowberg & Weber, 2015). The guidelines described in this document outline a general strategy that can be adapted to specific projects in order to address multiple sources of risk (e.g. technical, regulatory, commercial) that might affect the development process of a single marine and hydrokinetic technology. The technical and economic maturity levels of a designed device or system are expressed in terms of two numerical parameters named Technological Readiness Level (TRL) and Technological Performance Level (TPL) and some expected values for them are set as the ultimate goals of the development process. The NREL Marine and Hydrokinetics Risk Management Framework emphasizes the role of technical reviews and risk evaluations as key operations to enable rational decisions about how to proceed through the different stages of the development process, which can be summarized as:

1) assess and plan the TRL and TPL of the proposed system and/or its components;
2) design the system and/or its components;
3) build and integrate components into systems;
4) test the full-scale system.

As illustrated in Figure 1.2, steps 1) – 4) in the above list are iterated until the target values of TRL and TPL are reached or the whole development process is cancelled on the basis of the outcome of the technical reviews and risk evaluations performed on the design. The risk management plan is the key document that specifies how the risk is analyzed and quantified throughout the development cycle. The MHK Risk Management Framework provides already the basis for such a plan, but alternative documents developed at other organizations can also play that role. In any case, the knowledge acquired during the process (i.e., the “lessons learned”) is used to identify specific problems, document good practices for the benefit of future projects and revise the risk management plan itself, which is therefore conceived as a “living” framework open to continuous improvements and updates.

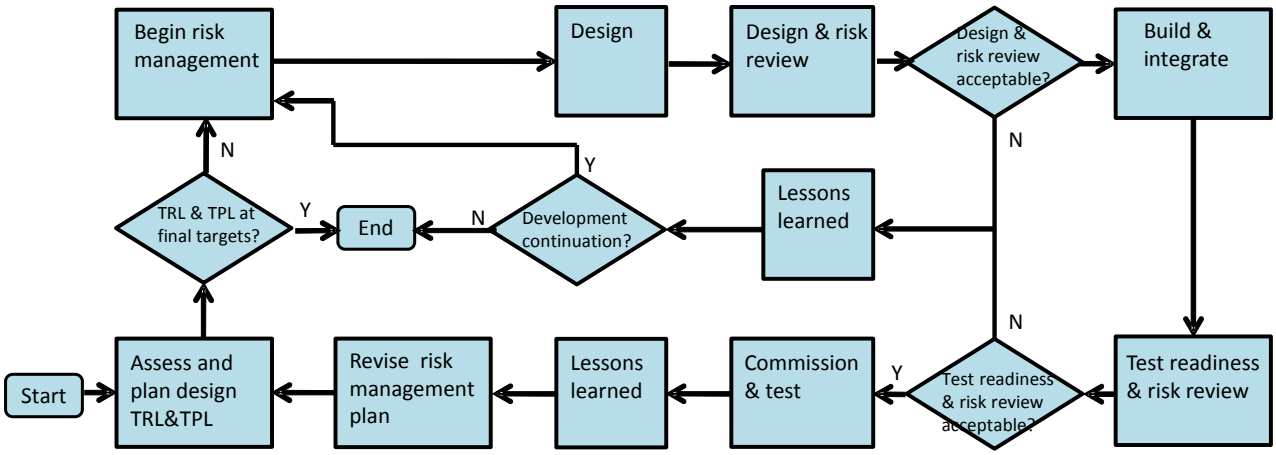


Figure 1.2: Risk management in the MHK technology development flowchart (adapted from (Snowberg & Weber, 2015)).

All the information regarding risk analysis, monitoring and response strategies is collected in a dedicated repository named "Risk Register", which is supposed to collect all the information about the uncertain elements of the MHK development process, namely their categorization and prioritisation as well as the actions designed to minimize their effects on the project (or maximize them in the case of positive risks, i.e. the opportunities). The risk identification process should consider all the uncertain elements (i.e. not only the technical ones), some of which could be dictated by international standards or suggested by past experience from other projects and industries (e.g. oil&gas).The list of all the identified uncertainties should have a hierarchical structure where the general risk categories (e.g. "technical" or "management") are broken down to more specific branches (e.g. "technology" and "system reliability" under "technical" and "funding" and "human resourcing" under "management") in order to facilitate the assessment of the severity of each risk and its consequences.

Due to the limited resources that can be allocated for risk management in any project, it is crucial to devise a systematic procedure to determine which elements of uncertainty should be prioritized in the analysis. The MHK Framework refers to existing standards (such as IEC/ISO 31010) and the relevant technical literature to guide the selection of the most suited risk analysis technique (e.g. fault tree analysis, scenario analysis, root cause analysis. For illustration purposes, the method of probability and impact matrix is presented in some detail, which is basically the same as the criticality assessment performed in FMEA/FMECA (see Section 1.2.2). Each identified risk is characterized by a severity value (SEV) and a frequency (FRQ), which are (to a large extent subjective) measures of the impact on different aspects of the project (e.g. safety, cost, time, quality, etc.) and the estimated probability of occurrence during one year (denoted by p and expressed in percentage form). Both severity and frequency values range from 0 (i.e. no impact, $p < 0.01\%$, respectively) to a maximum ranking, for example 5 or 10 (i.e. lethal/major consequences, $p > 50\%$). A Risk Priority Number (RPN) is then computed for each risk as the product of severity and frequency, i.e. $RPN = SEV \times FRQ$.

Generally, a low RPN should be targeted for all negative risks, a high RPN is unacceptable and intermediate values may be acceptable under certain circumstances, though the definition of the boundaries between the different intervals is left to the analyst. Although the probability and impact matrix method is straightforward to apply and largely independent of the technical content of the MHK development process, the robustness of its outcome is inevitably compromised by the arbitrariness introduced by the subjective nature of the assigned severity and frequency values.

Although that can be mitigated by substantiating the severity and frequency rankings with experimental data whenever they are available, it might be appropriate in some cases to replace, or to complement the probability and impact matrix with alternative procedures of risk assessment.

1.2.2 FMEA/FMECA

The NREL Risk Management Framework (Snowberg & Weber, 2015) includes Failure Mode and Effects Analysis (FMEA) among the critical activities to be performed to monitor and, possibly, minimize the impact of uncertain factors in the development of MHK technologies. In the same document, the release of a FMEA framework specific for MHK applications is also announced for the near future.

FMEA is a systematic technique to perform failure analysis which was initially developed in the late 1950s to study the consequences of malfunctions in military systems and later found widespread application as a tool for the early assessment of the reliability of manufactured products, especially in the aerospace and automotive industries. There are a number of published guidelines and standards for the requirements and recommended reporting format of FMEA/FMECA and relevant examples include SAE J1739, AIAG FMEA-4 (automotive) and MIL-STD-1629A (military). Many industries and companies have developed their own procedures to meet the specific requirements of their products/processes.

The general FMEA approach can be adapted to support the design of products, processes and functions and it can be performed at the functional or conceptual level (primarily at the earliest stages of the development) as well as in a more detailed fashion (typically when more information about the design becomes available). In any case, the system under consideration is analysed in terms of all its components, assemblies and subsystems, which are reviewed in order to identify possible failure modes together with their causes and effects.

“Failure” here is intended in a broad sense as any condition in which the system does not behave as expected according to the specifications, including partial or intermittent fulfillment of the requirements. Examples of failures could be a flat tyre or the fracture of a driving axle. Failure modes should not be confused with failure mechanisms or causes, that is any physical phenomenon which could eventually lead to failure (possibly in combination with other processes or circumstances), such as “corrosion of a structural beam”.

For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet, which may be structured in various forms depending on the application (see Figure 1.3 for an example worksheet used in automotive industry). It is common that experts in different fields contribute with some input to the FMEA analysis, in order to cover the largest possible number of possible failure modes, including their causes and potential effects on the overall system.

After the identification, each failure mode is characterized by three numerical parameters which model how severe its effects are on the whole system, how frequently its cause occurs and how easily it can be detected, denoted as SEV, FRQ (or OCC) and DET, respectively. Depending on the system under analysis and the available information, it could be possible to consider additional parameters to characterize the failure modes more finely, such as the latency period, that is the average time that the failure may be undetected. Similarly to what is done in the probability and impact approach described in Section 1.2.1, a Risk Priority Number is obtained for each failure mode as the product of the characteristic parameters, i.e. .

$$RPN = SEV \times FRQ \times DET \tag{1.1}$$

The calculation of RPN provides a qualitative criterion to evaluate which failure modes should be prioritized. When such evaluation of the “criticality” of the failure modes with respect to their

likelihood of occurrence is added to mapping of their causes and effects, the FMEA method is often renamed as FMECA, which stands for Failure Modes, Effect and Criticality Analysis. The criticality assessment can be based on numerical indicators other than the RPN. A common alternative are for example the "criticality numbers", which are computed using different factors than those shown in Equation (1.1), though their interpretation is basically the same as the one for RPN.

As a result of FMEA/FMECA, recommended actions are made to eliminate or mitigate the risk of failures (for example, by adding redundancy for critical systems). As for the probability and impact matrix procedure described in Section 1.2.1, no universal rule exist to determine the threshold RPN values which separate low and high risk regions. In practice, a starting point often used to decide which failure modes should receive earlier attention is the empirical rule attributed to Pareto: 80 per cent of the issues are caused by 20 per cent of the potential problems. According to that, the efforts to develop actions to eliminate or prevent unwanted effects on the designed system or process should concentrate on those failure modes which scored the highest 20 per cent of the RPN values.

POTENTIAL FAILURE MODE AND EFFECTS ANALYSIS
Front Door L.H.

FMEA Type
Item 1.1.1 - Front Door L.H.
Model Year(s)/Vehicle(s) 20XX/Lion 4dr/Wagon
Core Team A. Tate Body Engrg, J. Smith - OC, R. James - Production, J. Jones - Maintenance
Process Responsibility Body Engineering
Key Date 3/10/2015
FMEA Number 1450
Page 1 of 1
Prepared By J. Ford - X6521 - Assy Ops
FMEA Date (Orig.) 3/10/2015 (Rev) 3/21/2015

Name / Function Requirements	Potential Failure Mode	Potential Effect(s) of Failure	SEVi	Classification	Potential Cause(s) of Failure	OCCi	Current Process Controls (Prevention)	Current Process Controls (Detection)	DETi	RPNi	Recommended Action(s)	Responsibility & Planned Completion Date	Action Results: Actions Taken & Actual Completion Date	SEVr	OCCr	DETr	RPNr
1.1.1 - Front Door L.H.																	
Op. 70 Manual application of wax inside door/ cover inner door, lower surfaces with wax to specification thickness.	Insufficient wax coverage over specified surface	Allows integrity breach of inner door panel. Corroded interior lower door panels. Deteriorated life of door leading to: - Unsatisfactory appearance due to rust through paint over time - Impaired function of interior door hardware	7		Manually inserted spray head not inserted far enough	8		Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	280	Add positive depth stop to sprayer.	Mfg Engrg - 3/10/2003	Stop added, sprayer checked on line.	7	2	5	70
											Automate spraying.	Mfg Engrg - 3/10/2003	Rejected due to complexity of different doors on same line.				
					Spray head clogged- Viscosity too high- Temperature too low- Pressure too low.	5	Test spray pattern at start-up and after idle periods, and preventive maintenance program to clean heads.	Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	175	Use Design of Experiments (DOE) on viscosity vs. temperature vs. pressure.	Mfg Engrg - 3/10/2003	Temp and press limits were determined and limit controls have been installed - control charts show process is in control Cpk = 1.85.		1	5	35
					Spray head deformed due to impact	2	Preventive maintenance program to maintain heads.	Visual check each hour - 1/shift for film thickness (depth meter) and coverage.	5	70					2	5	70

Figure 1.3: Example of FMEA worksheet from automotive industry. The expected decrease of RPN after the introduction of Recommended Actions is shown in the last column.

1.2.3 Failure Causes and Uncertainties

The FMEA method aims at finding all possible causes of failure and to evaluate their effects. Industrial case studies of performed FMEAs have shown that the failure modes are in most cases triggered by unwanted variation, see (Lönnqvist, 2009). On the other hand, the VMEA method aims at finding all sources of variation that can trigger a failure mode. Thus, the FMEA is helpful for the VMEA in order to understand the system or component and especially to identify sources of uncertainties.

1.3 Reliability Assessment

A statistical model of a reliability problem is a combination of a failure criterion (or limit state function) and a number of random variables, each representing an identified source of uncertainty. The proper complexity of the statistical model is related to the intended use of the result, the physical model description, and the available information on each of the random variables.

There are several methods for reliability assessment, and the choice of model complexity can be described in two ways. From a statistical modelling point of view, one may choose a first moment, a second moment or a full probabilistic model. From the physical modelling point of view, it is of interest to study the model response to the variation in the input variables. The choice is between a first-order, that is a linear model, or higher-order models.

Here we will review reliability methods, focusing on describing assumptions, advantages and drawbacks of the methods. For more details on the reliability methods we refer to text books, e.g. (Ditlevsen & Madsen, 1996), (Melchers, 1999) and (O'Connor, 2002). Further, we will discuss what is a proper statistical model complexity in the case of reliability design of MECs.

1.3.1 First-Moment Methods

A first-moment reliability method is only based on a *single number* for each variable. This number may be the expected value or a certain percentile in the variable distribution. Typically, this method is formulated by using a "severe load condition" versus the "weakest component", which can be formalized using *partial safety factors*.

In structural safety applications for buildings, bridges and similar constructions, the partial safety factor method is used by the definition of *design values* for load, resistance (strength) and geometry, denoted q_{id}, r_{jd}, and l_{kd}, respectively. The design values may be written as

$$\begin{aligned} q_{id} &= \gamma_i \cdot q_{ic} \\ r_{jd} &= \varphi_j \cdot r_{jc} \\ l_{kd} &= \varsigma_k \cdot l_{kc} \end{aligned} \tag{1.2}$$

where q_{ic}, r_{jc}, and l_{kc} are characteristic values, γ_i are load factors, φ_j are resistance factors, and ς_k are geometrical factors. The structure is verified by using the design values in the load-strength calculation. Characteristic values and partial safety factors are often regulated in standards like the Eurocode. The characteristic values are typically the mean value for dead load and for geometrical parameters, the 98th percentile for annual maxima of loads, and the 5th percentile for strength parameters.

The advantage of this type of standardized method is that it may be constructed to be unambiguous and therefore suitable for constructions that are highly regulated by authorities. The drawbacks are that several worst-case factors may result in overdesign, since the probability of simultaneous events often is much smaller than reflected in the calculation method. This problem can be handled by empirical corrections, which however may make the method complex and difficult to handle.

1.3.2 The Second-Moment Method

The natural extension of the first-order methods is to also include the variances of the actual variables in the reliability calculation. Such an approach is based on the fundamental statistical property that the variance of the sum of two random variables equals

$$Var[X_1 + X_2] = Var[X_1] + Var[X_2] + 2 \cdot Cov[X_1, X_2]. \tag{1.3}$$

This property can be generalized to several variables, which means that if, for example, the fatigue life can be represented or approximated by a linear function of a number of random variables, the reliability calculation reduces to

$$\mathrm{Var}[\text{fatigue life}] \approx c_1^2 \mathrm{Var}[X_1] + c_2^2 \mathrm{Var}[X_2] + \ldots + \text{Covariances}, \tag{1.4}$$

where the c-values are sensitivity coefficients for the influence on fatigue life of the different variables. The covariances are often negligible and the final variance of the fatigue life can be

obtained by the simple quadratic summation. Second-moment methods include the Cornell reliability index, (Cornell, 1969), the Hasofer-Lind reliability index, (Hasofer & Lind, 1974), and the Variation Mode and Effect Analysis (VMEA) method.

Since the second-moment method takes both the mean value and the variance into account in a rational way, it is a large step towards a relevant probabilistic result compared to the first-order method. Still, it is simple enough to be used even for very complex physical relationships. Caution is needed to taken when the response function is highly non linear, and a linear approximation may result in large errors, e.g., in cases of periodic components, strong interaction effects or higher-order terms. However, in many cases a simple transformation of the response makes the linear approximation more reasonable, e.g., in the case of fatigue life, it is recommended to study the logarithm of the life rather than the life itself.

1.3.3 The Full Probabilistic Model

A further extension of the probabilistic approach means that higher moments of the variables are included or a full representation of the probability distribution of each variable is used. Such an approach would be the ideal for the reliability calculation, as it give a complete description of the life distribution. With today's computer resources, it is also possible to perform the heavy numerical calculations in order to compute, e.g., the failure probability, either by using numerical algorithms for integration of the multidimensional probability distribution or by making Monte Carlo simulations. There are several advanced numerical algorithm available for calculating the failure probability, e.g. importance sampling, directional sampling. Unfortunately, there is a strong limitation on the use of such methods: The exact distributions of the input variables are usually not known. Regardless of the great popularity of these methods, they are not recommended unless the input information is good enough. Without proper knowledge, the input distributions must be constructed by subjective choices, and the output will give a result with false accuracy, hiding uncertainties within a complex mathematical framework. In the case of the present problem, reliability of MECs, the knowledge about the input distributions is typically far too weak to take advantage of the greater complexity in the full probabilistic models.

1.3.4 Reliability Model Complexity

In the reliability design process for survivability and durability of MECs, both variation sources and lack of knowledge must be accounted for. Loads acting on a MEC vary according to different sea-states, both over time and between sites. The variation can to some extent be determined experimentally, but the available data needs to be completed by judgements based on experience, design codes and standards, together with other more or less uncertain sources. The description of load variation and uncertainty must be completed by a corresponding description of the strength, which needs experimental test results as well as mathematical and physical models for its relation to outer environmental loads. This means that also on the strength side, both variation and uncertainties must be considered.

Methods for the assessment of the reliability of a MEC include many different levels of complexity, both regarding the mathematical modelling and the statistical modelling. The statistical methods can be classified with respect to the basic statistical properties used, as first- or second-moment methods or full probabilistic approaches. The first-moment methods are extensions of the classical safety factor approach and lack immediate possibilities to take advantage of new knowledge, such as more experiments, more field measurements or better mathematical models. Second-moment methods include simple measures of the uncertainty, and make it possible to combine them in a rational way, keeping track of the different contributions of the sources. The full probabilistic approach includes detailed information about the probability distribution of the uncertainty sources, which are usually

not available. Consequently, we here recommend a second-moment approach, and in particular we will concentrate on the VMEA method.

1.4 VMEA in Different Design Phases

The VMEA is split into three different levels (see Figure 1.4), namely 1) basic VMEA, in the early design stage, when we only have vague knowledge about the variation, and the goal is to compare different design concepts, 2) enhanced VMEA, further in the design process when we can better judge the sources of variation, and 3) probabilistic VMEA, in the later design stages where we have more detailed information, and the goal is to assess the reliability and calculate safety factors. Appendix A provides "*A Short VMEA Reference Guide*".

1.4.1 Work Process – 7 Steps

The general procedure for making a VMEA is the same for all three VMEA levels, however the information available and the implementation of the different steps will differ somewhat. The work process can be described in the following steps:

1. **Target Variable Definition.**

   The first step is to define the target variable, i.e. the property to be studied, which can be the life of a component, the maximum stress or the largest defect.

2. **Uncertainty Sources Identification.**

   In this step all sources of uncertainty that can have an impact on the target variable are identified. The sources may be classified as scatter, statistical, and model uncertainties.

3. **Sensitivity Assessment.**

   Here the task is to evaluate the sensitivity coefficients of the sources of uncertainty with respect to the target variable, e.g. by numerical calculations, experiments, or previous experience.

4. **Uncertainty Size Assessment.**

   Here the task is to quantify the size of the different sources of uncertainty, e.g. by experiments, previous experience, or engineering judgement.

5. **Total Uncertainty Calculation.**

   The final step of the core VMEA activity is to calculate the total resulting uncertainty in the output of the target function by combining the contributions from all uncertainty sources according to their sensitivities and sizes.

6. **Reliability and Robustness Evaluation.**

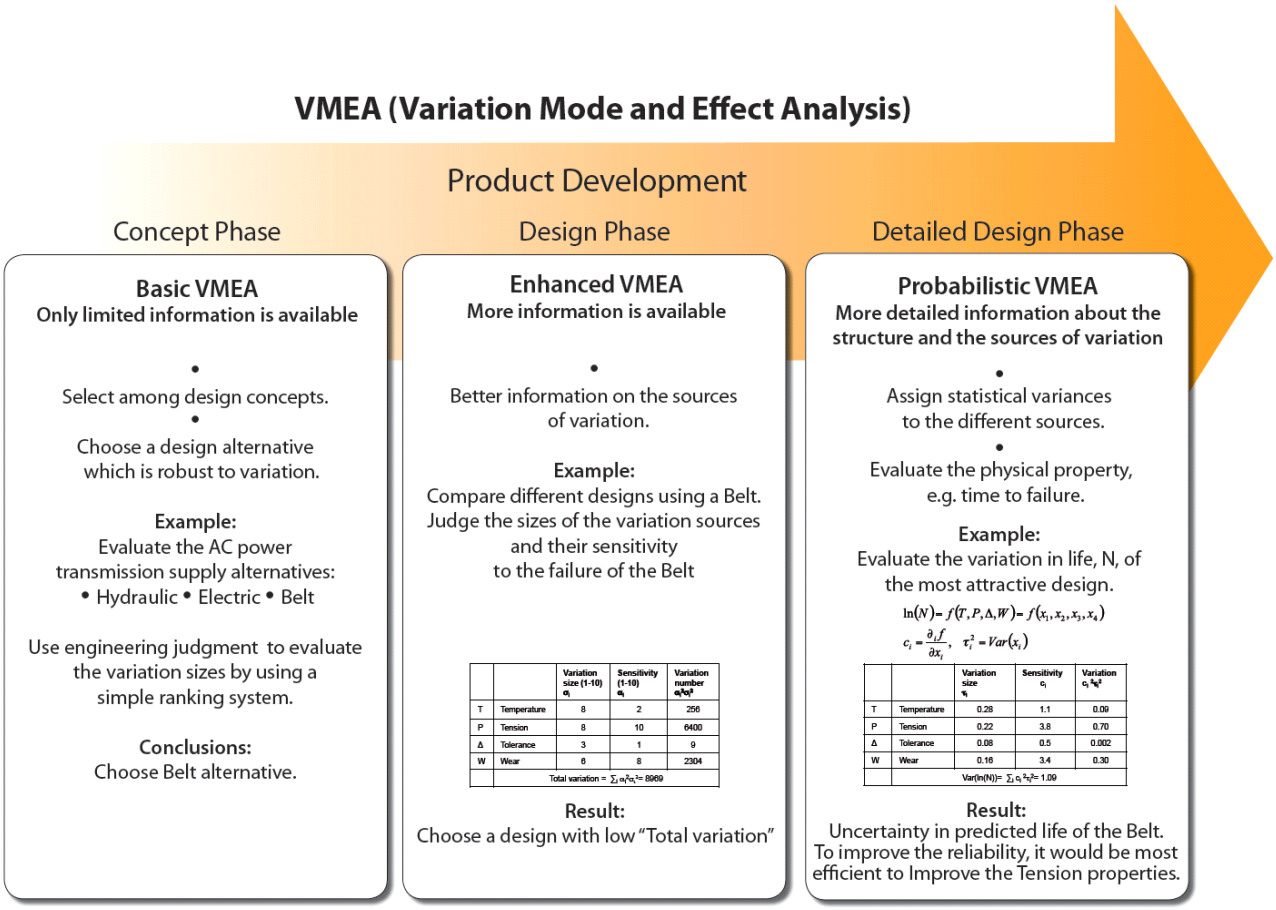
   The result of the VMEA can be used to evaluate the reliability and robustness, e.g. to compare design concepts, to find the dominating uncertainties or to derive safety factors.

7. **Improvement Actions.**

   An important last step is to feedback the results to the improvement process, e.g. by identifying uncertainty sources that are candidates for improvement actions and evaluate their potential for reliability improvements.

In the original VMEA method the focus was on steps 2 to 5, which can be seen as the core of the VMEA method, while the pre-processing (step 1) and the post-processing (steps 6 and 7) were discussed but not formally included in the procedure. Here we extend the VMEA method to include

also the definition, evaluation and improvement steps to become more of a VMEA methodology for reliability and robustness.



		Variation size (1-10) σ_i	Sensitivity (1-10) c_i	Variation number $c_i^2\sigma_i^2$
T	Temperature	8	2	256
P	Tension	8	10	6400
Δ	Tolerance	3	1	9
W	Wear	6	8	2304
	Total variation = $\sum_i c_i^2\sigma_i^2$= 8969			

		Variation size τ_i	Sensitivity c_i	Variation $c_i^2\tau_i^2$
T	Temperature	0.28	1.1	0.09
P	Tension	0.22	3.8	0.70
Δ	Tolerance	0.08	0.5	0.002
W	Wear	0.16	3.4	0.30
	Var(ln(N))= $\sum_i c_i^2\tau_i^2$= 1.09			

Figure 1.4: VMEA in different design stages.

1.4.2 Mathematical Principles of VMEA

The method is based on characterizing each source by a statistical standard deviation and calculating its sensitivity with respect to the target variable, e.g. fatigue life or maximum stress. The VMEA method combines these into the total prediction uncertainty, denoted τ, which is obtained by the root sum of squares (RSS) of the uncertainties

$$\tau = \sqrt{\tau_1^2 + \tau_2^2 + \tau_3^2 + \cdots} = \sqrt{c_1^2\sigma_1^2 + c_2^2\sigma_2^2 + c_3^2\sigma_3^2 + \cdots} \tag{1.5}$$

where τ_i is the resulting uncertainty from source i and is calculated as the product of the sensitivity coefficient c_i and the uncertainty σ_i of source i. Note that VMEA is a so-called second-moment method since it uses only the standard deviation to characterize the distribution of the uncertainty sources.

1.4.3 Basic VMEA

In a basic VMEA, (Chakhunashvili et al., 2004) and (Johansson et al., 2006) , the goal is to identify the most important sources of variation, for example when different design solutions are evaluated. The sizes of the sources of variation as well as their sensitivities to the studied product property are evaluated on a scale from 1 to 10. The robustness of the product is characterized by summing the square of the product of sensitivity and variation size. To conduct an adequate VMEA that incorporates different views and competences, a cross-functional team of experts should be formed. Such an analysis will indicate which sub-systems or components that are most critical, and thus need to be studied in more detail.

1.4.4 Enhanced VMEA

The enhanced VMEA, (Chakhunashvili et al., 2009), is a refinement of the basic VMEA further into the design process with the aim to understand and quantify the uncertainty sources in more detail. The main difference is that the sensitivities and variation sizes are assessed in real physical units instead of the 1 to 10 scale. The assessment uncertainties can be based on engineering judgement, but also be supported by initial testing, literature and data sheets from manufacturers.

1.4.5 Probabilistic VMEA

The probabilistic VMEA, (Chakhunashvili et al., 2009), (Johannesson et al., 2009) and (Svensson et al., 2009), is well suited in the later design phases, for example, when there is a need to predict the life of the product and to determine proper safety factors or tolerances. The general procedure of the probabilistic VMEA is the same as for the basic VMEA. The main difference compared to the basic VMEA is that here we make use of a model for the prediction and thus we need to include both statistical uncertainties and model uncertainties, together with the random variation. Scatter cannot be avoided, but needs to be handled by using safety factors, while the last two types of uncertainties can be decreased by gaining more data or by building better models. In a probabilistic VMEA the goal is to quantify the (most) important sources of uncertainty in physical units, and, as in the enhanced VMEA, we assess the magnitude of the uncertainties by standard deviations, instead of using a ranking scale.

The probabilistic VMEA represents the concept of First-Order Second-Moment (FOSM) reliability theory, see (Ditlevsen & Madsen, 1996) and (Melchers, 1999). The First-Order refers to the linearization of the target function, and the Second-Moment refers to the fact that only the means and variances (and covariances if needed) are used. The result is a prediction uncertainty in terms of the standard deviation of the response. The total uncertainty can be used to calculate a reliability index as a measure of the distance to the failure mode. Further, it can also be used for deriving safety factors for design, and it can also be used for aiding the planning of maintenance.

2 Reliability Design for Marine Energy Converters

The overall goal of reliability design is to make a robust and reliable product that meets the demands of the customers. In order to achieve this goal it is important not only to predict the life of a component, but also to investigate and take into account the sources of variability and their influence on life prediction. There are mainly two quantities influencing the life, namely the load the device is exposed to, and the structural strength of the device. Statistical methods provide useful tools for describing and quantifying the variability in load and strength. The variability in the structural strength depends both on the material scatter and geometrical variations. The load distribution may be influenced by the type of device, the control algorithm and the geographical location. Figure 2.1 illustrates the overall design process according to the EMEC Guideline for Design Basis of MEC systems, (EMEC, 2009a). The reliability methodology presented in this guidance fit well into this overall picture to support reliability design.

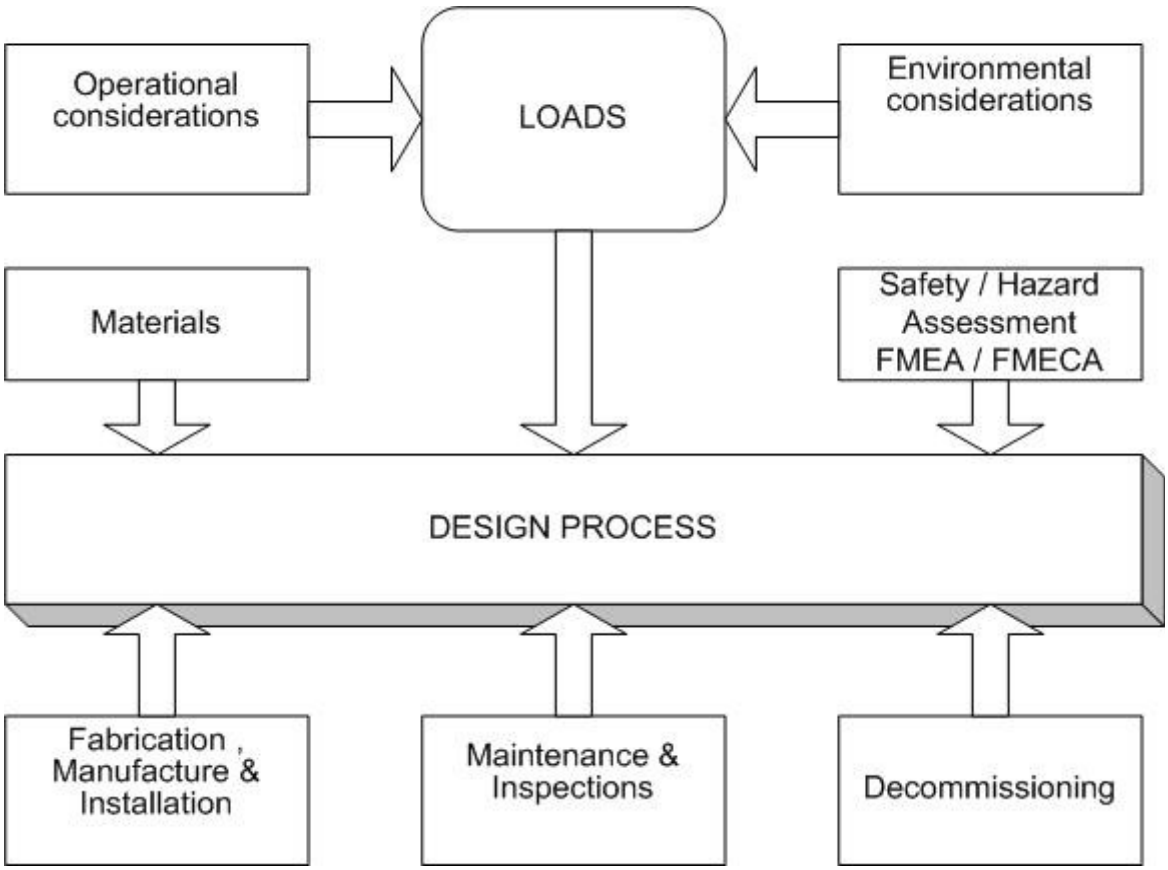


Figure 2.1: Block diagram of design process for MECs.

In this chapter, technologies for marine energy converters are first discussed, followed by a review of the load environment for MECs, focusing on describing wave characteristics. Design criteria for MECs are then discussed in general and especially in relation to structural, electrical and mooring/foundation functions. Lastly, the reliability design work process for MECs is discussed and compared to the automotive and aerospace industry.

2.1 Marine Energy Converters

Technologies for marine energy converters are reviewed in Section 2.6, introducing and describing different techniques for harvesting energy from waves and currents. Here we give a general overview of wave and tidal energy converters.

2.1.1 Wave Energy Converters

Waves have the potential to provide a completely sustainable source of energy, which can be captured and converted into electricity by wave energy converter (WEC) machines. There is a wide range of wave energy technologies, each using different solutions to absorb energy from waves depending on the water depth and location, extracting energy from the shoreline out to the deeper waters offshore, see e.g. (Cruz, 2008), (Falcao, 2010) and (Kempener & Neumann, 2014c). There is little convergence amongst the wave energy technologies, however, the industry shows many different alternatives to harnessing wave power under different conditions. The progression of WEC's becoming commercial requires further research into some of the basic components, aiming to reduce costs and increase the performance, see (Kempener & Neumann, 2014c).

2.1.2 Tidal Energy Converters

Tidal energy exploits the natural ebb and flow of coastal tidal waters caused principally by the interaction of the gravitational fields of the earth, moon and sun. The fast sea currents are often magnified by topographical features, such as headlands, inlets and straits, or by the shape of the seabed when water is forced through narrow channels. There are several technologies for harvesting tidal energy, see e.g. (Kempener & Neumann, 2014b). The tidal stream devices, which utilise these currents, are broadly similar to submerged wind turbines and are used to exploit the kinetic energy in tidal currents. Due to the higher density of water, this means that the blades can be smaller and turn more slowly, but they still deliver a significant amount of power. To increase the flow and power output from the turbine, concentrators (or shrouds) may be used around the blades to streamline and concentrate the flow towards the rotors.

2.2 Load Environment for Marine Energy Converters

There are technical and operational factors including metocean and environmental conditions that affect reliability of MECs through the loads under which the converters are exposed to. Therefore it is important to have a good understanding of the environmental loading conditions that the converter is exposed to.

The DNVGL Offshore Standards (OS) and Recommended Practice (RP) contain valuable information on load assessment and environmental conditions that is also applicable to marine energy converters. Some documents that will be referred to are "DNVGL-OS-C201:Structural design of offshore ships", (DNVGL, 2015a), "DNVGL-OS-E301: Position Mooring", (DNVGL, 2015b), and especially "DNV-RP-C205: Environmental Conditions and Environmental Loads", (DNV, 2010).

Environmental load effects that, according to DNVGL, shall be taken into account, for example for the location of the moorings, (DNVGL, 2015a), include:

- waves
- wind
- current

- marine growth
- tide and storm surge
- earthquake
- temperature
- snow and ice

According to (DNV, 2010), environmental conditions cover natural phenomena, which may contribute to structural damage or operation disturbances, and the most important phenomena for marine structures are:

- wind
- waves
- current
- tides

which are covered by the RP. Phenomena, which may be important in specific cases, but not covered by the RP include:

- ice
- earthquake
- soil conditions
- temperature
- fouling
- visibility

Here we will give a short selected review, focusing on wave loads, especially long term statistics for operational loads and extreme conditions, following Section 3 of (DNV, 2010). However, first the short term wave conditions will be described, according to Section 3.5 of (DNV, 2010).

2.2.1 Short-term Wave Conditions

It is common to assume that the sea surface is stationary for a duration of 20 minutes to 3 to 6 hours. Short term stationary irregular sea-states may be described by a wave spectrum; that is, the power spectral density function of the vertical sea surface displacement. Further, a stationary sea-state can be characterised by a set of environmental parameters such as the significant wave height H_s together with the peak period T_p or the zero-up-crossing period T_z. The significant wave height H_s was originally defined as the average height (trough to crest) of the highest one-third waves in the indicated time period, also denoted $H_{1/3}$. Nowadays, the significant wave height H_s is often defined as four times the standard deviation of the sea surface elevation, which can easily be computed from the wave spectrum. The peak period T_p is the wave period determined by the inverse of the frequency at which a wave energy spectrum has its maximum value. The zero-up-crossing period T_z is the average time interval between two successive up-crossings of the mean sea level.

There are several parametric models for describing the wave spectrum of short term wave conditions. The Pierson-Moskowitz (PM) spectrum and JONSWAP spectrum are frequently applied for wind seas; (Hasselmann et al., 1973), (Pierson & Moskowitz, 1964). The PM-spectrum was

originally proposed for fully developed sea. The JONSWAP spectrum extends PM to include fetch limited seas, describing developing sea-states. Both spectra describe wind sea conditions that often occur for the most severe sea-states. Moderate and low sea-states in open sea areas are often composed of both wind sea and swell. A two peak spectrum may be used to account for both wind sea and swell. The Ochi-Hubble spectrum and the Torsethaugen spectrum are two-peak spectra, see (Ochi & Hubble, 1976) and (Torsethaugen, 1996), respectively.

2.2.2 Long-term Wave Conditions

The long-term variation of wave climate can be described in terms of generic distributions or in terms of scatter diagrams for governing sea-state parameters such as (H_s, T_p) or (H_s, T_z) that are obtained from available data; (see Section 3.6 of (DNV, 2010)).

Two different analysis strategies are commonly applied, viz. global models and event models.

- The global model (or initial distribution method) utilises all available data from long series of subsequent observations (e.g. all 3-hour data).
- In the event model observations over some threshold level are used (Peak Over Threshold (POT) method or storm analysis method). Alternatively, annual extremes or seasonal extremes are analysed.

The first one is used for determining the long-term average properties, while the second one is used for assessing the extreme wave conditions, treated in the next section.

For describing the long-term average, a scatter diagram provides the frequency of occurrence of a given parameter pair, e.g. (H_s, T_p) or (H_s, T_z). Both marginal distributions and joint environmental models can be applied for wave climate description. Scatter diagrams for the North Atlantic and for World Wide trade of significant wave height and zero-crossing period, for use in marine structure calculations, are given in Appendix C of (DNV, 2010).

Based on data from the actual area, the empirically established scatter diagrams can be used, or parametric distribution models can be fitted. The most important parameter is the significant wave height, and typically a 3-parameter Weibull distribution is assumed for the marginal distribution of significant wave height H_s, (Nordenstrøm, 1973). Joint environmental models are required for a consistent treatment of the loading in a reliability assessment. Different approaches for establishing a distribution of significant wave height and period. One approach is the Conditional Modelling Approach (CMA), see e.g. (Bitner-Gregersen & Haver, 1991). In that case a recommendation is to model the significant wave height as a 3-parameter Weibull probability density function and the zero-crossing wave period T_z conditional on H_s is modelled as a lognormal distribution.

2.2.3 Extreme Wave Conditions

The extreme wave conditions, often characterized by the 100-year wave, need to be treated separately (see Section 3.7 of (DNV, 2005)). The n-year wave is characterized by the significant wave height with return period of n years, that can be defined as the $(1-1/n)$ quantile in the distribution of the annual maximum significant wave height, i.e. it is the significant wave height whose probability of exceedance in one year is $1/n$. An n-year design sea-state is then a sea-state of duration 3-6 hours, with significant wave height combined with adequately chosen characteristic values for the other sea-state parameters. For example the accompanying T_p or T_z values are typically varied within a period band about the mean or median period.

The environmental contour concept represents a rational procedure for defining an extreme sea-state condition. The idea is to define contours in the environmental parameter space, usually (H_s, T_p),

along which extreme responses with given return period should lie, and one such method is the IFORM approach; (Winterstein et al., 1993).

The design sea-state can be assessed assuming that the n -year extreme response can be estimated from the n -year maximum significant wave height condition. Generally, this requires some procedure that accounts for the short term variability of response within the sea-state.

There are several alternatives for estimating the n -year wave. For Peak Over Threshold (POT) analysis, an exponential distribution is recommended for the threshold excess values. Larger flexibility and model complexity may be obtained by using the generalized Pareto distribution, but should be used with caution. For the exponential distribution the scale parameter can easily be determined from the mean value of the excess variable, i.e. the mean value of the excess over the threshold. The storm statistics is suitable if a sufficient number of storm events exists. Also, the storm statistics results will depend on the lower threshold for storms, and the sensitivity to the threshold should be investigated. The annual extremes of an environmental variable, for example the significant wave height or maximum individual wave height, can be assumed to follow a Gumbel distribution. It should be noted that the Gumbel model for annual extremes is theoretically equivalent to the POT model with exponentially distributed excesses. The extreme value estimates should be compared with results from alternative methods.

Peak Over Threshold (POT) statistics should be used with care as the results may be sensitive to the adopted threshold level. If possible, POT statistics should be compared with results obtained from alternative methods.

Generally, the uncertainty in the estimated extreme load, say the n -year maximum significant wave height, is quite large due to extrapolation. It is therefore important to assess its uncertainty, which should be quantified and included in the VMEA analysis. It is generally recommended to base the annual statistics on at least 20 years of data. It is further recommended to define the year as the period from summer to summer (not calendar year).

2.3 Design Criteria for Marine Energy Converters

The harsh conditions in the marine environment where WECs and TECs are deployed lead to many irregular large load cycles being applied to their primary structures. The reliability target for developers is a design that can withstand environmental conditions during the lifespan of the device. These marine environment load conditions, combined with novel technologies for MECs, lead to a high degree of uncertainty that need to be addressed in the design process and the associated reliability calculations.

There are three main criteria for which marine energy converters should be designed for, durability, maintainability and survivability. These three go hand in hand and are crucial to the economic and environmental case for a marine energy converter. In this guidance we focus on reliability design criteria for MECs connected to:

- *Survivability*, where the typical the design criterion is with respect to the 100-year wave; and
- *Durability*, where the typical the design criterion is a life of 20-25 years.

Some systems, e.g. mooring systems, may also require special considerations concerning *Safety*, which can be addressed by a combination of appropriate safety factors and redundancy. Another possibility is to use inspections together with damage tolerance criteria.

There are several types of systems and components constituting a MEC, and they can be categorized as belonging to:

- *Mechanical functions*,

- *Electrical functions*, or
- *Mooring and foundation functions*.

Design criteria for the three above mentioned functions will be discussed, however, first a short review of the more general "GL Rules for Certification and Construction: IV Industrial Services" will be given.

2.3.1 GL Rules for Certification and Construction: Industrial Services

The criteria below is taken from the "GL Rules for Certification and Construction: IV Industrial Services" in terms of offshore substations and structural design, see "Chapter 2: Structural Design" in (GL, 2013).

Design loads for MEC's include:

- *Environmental*; from waves, wind, sea current, tsunamis, marine growth including hydrostatic pressure and buoyancy.
- *Permanent*; dead load, equipment, ballast and effects of hydrostatic pressure on buoyancy of the device.
- *Functional*; variable loads from weight of tools, varying ballast in stores, loads from crane operations, and mooring/fendering loads.
- *Accidental loading conditions*; loads not normally occurring during installation and operations such as collisions, falling or dropped objects, failing crane operations, and onboard fires.

MEC design under the above loading conditions is considered through structural strength calculations and design methods:

- ASD/WSD – Allowable stress design or Working stress design incorporating safety factors.
- LRFD and Load and resistance factor design with limit state and partial safety factor design criteria.

Criteria for designing under the above load conditions is determined by the limit states or states of loading or deformation at which a structure or component looses its operability function. They are classified as follows:

- *Ultimate limit state* (ULS) or maximum load structure or component can reach before failure.
- *Serviceability limit state* (SLS) impairment of operation other than structural failure; vibrations, deformation, or leakage.
- *Accidental limit state* (ALS) structural collapse after accidental damage.
- *Fatigue limit state* (FLS) structural failure due to cyclic loading.
- *Corrosion allowance*.

Another important consideration in MEC design assessment is through dynamic analysis. Dynamic analysis investigates the dynamic behaviour of the MEC in case of risk of resonance of global or local structural vibration modes imposed by environmental loads such as weaves, wind, current and variable functional loads from drilling, or other rotating equipment and from propulsion systems.

2.3.2 Structural Functions

Possible failure mechanisms that need to be considered are

- *for Survivability: Immediate failure* caused by exceedance of material ultimate strength, and
- *for Durability: Fatigue failure* caused by repeated mechanical loads below the ultimate material strength.

Both mechanisms must be subjected to reliability investigations, and they depend on 1) material strength in hot spots in the structure and 2) external loads caused by the intended conversion of wave or tidal water movements to energy.

The strength may also change during usage by

- *corrosion*, changing load carrying material content and geometry,
- *wear*, also changing load carrying material content and geometry,
- *marine growth* causing changed mechanical behaviour.

For the immediate failure case the ultimate strength of critical members must be investigated against the largest expected force. This largest force should be quite well known for tidal based energy devices, but for wave based devices it is difficult. Approximate assessments of extreme events must be considered.

For the fatigue failure case there are mainly two actual methodologies: 1) Design against the fatigue limit, where critical members are designed against external loads so as to guarantee that the outer forces do not cause stresses or strains that exceed the actual fatigue limit. 2) Design against fatigue life, i.e. against a predefined life for the device, possibly combined with inspection intervals.

In both cases the reliability issue may be formulated by means of a load/strength formulation:

$$Strength > Load\,, \tag{2.1}$$

where both the load and the strength are not known exactly at the design stage and the uncertainty regarding their values must be taken into account in the design by introducing a safety factor when determining the required strength.

$$Strength \geqslant Load \cdot SF\,. \tag{2.2}$$

For the case of designing for *immediate failure* or *fatigue limit* the strength is usually the ultimate tensile stress or the fatigue limit stress, measured in the unit MPa. The load is the expected stress in a hot spot in the structure caused by constraints of wave and tidal movements. Typical structural members that need to be designed for immediate failures include mooring members, such as, chains, wires or lines, and connecting members, such as, shackles. Members that typically need to be designed against fatigue limit are bearings, gears and other parts with smooth surface finish.

For the case of fatigue life design the *strength* must be related to a specified life for the device in question. This life, often measured in years of usage, must be translated to load cycles and then, by using a fatigue strength diagram, such as a Wöhler curve, transformed to a fatigue strength, measured in the unit MPa. The *load* is varying during the life and must therefore be transformed to an equivalent load, usually by using the Palmgren-Miner rule for fatigue damage summation. Structural members that typically are subjected to fatigue life design includes, as for immediate failures, chains, wires lines, and shackles, but also welded parts and structural members with sharp notches or with possible detrimental internal defects.

2.3.3 Electrical Functions

The survivability of electrical system in marine energy converters depends on the definition and application of representative extreme loadings and overall system operating conditions. Specific standards are still under development, partly because of the industry less maturity stage. Optimum system configuration is still to be rectified and defined. For example, to date, many of the MEC developers still op to locate their electrical systems onshore rather than offshore. Generally, MEC operators will shut down their MEC in case of extreme loading and operating condition, in this case electrical system whose main function is to deal with energy flow will be released from the potential heavy loading conditions, while others, i.e. mechanical and structure components/systems, will still physically experience the extreme environmental loading. Electrical system on the other end will have to face the abnormal operating condition introduced by the electrical grid during grid faults. The main components that have direct loading impact will be the cable and the switchgear (transformer will be less affected). Design of these components are governed by the highly regulated grid code in each country. Their design would have to consider the potential energy passing by during any grid faults before switchgear's protection function being activated. Therefore, based on current operating strategy, lifetime specification is a more realistic design requirement for the electrical system in marine energy converters. But no specific standard is available for lifetime design requirement due to immature characteristics of marine energy converter. Practically, it is usually predicted based on load conditions and judgement of development engineer, e.g. 10 or 15 years, with 2-3 major services in place during this period where key sub-components will be replaced.

There are a wide range of components in the electrical system. In particular the IGBT (Insulated-Gate Bipolar Transistor) module should be subjected to reliability analysis. The reason will be explained later in Chapter 7, where a case study on IGBT module is presented. As one of the fundamental components, IGBT module constructs the power conversion circuit which regulates variable voltage and frequency in compatible with grid requirement.

Possible failure mechanism for survivability of IGBT module in general are due to exceedance of the ultimate operating limit. Design methodology generally adopted is to optimise circuit operation and gate driving design to ensure voltage, current, power, temperature, etc. within the boundary of SOA (Safety Operating Area) specified by manufacturer in specific datasheet.

Possible failure mechanism for durability of a IGBT module could be fatigue caused by repeated loads below the ultimate strength of the component. A general methodology is to evaluate the accumulated damage suffered from load profile against a predefined life expectancy. A very similar load/strength formulation as mentioned in structure functions is also applicable here with safety factor. But the difficulty is that neither load nor strength is as direct and straightforward as those in mechanical and structure applications. Aerodynamic theory, control theory, power electronics, etc. are required to transfer wind/tidal profile into power loss inside IGBT module. Some basics of thermal physics and semiconductor are involved in transformation of power loss into actual load, junction temperature variation, and load-strength evaluation. These will be briefly introduced in Chapter 7, which is necessary to understand the load-strength mechanism in IGBT module.

2.3.4 Mooring and Foundation Functions

There are various standards for design and inspection of moorings and foundations and those most specifically for MEC's are summarized below:

- API RP 2I: In-service Inspection of Mooring Hardware for Floating Structures
- API RP SM Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring

- API RP SK Design and Analysis of Station keeping Systems for Floating Structures
- DNV OS 303 - Offshore Fibre Ropes
- DNV OS E301 - Position Mooring Rules and Standards
- DNV-RP-E304 -Damage Assessment of Fibre Ropes for Offshore Mooring
- Cordage Institute (2001) International Guideline CI 2001-04 Fiber Rope Inspection and Retirement Criteria Guidelines to Enhance Durability and the Safer Use of Rope. CI 2001-04 First Edition
- HSE RR695 – Structural integrity monitoring. Review and appraisal of current technologies for offshore applications
- ISO 19901-7: Station-keeping systems for floating offshore structures and mobile offshore units, clause 12 and annex A.12
- BS6349-1-1 and BS6349-1-2: Maritime Works

These standards or guidelines are a challenge to incorporate in the MEC design process. The design requirements based on site conditions exposed by Oil & Gas structures, for example are based on large safety factors for a design life larger than 25 years and made to survive waves from a permanent fixed position. Those site conditions are not relevant to the near shore or shallow water affects that MEC's are exposed to in the wave and tidal sector.

2.3.4.1 Mooring function in terms of survivability/life/safety

There are issues to consider in terms of reliability

- The ability to *survive discrete events* such as
  - Major storms, peak waves etc.
  - Large forces; and the effect on the mooring system and mooring load bearing structure
  - Collision with vessels or marine mammals
- The ability to *survive long term conditions* such as
  - The cumulative battering of the waves
  - The long term corrosion effects
  - Fatigue and other wear out processes
- The ability to *survive internal system limitations* such as
  - End-stops
  - Motion limitations (translation, rotations)
  - Load limitations (shock loading)

The ability to survive is based on understanding the mooring and foundation failures their causes (failure modes) and relevance in the system, subsystem and component design life cycle. There are three life failures;

- *Early Life failures* – where the equipment failed unexpectedly early, i.e. failures that are likely to have been caused by poor quality of manufacture or installation.
- *Through Life failures* – where equipment failed before its expected design life, i.e. failures

that are likely to have been caused by poor design, inappropriate operation and poor preventive maintenance.

- *Wear Out failure* – where equipment was worn out, i.e. failures that are likely to have been caused by equipment being operated at longer than specified life.

In terms of design safety, and due to lack of field experience, estimates of design loads and system response are largely based on numerical models and scaled model testing in controlled conditions and as such designs must be conservative (higher safety factor which drives costs and impacts LCOE).

Condition modelling programmes on early-stage prototypes will help to verify design load and motion predictions and will give greater confidence in the design of commercial scale systems and potentially allow definition of reduced safety factors to allow optimisation of LCOE and project viability in turn.

For instance, some classification societies apply a somewhat arbitrary increase to mooring line factors of safety for synthetic rope based systems. There is no clear justification for this and it is thought to be largely a historic 'carry-over' from the early days of synthetic rope applications in the oil and gas sector when confidence in their durability was low.

2.4 Reliability Work Process

A typical design process for MECs are presented in Figure 2.2, where it is exemplified for fatigue life evaluation. The steps are:

1. *Load assessment* – Evaluate the input load to the system, typically it is environmental loads such as waves, currents and wind, but it can also be internal loads from the drive train or electrical system.
2. *Loads to forces* – Evaluate forces on systems or components from the input loads, typically this involves a model for simulating the motion of the device, preferably in combination with measurements of input loads and forces to validate the simulation model.
3. *Forces to stress* – Evaluate local loads and identify hot spots of the construction, for mechanical stresses typically using FEM, preferably in combination with measurements of forces and stresses to validate the numerical model.
4. *Life assessment* – Evaluate the life of component/system under investigation, e.g. using Wöhler curve and damage accumulation in the case of fatigue life evaluation, preferably in combination with fatigue tests to validate the model.

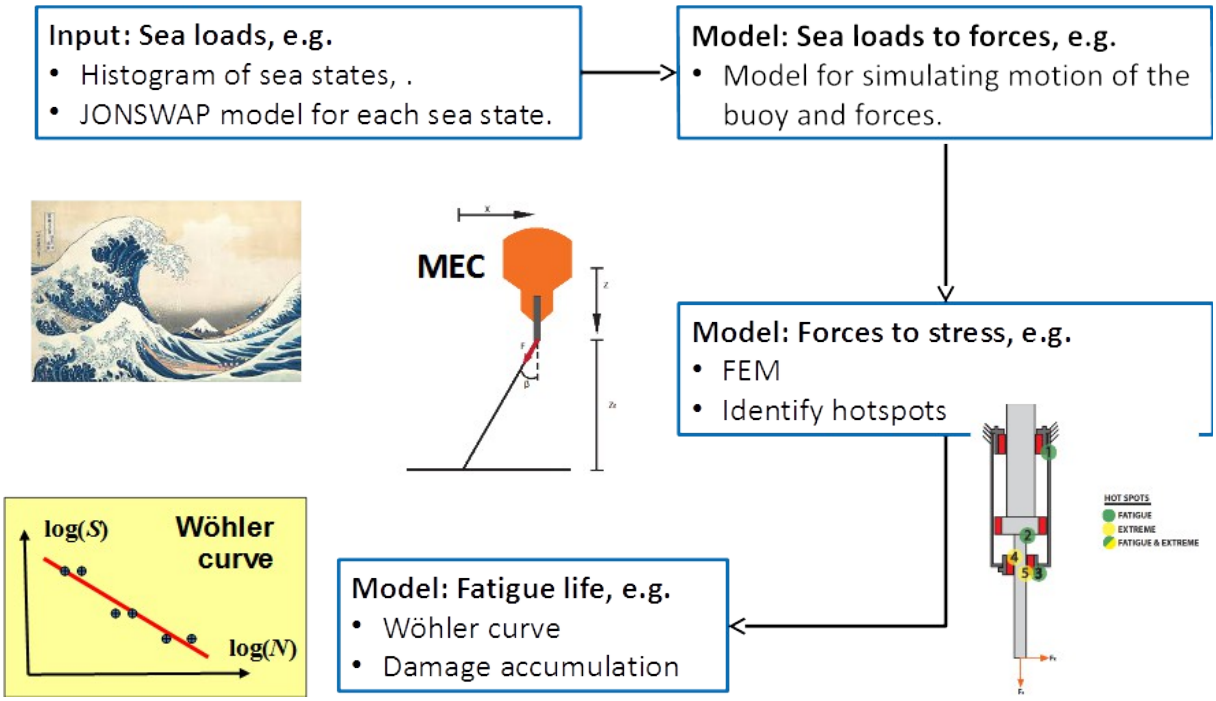


Figure 2.2: Design process for MECs.

With the scheme in Figure 2.2 as a starting point, the VMEA methodology for reliability of MECs will be described. However, note that the engineering principles of system design is universal and therefore reliability design approaches used in automotive industry and in aerospace applications are reviewed in Section 2.5. We now proceed with the VMEA for MEC application.

2.4.1 The Probabilistic VMEA Procedure

The probabilistic VMEA methodology is a probabilistic approach to calculate a proper safety factor. It regards "Load" and "Strength" as random properties. In order to take advantage of powerful mathematical/statistical tools these random properties are usually transformed to their logarithms, the random variables $\ln(S)$ for the strength and $\ln(L)$ for the load. The reliability target then transforms to

$$\ln(S) - \ln(L) > \delta_{req}, \tag{2.3}$$

where δ_{req} is the logarithm of the required safety factor γ_{req}, i.e. $\delta_{req} = \ln(\gamma_{req})$. The difference in the left hand side of this inequality is then studied as a random variable in the VMEA analysis. Its expected (or nominal) value is found as the result of the ordinary engineering analysis, using nominal values as inputs. Its uncertainty is calculated by means of its standard deviation in a statistical sense by pooling the uncertainties caused by all input variations and possible errors. This standard deviation is multiplied by the number 1.64 to obtain the statistical safety margin

$$\delta_S = 1.64 \cdot \tau, \tag{2.4}$$

where δ_S is the statistical part of the safety margin to be completed by an extra margin based on other considerations than statistics, and τ is the uncertainty (by means of a standard deviation) calculated from all input variations and possible errors. The statistical safety margin δ_S is constructed to represent approximately 95% survival probability and thus an extra safety margin δ_E must often be added to cover unknown and extreme events. The combined required safety margin becomes

$$\delta_{req} = \delta_S + \delta_E \,. \tag{2.5}$$

Transformed back into the safety factors it reads

$$\gamma_{req} = \gamma_S \cdot \gamma_E = \exp(\delta_S) \cdot \exp(\delta_E) = \exp(\delta_{req}) \,. \tag{2.6}$$

2.4.2 The Basic and Enhanced VMEA Procedures

In order to get an overall picture of the uncertainty sources in the design process it is useful to prepare the detailed probabilistic analysis by performing a *basic VMEA*. The result from such an analysis is a qualitative picture of the influence of different uncertainty sources which points out sources that must be further investigated and put priorities to different subject for further analysis.

When a preliminary design is established, the basic VMEA can be transformed to an *enhanced VMEA*. Then the comparison scores from the basic VMEA may be translated to approximate percentage variations in strength and load respectively. These percentage variations should represent standard deviations, and can then be pooled to the overall uncertainty to get a preliminary safety margin. This enhanced VMEA can, after possible design improvements, then be stepwise refined to a probabilistic one for a final reliability assessment.

2.5 Reliability in Automotive and Aerospace Industries

2.5.1 Reliability in Automotive Industry

In vehicle engineering the aim is to design a vehicle with certain physical properties. Such properties can be specified in the form of ‘design targets’ for so-called ‘physical attributes’ such as durability, NVH (Noise Vibration Harshness), handling, and crash safety. Design variants are analysed, optimized, and verified by means of physical tests and numerical simulations for the various attributes. An often used view of the vehicle engineering process is described in (Johannesson & Speckert, 2013), illustrated in Figure 2.3, and can be summarized as follows:

1. Concept for the new vehicle (class of vehicles, market segment, target cost, size, weight, wheel base, etc.).
2. Overall targets and benchmarks are defined for the physical properties of the vehicle (performance, durability, safety (crash), acoustics, vibration comfort, etc.).
3. Target cascading: Design targets for the sub-systems and components are derived (chassis suspension, engine, transmission, frame, body, etc.); those targets are again related to different physical attributes (durability, NVH, handling, crash, etc.).
4. Design of components, sub-systems and the full vehicle.
5. Design verification and optimization by means of physical tests and numerical simulations on the various levels for the various attributes.
6. Verification on vehicle level.

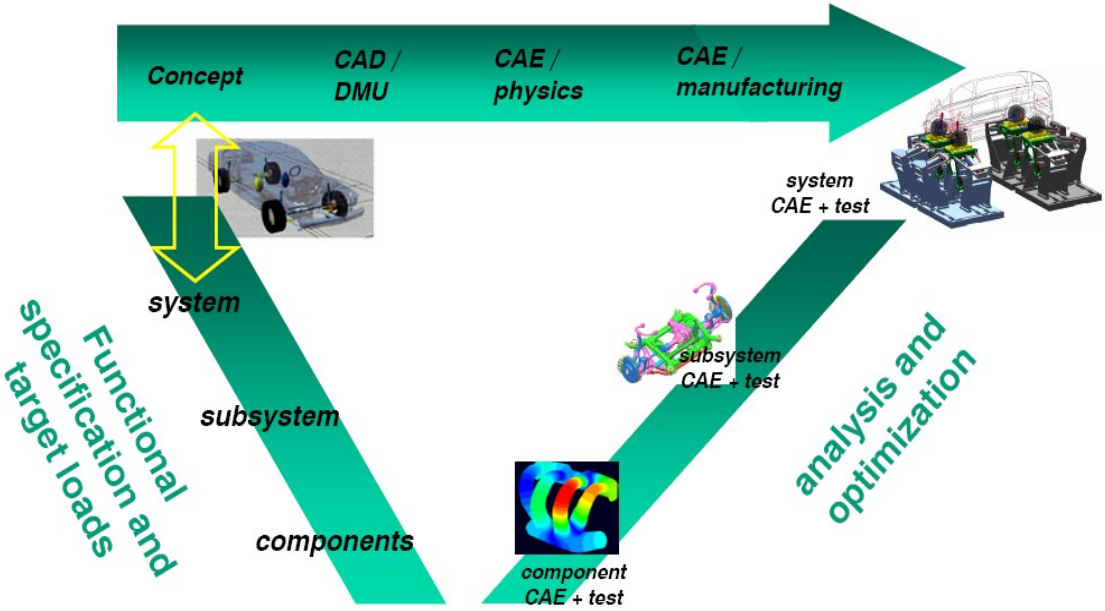


Figure 2.3: The vehicle engineering process; (Johannesson & Speckert, 2013).

A useful categorization of vehicle design approaches and their connection to load analysis is given in (Johannesson & Speckert, 2013):

- *Fatigue life* – Design for a finite life using cumulative damage.

  The design concept of fatigue life and cumulative damage is typically appropriate for structural components, such as, the frame, the cabin, and the axles of a truck. The fatigue regime considered is finite fatigue life, using for example the Wöhler curve for life prediction together with the Palmgren-Miner damage accumulation hypothesis.

- *Fatigue limit* – Design for an infinite life using maximum load.

  In this category we typically think of engine and transmission components. These components experience millions of cycles in quite a short period of time compared to the design life, and can not be allowed to contain any growing cracks. Thus they need to be designed using the fatigue limit philosophy, and consequently the maximum load is the most important load characteristic.

- *Sudden failures* – Design for rare events using maximum load.

  The maximum load may also be used as a design criterion for overloads that originate from misuse, rare events, or abnormal use. In this case the vehicle should not collapse suddenly, but may experience global plastic deformations, and may be severely damaged. When considering overloads the interpretation of the maximum load could be the load that appears on average one or a few times during the design life.

- *Safety critical components* – Design for high reliability using 'Zero' failure vision.

  A special category of components are the so-called safety critical components, for example the steering knuckle, which in principle are not allowed to fail. In practice the 'zero failure rate' needs to be interpreted as a very small risk of failure. Special care needs to be taken when considering the safety critical components, for example by using the load-strength approach.

2.5.2 Reliability in Aerospace Industry

The requirements and resources in the aerospace field differ from other industrial sectors. In general the aerospace industry can afford to use more advanced methods compared to other fields. To a large extent this is due to relatively simple crack geometries and the possibility of inspections in service, but also due to a difference in financial and safety constraints. The design concepts have been developed over the years, and the evolution is often described as follows, see (Wanhill, 2002) and (Stephens et al., 2001):

- *Infinite life* – Design for an infinite life using the fatigue limit approach, however historically using a static design approach.
- *Safe-life* – Design for a finite life using cumulative fatigue damage.
- *Fail-safe* – Design to be inspectable in service, in addition to safe-life design, in order to easily detect damage before safety is compromised. Generally, the requirement is that if one part fails, the system does not fail, and this includes concepts like redundancy, multiple load paths, and crack stoppers built into the structure.
- *Damage tolerance* – Design for a finite life using crack propagation methods, where a largest allowed initial crack is specified. This is a refinement of the fail-safe design.

2.6 Review of Marine Energy Converter Technologies

The aim of this section is to introduce and describe different wave and tidal energy converter technologies. The industry sector has not converged to one or some technologies, rather there is a large diversity of different techniques for harvesting energy. This diversity adds complexity to the building of knowledge and experience of reliability for marine energy converters.

2.6.1 Wave Energy Converters

There is a wide range of wave energy technologies, each using different solutions to absorb energy from waves depending on the water depth and location, extracting energy from the shoreline out to the deeper waters offshore, see e.g. (Cruz, 2008), (Falcao, 2010) and (Kempener & Neumann, 2014c).

2.6.1.1 Attenuator

An attenuator is a floating device which operates parallel to the predominant wave direction and effectively rides the waves. These devices capture energy from the relative motion of the two arms as the wave passes them. These technologies typically follow the design of long multi-segment structures with each segment following oncoming waves from the crest to trough. The floating pontoons are usually located either side of some form of power converting module. The relative motion between each pontoon can be converted to mechanical power in the power module, through either a hydraulic circuit or some form of mechanical gear train. Figure 2.4 demonstrates the standard design concept of an attenuator technology device.

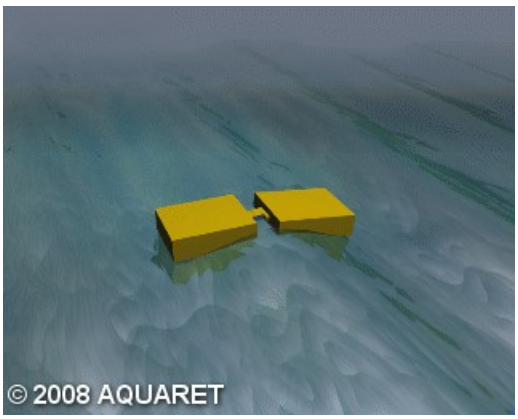


Figure 2.4: Attenuator device.
(credit: Aquaret, courtesy of EMEC)

2.6.1.2 Point absorber

A point absorber is a floating structure which absorbs energy from all directions through its movements at/near the water surface. It converts the motion of the buoyant top relative to the base into electrical power. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors. A point absorber typically possesses small dimensions relative to the incident wavelength. The structure can heave up and down on the surface of the water or be submerged below the surface relying on pressure differential. Figure 2.5 shows the point absorber, highlighting the two main components.

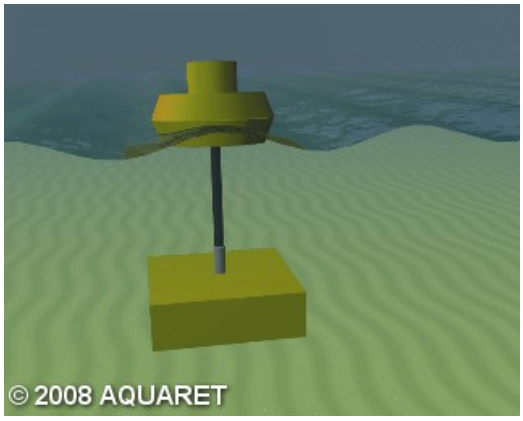


Figure 2.5: Point absorber device. (credit: Aquaret, courtesy of EMEC)

2.6.1.3 Oscillating wave surge converter

An oscillating wave surge converter (OWSC) extracts energy from wave surges and the movement of water particles within them. The arm oscillates as a pendulum mounted on a pivoted joint in response to the movement of water in the waves which then moves in a back and forth motion, exploiting the horizontal particle velocity of the wave. The design typically comprises of a surge displacer which can be hinged at the top or bottom. It can be attached on the seabed, or near the shore. Energy is usually extracted using hydraulic converters secured to a reactor. If the device is used on the shoreline it is common to hinge the displacer above the water, enabling the incoming surge waves to impact on the displacer first, and then be captured within the device to form a water column. Figure 2.6 shows an oscillating wave surge converter deployed on the sea-bed.

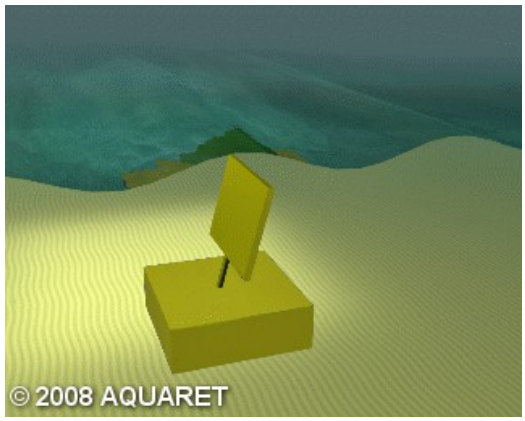


Figure 2.6: Oscillating wave surge converter device. (credit: Aquaret, courtesy of EMEC)

2.6.1.4 Oscillating water column

An oscillating water column is a partially submerged, hollow structure. It is open to the sea below the water line, enclosing a column of air on top of a column of water. Waves cause the water column to rise and fall, which in turn compresses and decompresses the air column. This trapped air can flow to and from the atmosphere via a turbine. A low-pressure Wells turbine is commonly used in conjunction with this device as it rotates in the same direction irrespective of the airflow direction. The rotation of the turbine is used to generate electricity. Figure 2.7 illustrates the water rising within the water column.

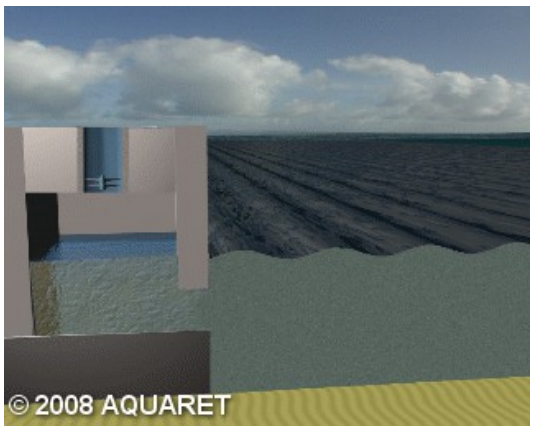


Figure 2.7: Oscillating water column device. (credit: Aquaret, courtesy of EMEC)

2.6.1.5 Overtopping/Terminator device

Overtopping devices capture water as waves break into a storage reservoir. The water is then returned to the sea passing through a conventional low-head turbine which generates power. An overtopping device may use 'collectors' to concentrate the wave energy. Figure 2.8 illustrates the wave about to break into the storage reservoir.

Figure 2.8: Overtopping device.
(credit: Aquaret, courtesy of EMEC)

2.6.1.6 Submerged pressure differential

Submerged pressure differential devices are submerged point absorbers that are typically located near shore and attached to the seabed. The motion of the waves causes the sea level to rise and fall above the device, including a pressure differential in the device. This water pressure above the device compresses the air within the cylinder, moving the upper cylinder down. The alternating pressure pumps fluid through a system to generate electricity. Figure 2.9 shows the device submerged on the seabed.

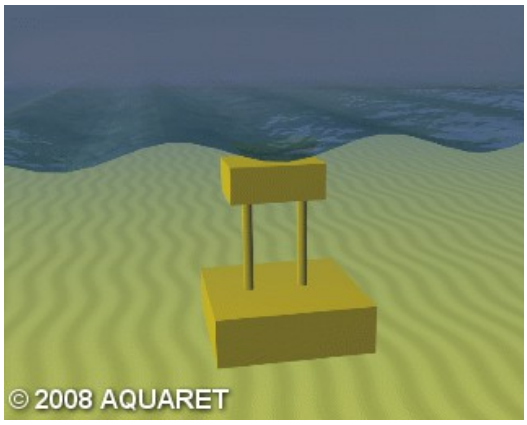


Figure 2.9: Submerged pressure differential device.
(credit: Aquaret, courtesy of EMEC)

2.6.1.7 Bulge wave

Bulge wave technology consists of a rubber tube filled with water, moored to the seabed heading into the waves. The water enters through the stern and the passing wave causes pressure variations along the length of the tube, creating a 'bulge'. As the bulge travels through the tube it grows, gathering energy which can be used to drive a standard low-head turbine located at the bow, where the water then returns to the sea. Figure 2.10 demonstrates the 'bulge' moving through the device.

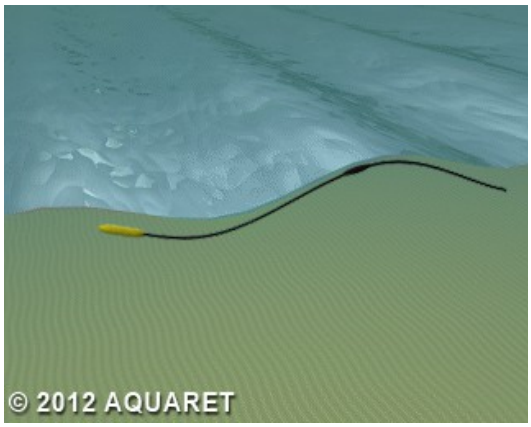


Figure 2.10: Bulge wave device.
(credit: Aquaret, courtesy of EMEC)

2.6.1.8 Rotating mass

A rotating mass concept device uses two forms of rotation to capture energy by the movement of the device heaving and swaying in the waves. This motion drives either an eccentric weight or a gyroscope causes precession. In both cases the movement is attached to an electric generator inside the device. Figure 2.11 shows the two different forms of rotation, one inside the technology and the body as a whole.

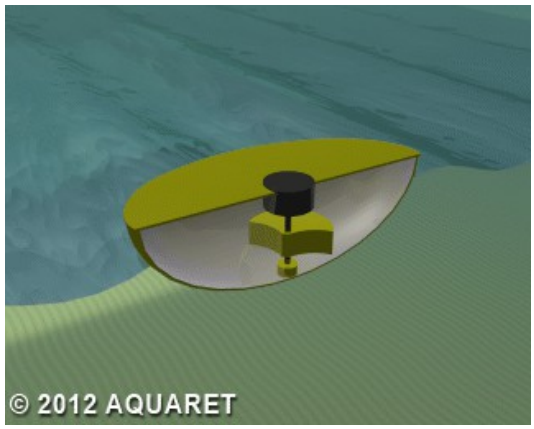


Figure 2.11: Rotating mass device concept. (credit: Aquaret, courtesy of EMEC)

2.6.1.9 Other

This covers those devices with a unique and very different design to the more well-established types of technology or if information on the device's characteristics could not be determined. For example, the Wave Rotor, is a form of turbine turned directly by the waves. Flexible structures have also been suggested, whereby a structure that changes shape/volume is part of the power take-off system.

2.6.2 Tidal Energy Converters

Tidal energy exploits the natural ebb and flow of coastal tidal waters caused principally by the interaction of the gravitational fields of the earth, moon and sun. There are several technologies for harvesting tidal energy, see e.g. (Kempener & Neumann, 2014b).

2.6.2.1 Horizontal axis turbine

Horizontal axis turbines extract energy from moving water in much the same way as wind turbines extract energy from moving air. The tidal stream causes the rotors to rotate around the horizontal axis and generate power. Figure 2.12 illustrates a horizontal axis turbine design.

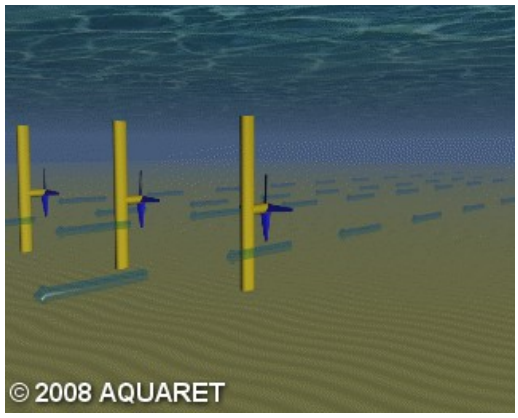


Figure 2.12: Horizontal axis turbine. (credit: Aquaret, courtesy of EMEC)

2.6.2.2 Vertical axis turbine

Vertical axis turbines extract energy from the tides in a similar manner to that above, however the turbine is mounted on a vertical axis. The tidal stream causes the rotors to rotate around the vertical axis and generate power. Figure 2.13 shows the turbine on a vertical axis.

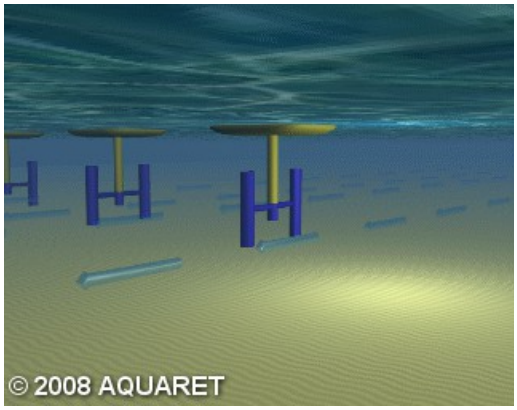


Figure 2.13: Vertical axis turbine.
(credit: Aquaret, courtesy of EMEC)

2.6.2.3 Oscillating hydrofoil

A hydrofoil is attached to an oscillating arm. The tidal current flowing either side of a wing results in lift. This motion then drives fluid in a hydraulic system to be converted into electricity. Figure 2.14 illustrates the tidal current and how it drives the motion in the oscillating arm.

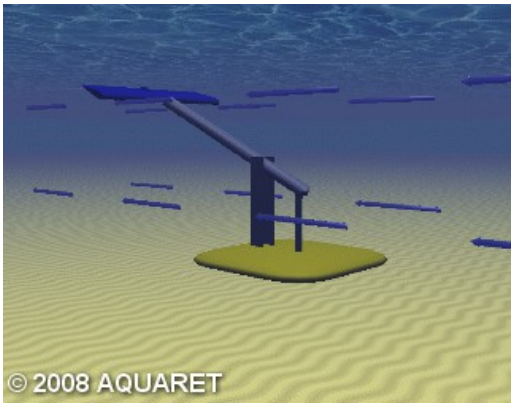


Figure 2.14: Oscillating hydrofoil device.
(credit: Aquaret, courtesy of EMEC)

2.6.2.4 Enclosed tips (Venturi)

Venturi Effect devices house the device in a duct which concentrates the tidal flow passing through the turbine. The funnel-like collecting device sits submerged in the tidal current. The flow of water can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine. Figure 2.15 illustrates the filtration of water through the device driving the turbine.

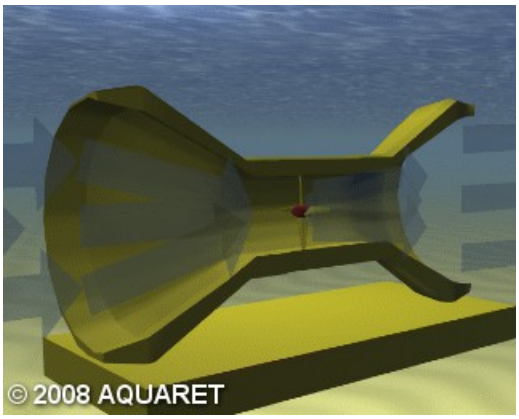


Figure 2.15: Venturi device.
(credit: Aquaret, courtesy of EMEC)

2.6.2.5 Archimedes screw

The Archimedes Screw is a helical corkscrew-shaped device (a helical surface surrounding a central cylindrical shaft). The device draws power from the tidal stream as the water moves up/through the spiral turning the turbines. Figure 2.16 shows the tidal stream move through the device causing the turning motion.

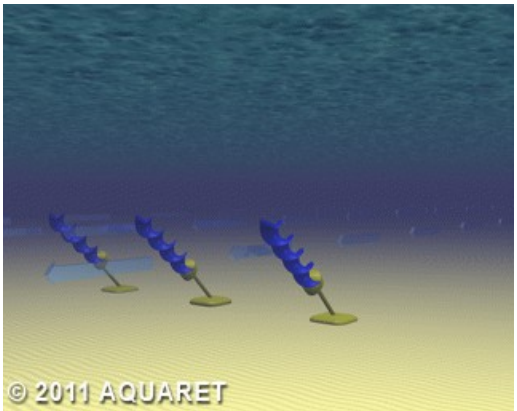


Figure 2.16: Archimedes screw device. (credit: Aquaret, courtesy of EMEC)

2.6.2.6 Tidal kite

A tidal kite is tethered to the sea bed and carries a turbine below the wing. The kite 'flies' in the tidal stream, swooping in a figure-of-eight shape to increase the speed of the water flowing through the turbine. Figure 2.17 demonstrates the tidal kite device technology movement.

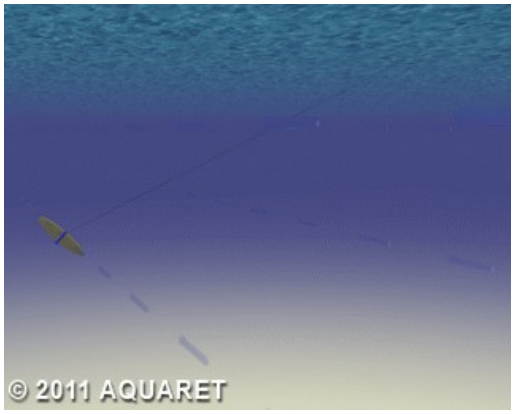


Figure 2.17: Tidal kite device. (credit: Aquaret, courtesy of EMEC)

3 Basic VMEA in Concept Phase

In a basic VMEA, see (Chakhunashvili et al., 2004) and (Johansson et al., 2006) , the goal is to identify the most important sources of variation, for example when different design solutions are evaluated. The sizes of the sources of uncertainties as well as their sensitivities to the studied product property are evaluated on a scale from 1 to 10. The robustness of the product is characterized by the summing the square of the product of sensitivity and uncertainty size. To conduct an adequate VMEA that incorporates different views and competences, a cross-functional team of engineers and experts should be formed. Such an analysis will indicate which sub-systems or components that are most critical, and thus need to be studied in more detail.

3.1 Work Process for Basic VMEA

The general procedure for making a VMEA is the same for all three VMEA levels, however the information available and the implementation of the different steps is somewhat different. The work process adopted to the basic VMEA can be described in the following steps:

1. **Target Variable Definition.**

   The first step is to define the target variable, i.e. the property to be studied, which can be the life of a component, the maximum stress or the largest defect.

2. **Uncertainty Sources Identification.**

   In this step all sources of uncertainty that can have an impact on the target variable are identified, focusing on variation sources.

3. **Sensitivity Assessment.**

   Here the task is to evaluate the sensitivity of the sources of uncertainty with respect to the target variable, which is mostly on engineering judgement.

4. **Uncertainty Size Assessment.**

   Here the task is to quantify the size of the different sources of uncertainty, which is mostly based on engineering judgement.

5. **Total Uncertainty Calculation.**

   The total uncertainty in the basic VMEA is characterized by the so-called Variation Risk Priority Number (VRPN), which shows the importance of the different sources.

6. **Reliability and Robustness Evaluation.**

   The result of the basic VMEA is mainly used to evaluate the robustness to variation, typically to compare design concepts and to find the dominating uncertainties.

7. **Improvement Actions.**

   The last step is to feedback the results to the improvement process, e.g. by identifying promising concepts and uncertainty sources that are candidates for improvement actions.

3.2 How to Define the Target Variable

The first step in the VMEA procedure is to define the target variable, i.e. the product property to be studied. The process starts by identifying the critical product characteristics, which is sometimes called Key Product Characteristics (KPC). They are characteristics that require special attention because their variability can affect product functions, safety, compliance with imposed regulations

and, more generally, the product quality. The KPCs can be obtained from a previously performed Quality Function Deployment (QFD) study, see (Hauser & Clausing, 1988) and (Cohen, 1995), or from a risk assessment, see Section 1.3. They can also be the outcome of a brainstorming session, preferably by a cross-functional team of engineers. For MECs the target variable is often some property of a critical component or sub-system, typically it can be the maximum stress, the life, or the difference between the strength and the load.

3.3 How to Find Sources of Uncertainties

The goal in this step is to identify all major sources of uncertainty that affect the target variable, and also here it is recommended to have a cross-functional team of engineers. A previously performed FMECA can give useful input, see Section 1.3, where also identification of uncertainties are discussed.

When identifying uncertainty sources it can be helpful to think about the different types of uncertainties. Uncertainties can be classified due to their nature. The first kind of uncertainty is due to random variation, while the second kind is due to our lack of knowledge, for example when modelling the product characteristics or estimating model parameters. In the basic VMEA the focus is on random variation, but also other uncertainties, such as possible model errors, may be included.

Next we will review two methods the P-diagram and the fishbone diagram, that represent useful tools for understanding the system or component and for identifying uncertainties.

3.3.1 P-diagrams

A useful graphical tool to identify inputs for VMEA (and also for FMEA/FMECA) and, more generally, to perform system analysis is represented by P-diagrams, where "P" may stand for "Parameter", "Process" or "Product", depending on the context. The basic components of a P-diagram are shown in Figure 3.1.

Control factors are the design parameters that can be set (or controlled) by the designer, such as, the choice of material, type of components, or system assembly method. *Signal factors* are the customer input that are used for adjusting the input dynamically in order to control the intended output, such as the volume lever on a transistor radio, or a steering wheel angle that specifies the turning radius of an automobile. Besides control and signal factors, *noise factors*, causing random variation, are always present, which cause the *response* of the system to deviate from the expected level.

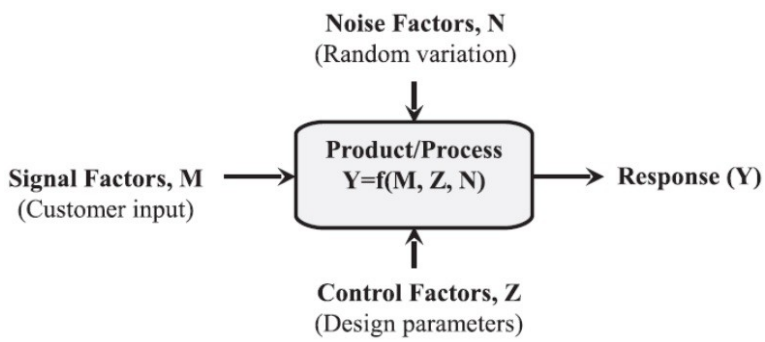


Figure 3.1: Generic P-diagram; the response Y includes both the expected (ideal) response or performance and any deviation from it (errors and losses).

The P-diagram can be used as a tool to understand the reliability of systems, subsystems, and components in early stages of product development when no prototypes exist. Unintended response,

that is, error states, can usually be linked to one or many of the noise factors identified. An early identification of these causes of possible error states offers designers the possibility to make design changes that eliminate the risk of the identified error states. Thus, the P-diagram can also be used in the process of identifying possible sourced of uncertainties.

Determining whether a factor is a noise or a control one often depends on the the scope and objectives of the project. A factor considered control in some cases might be considered noise in others. For example, consider the material hardness factor (measured in Rockwell units). Design engineers focus on the product, so they may categorize material hardness as a control factor. However, process engineers focus on the process, so they may categorize material hardness as a noise factor; from their perspective, the process needs to be insensitive to the hardness of the material.

Brainstorming is a useful tool for developing an initial list of control and noise factors. If the list of influential control and/or noise factors becomes prohibitively long, consider narrowing the scope of the study to a simpler subsystem. Then, you may need to redefine the response to establish a complete situational understanding of a wide range of data where several control factors may be interacting at once to produce an outcome.

There are many sources of noise. A general mapping of possible sources of noise results in five broad categories:

1) customer usage,
2) external environment,
3) internal environment as a result of neighbouring subsystems,
4) unit-to-unit or manufacturing variation, and
5) ageing or deterioration.

Note that the first three categories are connected to the loading conditions on the device, while the last two ones are connected to its strength to withstand the loading conditions; compare Section 1.1. Frequently, customer usage creates the most variability. Typically, control factors are obvious to engineers because they relate directly to design of the product. On the other hand, it is easy to overlook some noise factors because they are often external to system design.

3.3.2 Fishbone Diagrams

A fishbone (or Ishikawa) diagram is a graphical tool to explore and visualize the causes of a problem as well as the factors affecting the outcome of a process or the property of a product. It can be equally applied to track down the factors affecting a certain property or performance of a process or product, similarly to what done with p-diagrams. The key steps to proceed with a fishbone diagram are:

1) problem statement (or output definition);
2) define major causes categories;
3) brainstorm causes;
4) categorize causes;
5) determine deeper causes;
6) identify root causes.

Major causes categories depend on the context wherein the analysis is performed. For example, in manufacturing industry, the usual categories are Machines/Equipment, Methods, Materials, People.

Environment and Policy are also general categories commonly encountered in other contexts. The brainstorming step is then devoted to find out all possible mechanisms, conditions or events that contribute to make the final effect happen. The driving question at this stage is "why does it happen". Each item in the list of causes resulting from the brainstorming session is assigned to one or more categories defined at the beginning. In graphical terms, that amounts to drawing a branch from the appropriate category for each suggested cause/idea. Causes can be written in several places if they relate to several categories. If needed, the analysis can be iterated on each cause in order to go one level down in the causal chain (i.e. looking at secondary causes, or the "causes of the cause"), thus providing a more detailed picture of the process leading to the occurrence of the final effect. The depth of the levels to be explored in the analysis as well as the method to identify the root causes are application-dependent and decisions on these matters are left to the analyst's judgement. For example, one could look at the causes that appear repeatedly and select the root cause on the basis of its frequency of occurrence. Alternatively, the consultation of a team of experts (even the same who performed the analysis) could provide sufficient guidance for the identification of one or more root causes.

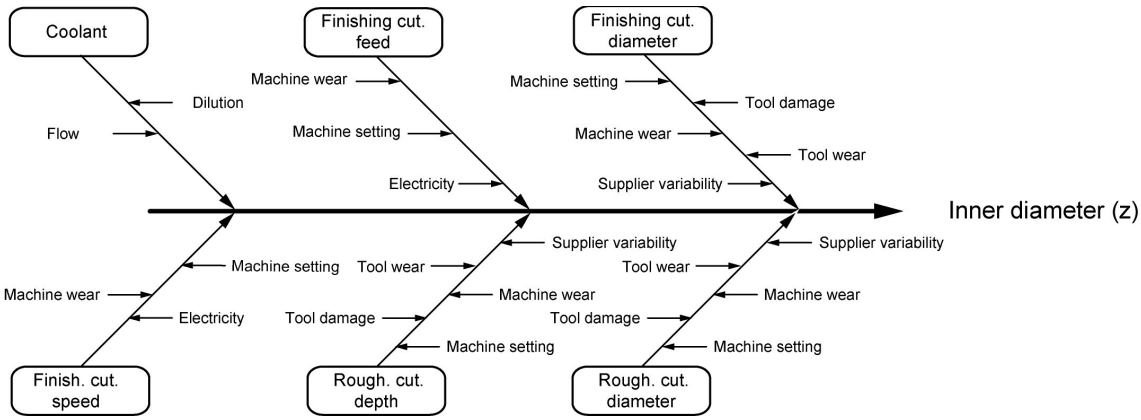


Figure 3.2: Example of complete fishbone diagram for a manufacturing problem; (Johansson et al., 2006).

An example of application of fishbone diagrams to analyse cause-effect relationships and optimize manufacturing processes is described in (Johansson et al., 2006). In that case, the "effect" of interest was the inner diameter of a valve used in industrial refrigeration systems. A team of experts discussed the role played by several factors in the manufacturing process of the valve and visualize them as the fishbone diagram shown in Figure 3.2. Mapping out all the factors involved in the manufacturing process and their associated uncertainty provided a solid ground to estimate the expected uncertainty for the diameter of the valve and design appropriate optimization strategies. That was an example of how the outcome of cause-effect analysis can facilitate the execution of VMEA, especially in its basic and enhanced formulations.

3.4 How to Find Sensitivity

The sensitivity and uncertainty size assessments are often executed in parallel. The assessments are evaluated on a 1-10 scale and is based mostly on engineering experience, judgements and informed guesses. Here we will follow the description by (Johansson et al., 2006).

In the second step of the VMEA procedure, engineers assess the sensitivity of the target variable to the influence of each identified uncertainty source. To assess sensitivities, engineers can use objective measures or subjective assessments based on their experience and theoretical knowledge. Since it is not always possible to obtain objective measures, especially in the early phases of

development, we propose utilizing subjective assessment criteria for capturing engineering knowledge. The assessment is based on a scale ranging from 1 to 10, where 1 corresponds to very low sensitivity and 10 corresponds to very high sensitivity. The criteria are given in Table 3.1.

Table 3.1: Sensitivity assessment criteria.

Sensitivity	***Criteria for assessing sensitivity***	***Score***
Very low	The uncertainty is (almost) not at all transmitted	1—2
Low	The uncertainty is transmitted to a small degree	3—4
Moderate	The uncertainty is transmitted to a moderate degree	5—6
High	The uncertainty is transmitted to a high degree	7—8
Very high	The uncertainty is transmitted to a very high degree	9—10

3.5 How to Find Uncertainty Size

In the third step of the VMEA procedure, engineers examine uncertainty sources and assess the magnitude of their size in operating conditions. In Table 3.2 we propose subjective assessment criteria for capturing engineering knowledge about the magnitude of uncertainty. The assessment is based on a scale ranging from 1 to 10, where 1 corresponds to very low uncertainty and 10 corresponds to very high uncertainty.

Table 3.2: Uncertainty size assessment criteria.

Uncertainty	***Criteria for assessing uncertainty size***	***Score***
Very low	The uncertainty source is considered to be *almost constant* in all possible conditions	1—2
Low	The uncertainty source exhibits *small fluctuations* in all possible conditions	3—4
Moderate	The uncertainty source exhibits *moderate fluctuations* in all possible conditions	5—6
High	The uncertainty source exhibits *high fluctuations* in all possible conditions	7—8
Very high	The uncertainty source exhibits *very high fluctuations* in all possible conditions	9—10

3.6 How to Calculate the Total Uncertainty

The importance of the different sources in the basic VMEA is characterized by the so-called Variation Risk Priority Number (VRPN) which is calculated for each source

$$VRPN = \sum_i VRPN_i \qquad \text{with} \qquad VRPN_i = c_i^2 \sigma_i^2 = \tau_i^2 \tag{3.1}$$

where $VRPN_i$ is the variation contribution due to source i, which is the square of the uncertainty, τ_i, which in turn is the product is the sensitivity, c_i, and the uncertainty, σ_i.

The result of the basic VMEA is well suited to be presented in a so-called VMEA table, see Table

3.3 and Table 3.4 below for examples, presenting the identified uncertainty sources together with the assessed sensitivities and uncertainty sizes. The resulting uncertainties and the VRPNs are presented together with the proportion of the variance contributions of the sources. The last row of the VMEA table present the total uncertainty and VRPN.

3.7 Reliability Evaluation and Improvement Process

The result of the basic VMEA is mostly used to evaluate the robustness of the product to variations. Typical applications are to compare design concepts and to find dominating uncertainty sources. This leads directly to the improvement process where the results are used to identify promising concept solutions, that should be studied in more detail. The feedback to the improvement process can be dominating uncertainty sources that could be candidates for improvement actions.

3.8 Application to a Mooring Line

A mooring for a buoy need to be designed for a long enough service life. The task here is to study the fatigue life of the mooring line, and to evaluate two design alternatives; a steel wire and a polyester rope. The target variable for the VMEA is the fatigue life of mooring line that depends on the fatigue load it is subjected to and its fatigue strength (i.e. the load bearing capacity in the same unit as the load). At a meeting with the design team, the following uncertainties were identified:

- Load variation
- Uncertainty in load assessment
- Scatter in fatigue life
- Uncertainty in the fatigue model
- Uncertainty due to influence of environment
- Geometry variations

The result of the assessment of sensitivity and uncertainty size is presented in Table 3.3 and Table 3.4. The importance of the different sources are illustrated by pie charts in Figure 3.1, showing the variance contributions. The conclusion is that the variation number is larger for the polyester rope, mainly due to the lack of knowledge about the fatigue properties of polyester ropes. Thus, the steel wire was found to be the most promising design solution. In order to progress with the polyester rope, it would probably imply either very large safety factors, or the need for extensive studies of the fatigue properties of polyester ropes.

Table 3.3: Basic VMEA for steel wire.

Basic VMEA: Steel wire

Input			Result		
Uncertainty sources	Sensitivity c_i (1-10)	Uncertainty σ_i (1-10)	Uncertainty $\tau_i = c_i \cdot \sigma_i$	Variation contribution VRPN	Variation contribution Proportion
- Load variation	5	4	20	400	14%
- Uncertainty in load assessment	5	6	30	900	31%
- Scatter in fatigue life	5	5	25	625	22%
- Uncertainty in the fatigue model	5	4	20	400	14%
- Uncertainty due to environment	5	4	20	400	14%
- Geometry variations	6	2	12	144	5%
Total			**54**	**2869**	**100%**

Table 3.4: Basic VMEA for polyester rope.

Basic VMEA: Polyester rope

Input			Result		
Uncertainty sources	Sensitivity c_i (1-10)	Uncertainty σ_i (1-10)	Uncertainty $\tau_i = c_i \cdot \sigma_i$	Variation contribution VRPN	Variation contribution Proportion
- Load variation	5	4	20	400	9%
- Uncertainty in load assessment	5	6	30	900	19%
- Scatter in fatigue life	5	7	35	1225	26%
- Uncertainty in the fatigue model	5	8	40	1600	34%
- Uncertainty due to environment	5	3	15	225	5%
- Geometry variations	6	3	18	324	7%
Total			**68**	**4674**	**100%**

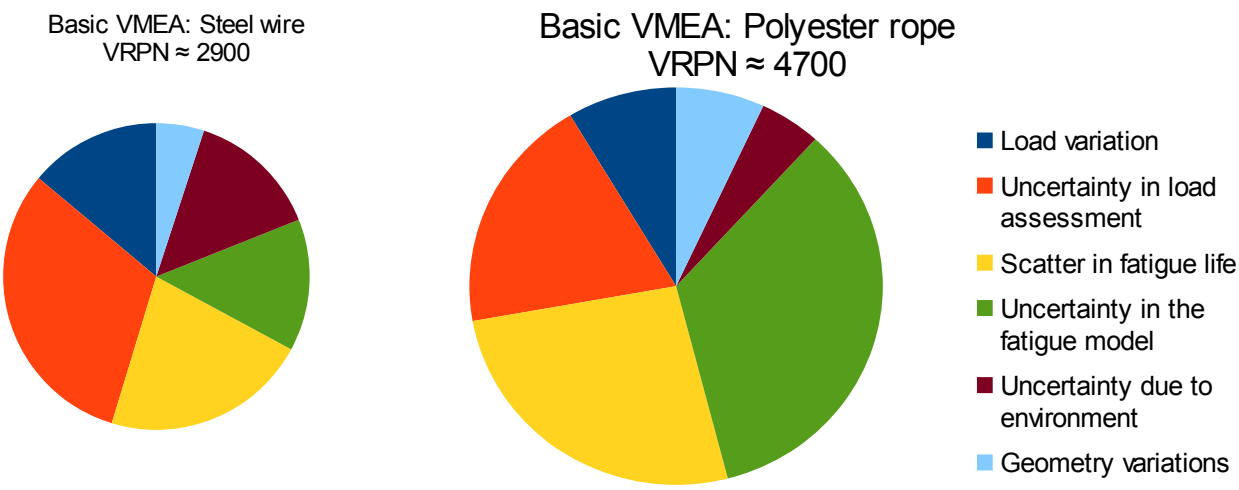


Figure 3.1.Basic VMEA; Pie charts of uncertainty contributions for steel wire and polyester rope.

4 Enhanced VMEA in Design Phase

In the enhanced VMEA, the assessment of sensitivities and uncertainty sizes is made more carefully using physical units, see (Chakhunashvili et al., 2009) and (Johannesson et al., 2013). The physical uncertainty coefficient and the standard deviation of the uncertainty is evaluated, which is the same metrics as is used in the probabilistic VMEA, and thus the enhanced VMEA should be seen as an initial version of the probabilistic one. The main goals of the enhanced VMEA are to identify weak spots of information and to prioritize work. It can be used as input to planning of prototype testing and to find a balance between unavoidable variation and uncertainty due to lack of knowledge. As the work progresses, the enhanced VMEA is transformed into a probabilistic VMEA.

4.1 Work Process

The general work process follows the same description as in Chapter 1. The methods for defining the target variable and identifying sources of uncertainty is the same as for the basic VMEA presented in Chapter 3. However, the epistemic uncertainties due to lack of knowledge should also be considered, which is discussed in more detail for the probabilistic VMEA in Chapter 5.

4.2 How to Find Sensitivity

In order to better understand the enhanced assessment scale, let us consider a relationship between a target variable Y and a uncertainty source X, analytically described by a function $Y = f(X)$. Thinking in engineering units may be helpful. If the mechanical stress at a radius is of interest, on need to find the sensitivity c in unit MPa/mm. Mathematically, the sensitivity coefficient of Y to X is the first derivative of the function

$$c = \frac{d f}{d X} \tag{4.1}$$

and the sensitivity is graphically represented by the slope of the curve, as illustrated in Figure 4.1.

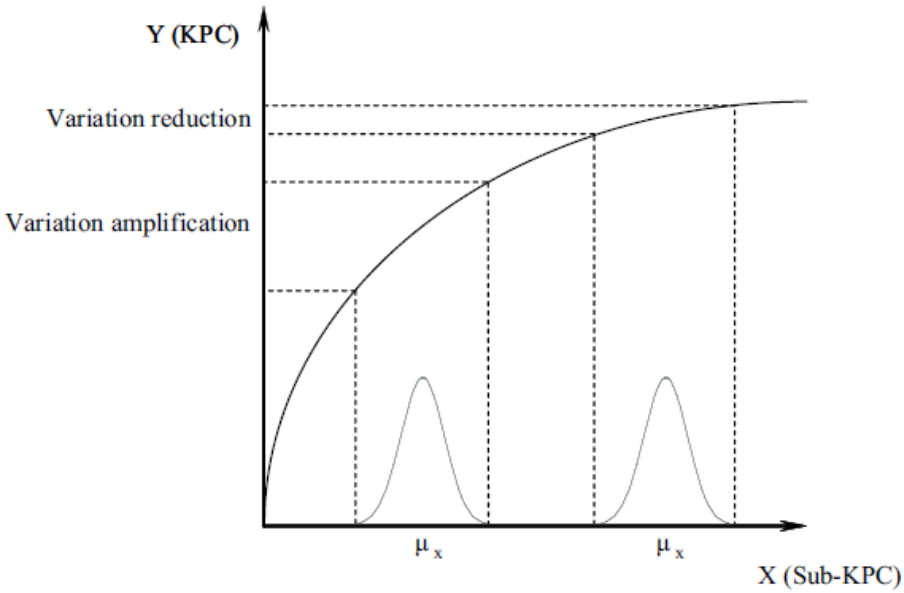


Figure 4.1: Variation transmission, amplification and reduction; (Chakhunashvili et al., 2009).

Obviously, the sensitivity will depend on the point, μ_x, at which it is calculated. The sensitivity determines how much of the uncertainty that is transferred to the target variable. The absolute value of the sensitivity can theoretically range between 0 and +∞. It is possible to graphically represent a sensitivity value by means of a line drawn in the positive quadrant of the coordinate system. A horizontal line represents the sensitivity value equal to 0, a vertical line represents the sensitivity value equal to +∞, and a line drawn at 45 degrees represents a sensitivity value equal to 1.

Therefore, in (Chakhunashvili et al., 2009) , a sensitivity assessment scale, called the *sensitivity fan*, was proposed. It spans the positive quadrant of the Cartesian graph, dividing it into 11 sectors of approximately the same angular size, see Figure 4.1. The idea of assessing sensitivities using this assessment, instead of the 1-10 scale used in the basic VMEA, comes from the fact that it takes into account the real nature of sensitivity. Each of the lines on the sensitivity fan corresponds to a specific sensitivity value. For practical reasons, the points on the scale are chosen to make the assessment as easy as possible. The last scale line is not vertical because it would in that case correspond to an unrealistic scale value equal to +∞. The scale also contains values 0 and 1, representing absolute insensitivity and direct proportional transfer cases, respectively. The scale value 0 can be used when it is believed that the uncertainty is not transferred to the target variable. The scale value 1 can be used when it is believed that the uncertainty is transferred in the same magnitude to the target variable. In other words, there is neither amplification nor reduction of uncertainty in the transfer function. Consequently, a sensitivity value equal to unity corresponds to a neutral position. In general, we can say that sensitivity values less than unity (low-moderate sensitivities) represent cases of uncertainty reduction, while sensitivity values higher than unity (high-highest sensitivities) represent cases of uncertainty amplification.

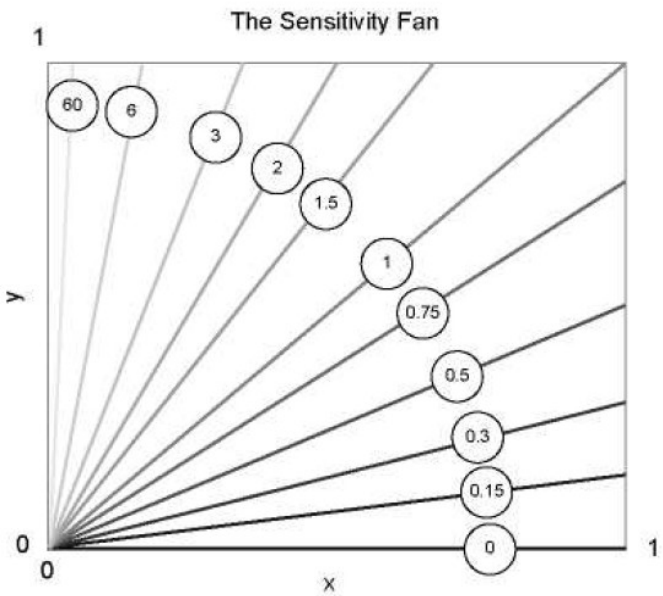


Figure 4.2: The sensitivity fan; (Chakhunashvili et al., 2009) .

4.3 How to Find Uncertainty Size

The uncertainty size is quantified using the standard deviation of the uncertainty source. The assessment can be based on engineering judgement, e.g. by estimating the variation range of a parameter, which is translated into a standard deviation. This seems to be easily accomplishable as engineers can often quantify the uncertainty size by means of variation range. For instance,

engineers can say: "The ambient temperature is an uncertainty. Its typical value is 30°C, but it can in extreme cases be as low as 15°C and as high as 45°C.". In such a case, i.e. when it is possible to provide the estimates of a range, one way to assess the uncertainty size is to divide the given range by six, see e.g. (Montgomery, 2001). If we denote range by R, we can then assess the size of the uncertainty with the following formula:

$$\sigma = \frac{R}{6} = \frac{30\,^{o}C}{6} = 5\,^{o}C \tag{4.2}$$

which corresponds to the width of a 99.8% confidence interval based on the normal distribution, i.e. there is an equal chance of chance of 1/1000 to have value above or below the interval.

However, in many cases it is more realistic to assume a uniform distribution, i.e. any value within the interval is equally likely. For instance, engineers can say: "The ambient temperature is an uncertainty. Its typical range is between 15°C and 45°C.". In such a case, we can then assess the size of the uncertainty with the following formula:

$$\sigma = \frac{R}{\sqrt{12}} = \frac{30\,^{o}C}{3.46} = 8.66\,^{o}C\,. \tag{4.3}$$

Another approach is to judge the uncertainty directly in terms of relative uncertainty, i.e. in terms of percentage uncertainty. The uncertainty of many engineering quantities are more stable using relative uncertainty, since it does not depend on the absolute level of the quantity, and is thus easier to judge by engineers.

After assessing sensitivities and uncertainty sizes, the resulting uncertainties are calculated in the same way as for the basic and probabilistic VMEA.

4.4 Evaluation and Improvement Process

The main goal of the enhanced VMEA is to support the improvement process by identifying weak spots of the design and by identifying areas where more knowledge or new information give most effect. It will thus give input for prioritizing work and for guiding the planning of prototype testing. Further, it is often useful to study model complexity in terms of a balance between unavoidable variation and uncertainty due to lack of knowledge.

In the initial phases of design it may be rather common to have some high sensitivities, but the highest sensitivity values should gradually decrease as the design process moves forward, leading to a greater degree of robustness in the improved design. If the resulting uncertainty contribution from one source is very high, it indicates a non-robust design solution, requiring large safety factors. However, some phenomena have inherently high sensitivity and/or variability, which, for example, is the case for fatigue life assessment.

The information on sensitivity and uncertainty size is updated as new information becomes available. The sensitivities and uncertainty sizes can, for example, be updated and/or estimated by load measurements, initial testing, numerical calculations, literature data and manufacturer data sheets. As the work progresses, the enhanced VMEA is transformed into a probabilistic VMEA.

4.4.1 Design of Experiments

The improvement step often involves physical experimentation. Experiments followed by analysis are frequently performed to measure the effects of one or more factors on a response. For this purpose, it is extremely important to design a priori an experiment that can provide information at the right cost. The basic problem of experimental design is deciding what pattern of factor

combinations (design points) will best reveal the properties of the response and how it is affected by the factors. Unfortunately, the question of where to place the points is often a circular one: if we knew the response function, we might easily decide where the points should be placed – but the response function is the very object of the investigation!

Design of experiments (DOE) can be defined as selecting the combinations of factor values to be employed that will provide the most information on the input-output relationship in the presence of variation. Many classical designs are presented in several publications, for example in (Box et al., 2005) or (Montgomery, 2005).

A class of designs of great practical importance is represented by the class of factorial designs. Such designs are easy to implement, and the interpretation of the observations produced can proceed largely by using common sense and elementary arithmetic. Factorial designs are defined to measure the effects of the input factors on the response: not only additive effects for each factor, but also the relevance of the interactions between factors can be quantified. The application of DOE is not limited to problems with only quantitative input factors, defined over a cardinal (0.5, 1.0, 2.3,...) or at least ordinal (low, medium, high,...) scale. In DOE one can also use qualitative factors defined over nominal scales (white, yellow, red,...). Whether a factor's scale is weak (e.g. nominal) or strong (e.g. cardinal), in DOE one assumes a variation among two (or more) possible values, called levels, for each factor.

The outcome of an experiment can be analysed via arithmetics and basic statistics or with more sophisticated methods such as regression models. The latter case is typically applied in the context of building a predictor for the system under analysis, which is a different task from the identification of effects and their magnitude.

4.4.2 Pareto Charts

A Pareto chart is a graphical tool for presenting uncertainties, for example, the result of an experiment for screening uncertainties. It is a type of chart that contains both bars and a line graph, where individual values are represented in descending order by bars, and the cumulative total is represented by the line, see Figure 4.1 for an example.

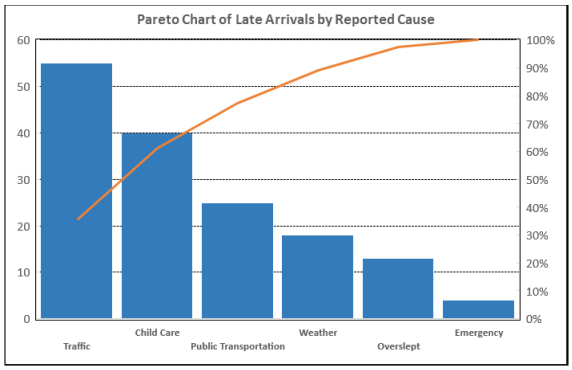


Figure 4.1: Example of Pareto Chart (By Dense2013 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=52541970

The left vertical axis is the variance of the source, but it can alternatively represent cost or another important unit of measure. The right vertical axis is the cumulative percentage of the total variance, total cost, or total of the particular unit of measure. The purpose of the Pareto chart is to highlight the most important among a (typically large) set of factors, which is the same purpose as for the pie charts, see e.g. Figure 4.3 below.

4.5 Application to a Mooring Line

The design with the steel wire seemed most promising and the enhanced VMEA, presented in Table Table 4.1 and Figure 4.3, was derived using engineering experience. The sensitivities were evaluated using the sensitivity fan, while the uncertainties were evaluated in terms of percentage uncertainty. The result will be the initial version of the probabilistic VMEA, where especially the dominating uncertainty sources will be further studied, and the sensitivities and uncertainty sizes will be updated.

Table 4.1: Enhanced VMEA for steel wire.

Enhanced VMEA: Steel wire

Input			Result		
	Sensitivity	Uncertainty	Uncertainty	Variation contribution	
Uncertainty sources	c_i	σ_i	$\tau_i = c_i \cdot \sigma_i$	τ_i^2	Proportion
- Load variation	1,0	5%	5%	0,25%	9%
- Uncertainty in load assessment	1,0	10%	10%	1,00%	36%
- Scatter in fatigue life	0,3	25%	8%	0,56%	20%
- Uncertainty in the fatigue model	0,3	30%	9%	0,81%	29%
- Uncertainty due to environment	0,3	10%	3%	0,09%	3%
- Geometry variations	2,0	1%	2%	0,04%	1%
Total			**17%**	**2,75%**	**100%**

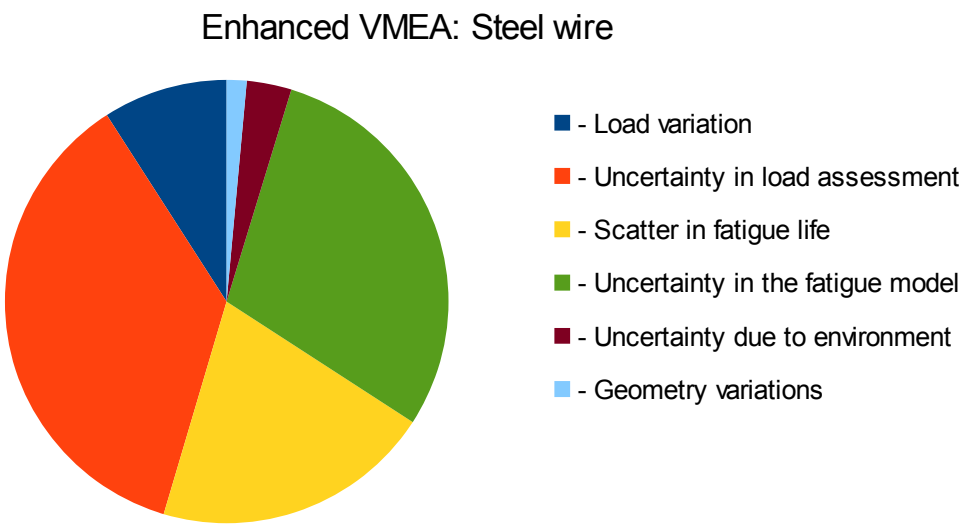


Figure 4.3: Enhanced VMEA for steel wire; Pie chart of uncertainty contributions.

5 Probabilistic VMEA in Detailed Design Phase

The main difference between probabilistic VMEA and basic and enhanced is that it evaluates final quantitative measures on uncertainty in order to ensure the design to fulfil demanded safety. The quantitative measures are the same as for the enhanced VMEA, namely, 1) sensitivities by means of mathematical *sensitivity coefficients* and 2) measures of uncertainty or dispersion by means of *statistical standard deviations*. Since, for the probabilistic VMEA, these quantifications demand detailed studies of the influencing parts and external loads, it is focussed on specific weak spots in the design, identified by engineering experience or from preceding FMECA, basic and enhanced VMEA studies.

The first evaluation of the probabilistic VMEA is usually not THE final step in a reliability assessment but is rather a framework to compare and combine detailed investigations on the influences on a weak spot. The first evaluation often results in demands of too large safety factors and new knowledge or information must be added to reduce some uncertainties. This may be done by searching for more detailed material specifications, making physical experiments, or finding validations for more correct model theory. By comparing the dominating sources of uncertainty with unavoidable sources, exaggerated detailed mathematical models may be avoided and efforts can be more focused on essentials. Step by step the procedure hopefully converges to a final design that fulfils the required reliability.

5.1 Work Process for Probabilistic VMEA

The general procedure for making a VMEA is the same for all three VMEA levels, however the information available and the implementation of the different steps will differ somewhat. The work process adopted to the probabilistic VMEA can be described in the following steps:

1. **Target Variable Definition.**

   The first step is to define the target variable, i.e. the property to be studied, which can be the life of a component, the maximum stress or the largest defect.

2. **Uncertainty Sources Identification.**

   In this step all sources of uncertainty that can have an impact on the target function are identified. The sources should be classified as scatter, statistical, or model uncertainties.

3. **Sensitivity Assessment.**

   Here the task is to evaluate the sensitivity coefficients of the sources of uncertainty with respect to the target function, e.g. by numerical calculations, experiments, or previous experience.

4. **Uncertainty Size Assessment.**

   Here the task is to quantify the size of the different sources of uncertainty, e.g. by experiments, previous experience, or engineering judgement.

5. **Total Uncertainty Calculation.**

   The next step is to calculate the total uncertainty in the target variable by combining the contributions from all uncertainty sources according to their sensitivities and sizes.

6. **Reliability and Robustness Evaluation.**

   The result of the VMEA can be used to evaluate the reliability and robustness, especially to find the dominating uncertainties and to derive proper safety factors.

7. **Improvement Actions.**

   The feedback to the improvement process can be identifying uncertainty sources that are candidates for improvement actions and evaluate their potential for reliability improvements.

In the coming sections each of the steps in the probabilistic VMEA will be explained in detail, and finally the mooring rope example will finish off the chapter.

5.2 How to Define the Target Variable

The VMEA procedure is based on the idea of defining a target variable representing the quantity of interest, e.g. life, load versus strength, maximum stress, or maximum defect size. Often the target variable is based on comparing load and strength, both associated with uncertainties and thereby modelled as random variables. The basic reliability target is often formulated that the strength should exceed the load with a certain safety margin where the margin must be chosen to account for *all possible uncertainties* in the evaluation.

In the load-strength context the strength should be larger than the load to have a safe operation, which can be formulated in different ways

$$S > L \quad \text{or} \quad \frac{S}{L} > 1 \quad \text{or} \quad \ln(S) > \ln(L), \tag{5.1}$$

where the units for S and L may be kN or MPa. The most common target variable is based on the logarithms of numerical metrics of load and strength, and the *target variable,* denoted Y, can thus read

$$Y = \ln(S) - \ln(L). \tag{5.2}$$

since

$$\ln(S) > \ln(L) \quad \Rightarrow \quad \ln(S) - \ln(L) > 0, \tag{5.3}$$

Other target functions can be defined, for instance in the case when one have defined a target life and the criterion for safe operation can be formulated as

$$N_f > N_T \quad \text{or} \quad \ln(N_f) > \ln(N_T), \tag{5.4}$$

where the calculated life N_f is associated with uncertainties, and the target life N_T is a fixed number without uncertainty. Also here the logarithmic metrics are generally recommended, and the target variable can read

$$Y = \ln(N_f) \quad \text{or} \quad Y = \ln(N_f) - \ln(N_T). \tag{5.5}$$

The output of the target function in the VMEA concept is regarded as a random variable and, in most cases, its logarithmic form makes the procedure more stable. There are mainly two reasons for this, namely 1) The linear approximation used when combining uncertainty sources often becomes more accurate, and 2) the uncertainty measure, the standard deviation, becomes more stable (constant) within the range of interest.

The target variable Y can be formulated as a target function of input variables, the sources of uncertainty, namely,

$$Y = f(X_1, X_2, X_3, \ldots) \tag{5.6}$$

where $f(X_1, X_2, X_3, \ldots)$ is the target function depending on sources of uncertainty $X_1, X_2, X_3, \ldots$.

5.2.1 Limit State Function

In structural reliability the connection between the target function and the failure criterion is often formalized by the so-called limit state function, defining the border line between failure and safe operation. The limit state function can be formulated as $g(X_1, X_2, X_3, \ldots)$, where $X_1, X_2, X_3, \ldots$ are sources of uncertainty. The failure domain is then defined as $g(X_1, X_2, X_3, \ldots) \leqslant 0$, and thus the safe domain is $g(X_1, X_2, X_3, \ldots) > 0$.

The load-strength target variable defined above is in fact representing the limit state function

$$g(X_1, X_2, X_3, \ldots) = \ln(S) - \ln(L), \tag{5.7}$$

while for the target life formulation it can read

$$g(X_1, X_2, X_3, \ldots) = \ln(N_f) - \ln(N_T). \tag{5.8}$$

The design target for reliability is that the limit state function should exceed zero with a proper safety margin, which is discussed in Section 3.7.

5.3 How to Find Sources of Uncertainties

All possible sources of uncertainties in the nominal target function must be considered. These includes scatter sources, i.e. inputs that are expected to have a random variation, and possible error sources, i.e. inputs, model errors and additional influentials whose values are not known beforehand, but must be assumed to certain values containing possible errors.

Methods for finding all possible sources of uncertainties are the same for probabilistic VMEA as for basic and enhanced VMEA, and are described in Chapters 3 and 4. However, in order to evaluate the probabilistic VMEA each source of uncertainty must be represented by a measurable quantity that can be characterised by a nominal value and a standard deviation.

In the later design stages it is important to consider all types of uncertainty, not only scatter sources, but also statistical uncertainties and possible model errors. Recall the classification of the different types of uncertainties

- ***Scatter*** or physical uncertainty which is that identified with the inherent random nature of the phenomenon, e.g. the variation in strength between different components.
- ***Statistical uncertainty*** which is that associated with the uncertainty due to statistical estimation of physical model parameters based on available data, e.g. estimation of parameters in the Coffin-Manson model for life based on fatigue tests.
- ***Model uncertainty*** which is that associated with the use of one (or more) simplified relationship to represent the 'real' relationship or phenomenon of interest, e.g. a finite element model for the relation between outer loads and local stresses.

Scatter cannot be avoided, while the last two types of uncertainties can be decreased by gaining more data or by building better models.

5.4 How to Find Sensitivity Coefficients

The VMEA procedure is a simplification in mainly two respects. The first one is that the statistical evaluation is based only on second order moments, which means that only variances (or standard deviations) are used to specify the statistical property of an uncertainty component. The other important simplification is that the total variance is based on a linearization of the transfer function from influential variables to the target variable. These linear approximations makes it sufficient to use a sensitivity coefficient for each variable.

In theory the sensitivity coefficient c_i with respect to the *i*:th uncertainty source X_i, is the partial derivative

$$c_i = \frac{\partial f(\ldots, X_i, \ldots)}{\partial X_i}, \tag{5.9}$$

where $f(\ldots, X_i, \ldots)$ is the target function. However, in practice it is often easier and more robust to evaluate the sensitivity coefficient using difference quotients, where the steps should be chosen in the order of one or some standard deviations of the input variable, see (Svensson & de Maré, 2008). Further, often the target is the difference between the logarithmic strength and the logarithmic load,

$$f(\ldots, X_i, \ldots) = \ln(S) - \ln(L), \tag{5.10}$$

which will be used in the examples.

Example 5.1 (Wöhler curve).

Assume that the failure mechanism is high cycle fatigue and that we model the life by a Wöhler curve with exponent 3.5 *. We want to evaluate the sensitivity of the fatigue strength on the scatter in life. The fatigue strenth is defined as the stress amplitude at two million cycles*[1]*. The Wöhler curve can be described mathematically by the so-called Basquin equation, here formulated as,*

$$N = 2 \cdot 10^6 \cdot \left(\frac{S_a}{S_{FAT}} \right)^{-3.5}, \tag{5.11}$$

where S_a *is the stress amplitude, and* S_{FAT} *represents the fatigue strength. In a log-log diagram the relation becomes a straight line in,*

$$\ln(N) = \ln(2 \cdot 10^6) - 3.5 \cdot (\ln(S_a) - \ln(S_{FAT})). \tag{5.12}$$

In order to use this equation to describe each individual test result we add an error term, ε *,*

$$\ln(N) = \ln(2 \cdot 10^6) - 3.5 \cdot (\ln(S_a) - \ln(S_{FAT})) + \varepsilon. \tag{5.13}$$

The value of this error term will be different for each test and the standard deviation, calculated from the linear fit, is simply the estimated standard deviation of this error term, which then represent the scatter in log life. However, the fatigue strength is formulated by means of a load amplitude and we rearrange the formula with respect to $\ln(S_{FAT})$ *, viz.*

$$\ln(S_{FAT}) = \frac{1}{3.5} \cdot (\ln(N) - \ln(2 \cdot 10^6)) + \ln(S_a) - \frac{\varepsilon}{3.5}. \tag{5.14}$$

The partial derivative of the target function with respect to the error ε *is then,*

$$c_i = \frac{\partial [\ln(S) - \ln(L)]}{\partial \varepsilon} = \frac{\partial \ln(S_{FAT})}{\partial \varepsilon} = -\frac{1}{3.5} = -0.286. \tag{5.15}$$

To summarize, the general expression for the sensitivity coefficient is $c_i = -1/k$ *, where* k *is the so-called Wöhler exponent. In the specific case with Wöhler exponent* $k = 3.5$ *, the sensitivity coefficient becomes* $c_i = -1/3.5 = -0.286$ *.*

Often the dependence of the target variable on influential variables cannot be expressed as an explicit formula, but can instead be determined from a numerical procedure like a finite element program. In such cases the partial derivative must be approximated by a sensitivity analysis.

Denote the numerical procedure with $f(\ldots, X_i, \ldots)$, where X_i is the variable whose sensitivity coefficient we want to find and the ellipsis's represent the nominal values of all other variables in

1 This is a property often used for weld fatigue design and there called the *FAT-value* for a given type of weld.

the procedure. Then the sensitivity coefficient can be evaluated using a difference quotient, namely

$$c_i = \frac{f(\ldots, X_{i,nom} + s_i, \ldots) - f(\ldots, X_{i,nom} - s_i, \ldots)}{2 \cdot s_i}, \tag{5.16}$$

where $X_{i,nom}$ is the nominal value of the actual variable and s_i is the standard deviation of this variable. Note that the steps should be chosen in the order of typical variations of the input variable; here it is chosen to one standard deviation, see (Svensson & de Maré, 2008).

Alternatively, the sensitivity coefficient can be evaluated in the direction of the failure mode,

$$c_i = \frac{f(\ldots, X_{i,nom}, \ldots) - f(\ldots, X_{i,nom} \pm 1.64 \cdot s_i, \ldots)}{1.64 \cdot s_i}, \tag{5.17}$$

where the use of plus or minus depends on how X_i influences the target function. The sign shall be chosen to get closer to the limit, e.g., in the case of life, it should be chosen towards lower life, making the sensitivity coefficient positive.

5.5 How to Find the Size of the Uncertainty Sources

Each source of uncertainty need to be characterised by means of its possible uncertainty. In probabilistic VMEA we use the *standard deviation*. The standard deviation is a statistical measure and defined as the square root of the *variance*. The variance in turn is formally defined as the mean of all squared distances from the mean value of the population.

In many situations a logarithmic transformation is useful, e.g. when studying positive quantities, such as load, strength or life. The reason for using the standard deviation of the logarithmic property is twofold, 1) engineering relations are often very well described as straight lines in log-log diagrams and the variation around such a line has similar spread around it for the magnitudes of interest, 2) the standard deviation of the logarithmic property is approximately the same as the coefficient of variation of the property itself, namely

$$std(\ln X) \approx \frac{std(X)}{E(X)}, \tag{5.18}$$

where std is the standard deviation and E is the mean value (or population mean). This means that it is easy to use engineering judgements for estimates by means of *percentage variation,* if a property has an uncertainty of 10%, the standard deviation of its natural logarithm is approximately 0.10.

Based on these statistical definitions we can outline methods for estimating the uncertainties for input variables to the VMEA analysis.

5.5.1 Evaluate Uncertainty from Statistical Observations

Suppose that we have a sample from a population that is representative for the construction. It can be measurements of load or outcomes of fatigue tests of a component. Then this sample may be used to find both its expected value and its standard deviation.

Example 5.2 (Chain).

We want to have a measure of the uncertainty due to scatter in strength of a chain. We take a sample of five chains and make tensile tests with the following result for the ultimate strength in kN: 215, 198, 230, 205 and 217. The logarithms of the results are 5.37, 5.29, 5.44, 5.32, and 5.38. The average value, which will be used to define the nominal strength is

$$m=\frac{5.37+5.29+5.44+5.32+5.38}{5}=5.36\,, \tag{5.19}$$

and the differences from the mean are 0.01, -0.07, 0.08, -0.04, 0.02, giving the standard deviation

$$s=\sqrt{\frac{(0.01)^2+(-0.07)^2+(0.08)^2+(-0.04)^2+(0.02)^2}{5-1}}=0.058\,. \tag{5.20}$$

This number represents the standard deviation due to scatter.

The first estimates, based on average and standard deviation are uncertain themselves, and we use standard statistical theory to account for this. Namely, the standard deviation is multiplied with a constant which depends on the number of samples behind its estimation. This constant is based on the statistical *t*-distribution[2] and is found in the Table 5.1. Further, the uncertainty of the average value depends both on the standard deviation and the number of samples and equals the standard deviation divided by the square root of the number of samples.

Table 5.1: Values for the t-correction factor.

n	2	3	4	5	6	7-10	11-26	27-
t_n	**6.5**	**2.2**	**1.6**	**1.4**	**1.3**	**1.2**	**1.1**	**1.0**

Example 5.3 (Chain, continued).

The standard deviation was estimated to 0.058 *and was based on five tests. Using Table 5.1 we find that the value should be amplified by the t-correction* 1.4*, and the uncertainty component due to scatter to be used in the VMEA analysis is* $0.058\cdot 1.4=0.081$*. The average value was* 5.36 *and its uncertainty, often called the statistical uncertainty, is* $0.081/\sqrt{5}=0.036$*. The results are summarized in Table 5.2.*

Table 5.2: A VMEA working sheet including results from Example 5.3.

Evaluation of Uncertainties

Example: Chain

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Strength scatter	x		1,000	1,400	0,058	0,081		
Statistical uncert. strength		x	1,000	1,400	0,026		0,036	

A typical working sheet for a probabilistic VMEA is shown in Table 5.2 showing the results from Example 5.3. Each row in the sheet represents one uncertainty component. The uncertainty component is first classified according to its type, either a random variation (scatter or aleatory uncertainty) or a systematic unknown error (epistemic uncertainty). In the actual case the first row represents the material scatter found by the sample test. This classification is useful in two respects, firstly because uncertainties are possible to reduce by including more knowledge, i.e. if such a component dominate the total uncertainty, then efforts should be paid to find better precision in its

2 The number is the 2.5% quantile in the statistical *t*-distribution with *n*-1 degrees of freedom divided by the 2.5% quantile in the normal distribution, which corresponds to the *t*-distribution with infinite degrees of freedom.

estimated value. Secondly, in case there are more than one critical failure mode it is possible to use statistical theory to estimate the variance of the worst case by calculating the distribution of maximum of random contributions.

In Table 5.2, the first row represents the observed scatter in the sample, which is assumed to be a random contribution also in future choices of components. However, the statistical uncertainty, i.e. the uncertainty in the mean value due to limited number of tests, is an unknown systematic error in the nominal strength value and classified as an "uncertainty". It may be reduced by making more tests.

The sensitivity coefficient is here put to unity, assuming that the target function is chosen as the difference between log strength and log load. Since the calculated standard deviation is based on the logarithmic strength values, the sensitivity equals one.

The *t*-correction factor is chosen as explained above, the standard deviation is just what we found from the experiment and the resulting scatter and uncertainty components are the product of the three columns c, t and s. For the statistical uncertainty the standard deviation is the scatter standard deviation divided by the square root of five as explained earlier.

The simple sample as shown in Example 5.3 may be a little more complex in case of no direct observation of the strength. For fatigue strength, for instance, the strength may be represented by a Wöhler curve, a Coffin-Manson-curve or a fatigue limit, where the strength value is estimated from the number of cycles to failure or failure/survival of the test. In the Wöhler curve case the standard deviation of the scatter is based on the scatter around the straight line in the log-life versus log-load diagram.

Example 5.4 (Wöhler curve, continued).

The failure mechanism is high cycle fatigue and we define the strength as the stress amplitude at two million cycles in the Wöhler diagram. A test is performed with nine specimens at three different stress levels: 330, 350 and 420 MPa. The lives of the three times three specimens were: 1360, 1420, 1740, 998, 1090, 1070, 646, 498, 587 thousand cycles. The result is illustrated in Figure 5.1.

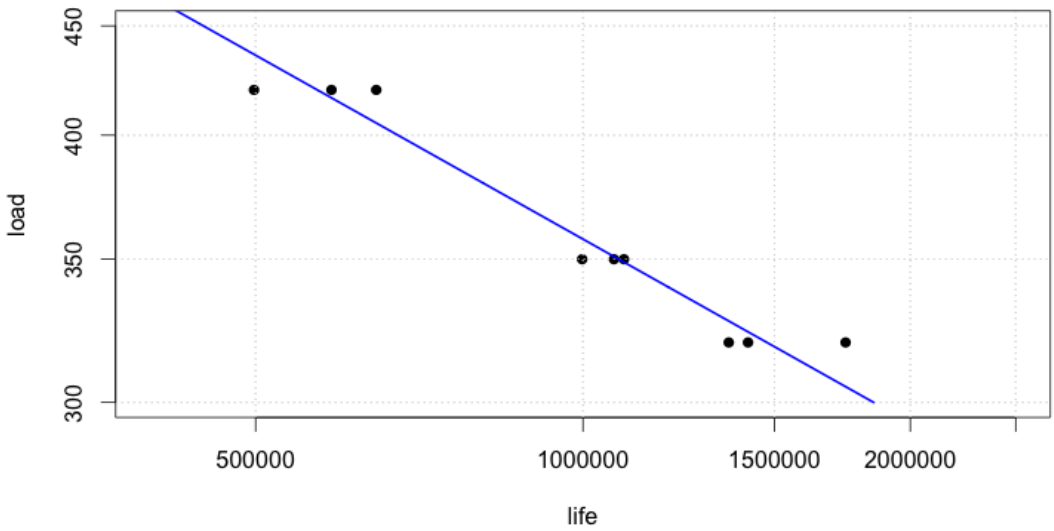


Figure 5.1: The experimental Wöhler diagram for Example 2 including a linear fit.

Using a standard linear regression procedure, the resulting linear fit is

$$\ln(N) = 34.4 - 3.5 \cdot \ln(S_a), \tag{5.21}$$

and the scatter around the line in log-life direction is 0.105. Using the formula we find the nominal fatigue strength at 2 million cycles:

$$S_{FAT} = \exp((34.4 - \ln(2 \cdot 10^6))/3.5) = 294\ \text{MPa}. \tag{5.22}$$

In the VMEA sheet, Table 5.3, the standard deviation for the strength scatter is 0.105 as found from the linear fit. However, this scatter is related to log-life and not log-strength. To account for this we use the sensitivity coefficient, which is the reciprocal of the linear slope, 1/3.5=0.286, which was explained in Example 5.1 about sensitivity coefficients. The t-correction factor in this case is based on having 9 tests[3] and the statistical uncertainty in the second row is the scatter standard deviation divided with the square root of nine.

Table 5.3: VMEA sheet for Example 5.2.

Evaluation of Uncertainties

Example: Wöhler curve

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Strength scatter	x		-0,286	1,200	0,105	0,036		
Statistical uncert. strength		x	-0,286	1,200	0,035		0,012	

The load is in the actual application often based on wave movements, usually characterised by characteristic wave height and period for different sea states. For a certain location one may assume that the distribution of sea states is the same during the life of the wave energy equipment and the variation within the life is only a subject for cycle counting for fatigue evaluation.

However, in case the equipment is designed to withstand different locations there is an uncertainty about the distribution of sea states at each location that need to be included in the VMEA analysis.

Example 5.5 (Load).

Our equipment should be designed for any location in the world oceans. Measurements have been performed at ten randomly chosen locations and at each location a median characteristic wave height $\tilde{H}_s$ has been calculated. The average and standard deviation of the logarithm of $\tilde{H}_s$ are calculated. The average is transformed by a finite element procedure to a nominal load at the "hot spot" in the construction. The standard deviation is used as an uncertainty component, amplified by the t-correction factor 1.2 and with the sensitivity coefficient based on a sensitivity analysis within the finite element procedure.

5.5.2 Evaluate Uncertainty from Interval Judgements

When no statistical sample is available, the standard deviation must be assessed in other ways. The best method for engineering use is to estimate an interval that is assumed to contain most variation for a property. A typical situation for this application is for geometric tolerances. Such an interval may be transformed to a standard deviation by assuming that the statistical distribution of variation

3 To be statistically correct, the t-correction factor in this case should be read from the table at *n*=8 tests, since two parameters are estimated from the same data set giving 7 degrees of freedom for the standard deviation, i.e. one less that in the simple case when only the average of the data set is estimated.

within the interval is uniform, i.e. the probability is the same for all points within the interval. This is a somewhat conservative assumption, but without detailed knowledge about the distribution it is the most practical solution.

If a property X is assumed to vary within the interval $[m-d, m+d]$, then, assuming a uniform distribution, the standard deviation is

$$s_X = \frac{d}{\sqrt{3}}. \tag{5.23}$$

Example 5.6 (Radius).

A radius in component will affect the stress at fatigue sensitive hot spot. In the drawing the radius is given as 4 mm with the tolerance ±0.1 mm. The standard deviation for this uncertainty component is $0.1/\sqrt{3}=0.058$ *and is written in the VMEA sheet according to Table 5.4. The sensitivity coefficient must here be calculated by means of the transfer function from radius to the logarithm of strength, perhaps given by a finite element procedure.*

Table 5.4: VMEA sheet for Example 5.6.

Evaluation of Uncertainties

Example: Radius

Input						Result		
Uncertainty components	scatter	uncert.	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Radius uncertainty		x	c	1,000	0,058			

5.5.2.1 Approximations and Possible Model Errors

The uniform distribution is also a most important tool to include possible model errors. Any load/strength evaluation incorporate mathematical-physical models, such as linear approximations as the Wöhler curve. Material specifications are usually found from laboratory experiments which differ from the conditions in service. Finite element procedures contains approximations by means of boundary conditions and resolution. Multi-axial load conditions may be too complex to be modelled properly and external forces like sea states are simplified projections of the full multi-axial wave behaviour.

Model errors of that kind are hard but necessary to take into account. The solution is to use engineering experience and physical understanding to make judgements about the possible error that a certain approximation may introduce.

In most cases judgements are best expressed as *possible percentage error.* If such an error is judged by means of the load or strength variable, then it can be interpreted as a possible error interval and by using the uniform distribution assumption it can be transformed to a standard deviation for the logarithmic properties, ±p% error is transformed to the standard deviation

$$\frac{\frac{p}{100}}{\sqrt{3}} = \frac{p}{100\sqrt{3}}. \tag{5.24}$$

Example 5.7 (Steel wire).

The tensile strength of a stainless steel wire is specified to be 520 kN. However, the strength

represents laboratory conditions in dry air at ambient temperature. In the application the wire will be used in sea water. It is judged that the strength in sea water may be reduced by up to 10%. The nominal strength to be used in the analysis is the specified strength reduced by 5%, giving $(520-0.05\cdot 520)\,\mathrm{kN}=494\,\mathrm{kN}$ *, and the judgement uncertainty of the logarithm of strength has the standard deviation corresponding to ±5%:*

$$s=\frac{0.05}{\sqrt{3}}=0.029. \tag{5.25}$$

The judgement in this case is related to the reduction of strength in the same unit as the load/strength target and the sensitivity coefficient is unity. The t-correction factor is irrelevant when no statistical test has been performed and is therefore also put to unity. The results are summarized in Table 5.5.

Table 5.5: VMEA sheet for Example 5.5.

Evaluation of Uncertainties

Example: Steel wire

Input						Result		
Uncertainty components	scatter	uncert	Sensitivity coefficient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Equvialence with lab conditions		x	1,000	1,000	0,029			

5.5.2.2 Biased Samples

One important source of uncertainty is when statistical samples are used, but their representation is poor. For instance, it is usually not possible to take a random sample of future sites, since their location are not known beforehand. Another typical situation is that material specifications represent a certain supplier or batch of material, but in future usage other suppliers may be used. Also this type of uncertainty must be judged by experience and physical understanding and can be given a measure by the same tool as for model errors. The knowledgable engineer gives a possible percentage error in the target property, the number is divided by the square root of three and put as an uncertainty component in the VMEA sheet.

5.6 How to Calculate the Total Uncertainty

The result of the probabilistic VMEA is used to evaluate the reliability, and to guide the engineers in the improvement work. Once all uncertainty sources have been quantified by means of their standard deviations and their influence on the target function has been approximated by their sensitivity coefficients, the final uncertainty can be determined. Namely, the variance components, i.e. the sensitivity coefficients squared multiplied by the squares of the estimated standard deviations, are added:

$$\tau=\sqrt{\tau_1^2+\tau_2^2+\ldots+\tau_n^2}=\sqrt{c_1^2\cdot\sigma_1^2+c_2^2\cdot\sigma_2^2+\ldots+c_n^2\cdot\sigma_n^2}, \tag{5.26}$$

where τ is the final target function uncertainty.

The above formula can be justified by studying the variance of the target function

$$Y=f\left(X_{1,}X_{2,}X_{3,}\ldots\right), \tag{5.27}$$

where Y is the output, $f\left(X_{1,}X_{2,}X_{3,}\ldots\right)$ is the function representing the physical phenomenon

studied, and $X_1, X_2, X_3, \ldots$ are sources of uncertainty. In order to assess the uncertainty we will use Gauss' approximation formula, which is based on a linearization of the target function

$$Y \approx f(x_1, x_2, \ldots) + c_1(X_1 - x_1) + c_2(X_2 - x_2) + \ldots \quad \text{with} \quad c_i = \left[\frac{\partial f}{\partial X_i}\right]_{X_i = x_i}. \tag{5.28}$$

Thus, the prediction variance can be approximated by

$$\mathrm{Var}[Y] \approx c_1^2 \sigma_1^2 + c_2^2 \sigma_2^2 + \cdots + \sum_{(i \neq i)} c_i c_j \mathrm{Cov}[X_i, X_j], \tag{5.29}$$

where σ_i is the standard deviation of X_i, representing the uncertainty in sources i, resulting in prediction uncertainty $\tau_i = |c_i| \cdot \sigma_i$. The covariance terms can often be assumed to be zero or negligible, but otherwise the relevant covariances need to be incorporated in the formula for the total uncertainty.

5.7 Reliability Evaluation

The reliability target is often that target function should exceed some limit with a proper safety margin. Here we assume that the target function is formulated as (or can be re-formulated as) a limit state function, i.e. the target function should exceed zero with a proper safety margin. First we present safety factors derived through the Cornell reliability index, and then we present the concept of an extra safety factor.

5.7.1 The Cornell Reliability Index

The result from the probabilistic VMEA can easily be transformed into the *Cornell reliability index*, which, in turn, can be related to the Taguchis' signal-to-noise ratio. For the load-strength case, the reliability index reads,

$$\beta = \frac{\delta}{\tau} \quad \text{with} \quad \delta = \ln(S_{nom}) - \ln(L_{nom}), \tag{5.30}$$

where the nominator δ is the nominal (or mean) difference between the logarithmic values of scalar metrics of strength $\ln(S_{nom})$ and load $\ln(L_{nom})$, respectively, and the denominator is a measure of the uncertainty corresponding to the statistical property: *standard deviation*.

For the general formulation using the limit state function the reliability index reads, $\beta = \delta / \tau$ with

$$\delta = E[g(X_1, X_2, X_3, \ldots)] \quad \text{and} \quad \tau = \sqrt{\mathrm{Var}[g(X_1, X_2, X_3, \ldots)]}. \tag{5.31}$$

The reliability index is sometimes denoted as *safety index* or *distance from failure mode* since it can be interpreted as the number of standard deviations from the failure mode; (O'Connor, 2002; Davis, 2006). The reliability index is very useful for comparing different design alternatives and to evaluate effect improvement measures.

Example 5.8 (Reliability of metal bar).

When the ultimate strength, S of a metal bar is compared to the stress L that is acting on it, the difference is usually not considered, but instead the quotient S/L. In order to use the reliability index the properties are transformed by their logarithms giving the distance $\ln(S) - \ln(L)$. For the specific case the nominal load is 406 MPa, the nominal strength is 760 MPa, and the uncertainty is 0.23, giving reliability index

$$\beta = \frac{\ln S_{nom} - \ln L_{nom}}{\tau} = \frac{\ln 760 - \ln 406}{0.23} = \frac{0.632}{0.23} = 2.75. \tag{5.32}$$

The reliability index is often used for comparing the determined index value with a predefined

requirement, say $\beta > \beta_{req}$, giving the requirement of the safety margin, i.e. the separation between nominal strength and load values:

$$\ln S_{nom} - \ln L_{nom} > \beta_{req} \cdot \tau = \delta_{req}. \tag{5.33}$$

For structural reliability, the Joint Committee on Structural Safety, (JCSS, 2001), gives guidance on determining the required safety index, β_{req}.

Example 5.9 (Reliability of metal bar, continued).

For the metal bar the requirement of the reliability index was set to $\beta > \beta_{req} = 3.4$. *Since* $\beta = 2.75$, *which is less than the requirement, and some improvement actions are needed.*

In addition, if it is assumed that the difference $\ln(S_{nom}) - \ln(L_{nom})$ is normally distributed, the reliability index can be converted to a probability of failure. However, such relations are highly doubtful, since the assumption of normality is usually nothing but a guess for such low probabilities of failure that are usually the result of high requirements on β.

The relation between the reliability index and a safety factor is just a mathematical transformation, namely

$$\gamma_\beta = \exp(\beta_{req} \cdot \tau). \tag{5.34}$$

Reliability engineering properties that are subjects to safety factors are often best modelled in the index as their logarithms.

Example 5.10 (Reliability of metal bar, continued).

The required safety margin can be back transformed to a safety factor by taking the exponential $\gamma_\beta = \exp(\beta_{req} \cdot \tau)$. *For the metal bar the required safety factor becomes*

$$\gamma_\beta = \exp(\beta_{req} \cdot \tau) = \exp(3.4 \cdot 0.23) = 2.19, \tag{5.35}$$

using the required reliability index $\beta_{req} = 3.4$, *and the uncertainty* $\tau = 0.23$.

5.7.2 The Extra Safety Factor Approach

The doubtfulness of probabilistic interpretations of high reliability indices does not remove the need for safety margins to rare events. Therefore, high reliability indices must be used and the corresponding probabilities are regarded not as failure rates, but rather as notional values for comparisons. Here we advocate an alternative to this notional value of probability that may be interpreted as an application of the Shewhart idea of distinguishing between chance and assignable causes, (Shewhart, 1931).

The margin is thus preferably subdivided into two parts. The first part is related to the statistical properties of all possible uncertainty sources. This part is called the *statistical safety margin,* δ_S, and is found by the enhanced or probabilistic VMEA procedure. The second one is related to unknown and extreme events and chosen by engineering experience combined with judgement about the severity of risk, i.e. the likelihood of detrimental rare events and the consequence of failure. We denote this part the *extra safety margin,* δ_E. The reliability target can then be formulated as

$$\ln(S_{nom}) - \ln(L_{nom}) > \delta_S + \delta_E, \tag{5.36}$$

where the two terms on the right hand side represent the statistical and the extra safety margin, respectively, and the strength and load properties are represented by their nominal values.

By taking anti-logarithms of the properties, the margins transform to *safety factors*,

$$\frac{S_{nom}}{L_{nom}} > \exp(\delta_S)\cdot\exp(\delta_E), \tag{5.37}$$

and thus the resulting *total safety factor* is a product

$$\gamma = \gamma_S \cdot \gamma_E = \exp(\delta_S)\cdot\exp(\delta_E). \tag{5.38}$$

5.7.2.1 The Statistical Safety Factor

The result from the probabilistic VMEA procedure is an estimate of the *standard deviation for the target variable*, τ, and the statistical safety margin is defined to be

$$\delta_S = 1.64\cdot\tau, \tag{5.39}$$

and the fulfilment of the reliability target

$$\ln(S_{nom}) - \ln(L_{nom}) > \delta_S, \tag{5.40}$$

corresponds to approximately 95% probability of survival. This approximation is justified by the statistical *central limit theorem* which can be assumed to hold good enough for such a moderate choice of survival probability.

Example 5.11 (Reliability of metal bar, continued).

For the metal bar the statistical safety factor becomes

$$\delta_S = 1.64\cdot\tau, = 1.64\cdot 0.23 = 0.377, \tag{5.41}$$

and the corresponding statistical safety factor becomes

$$\gamma_S = \exp(\delta_S) = \exp(0.377) = 1.46. \tag{5.42}$$

5.7.2.2 The Extra Safety Factor

For a normal engineering design a 95% probability of survival is not sufficient and the statistical safety distance need to be completed by an additional distance for larger safety. However, since the knowledge about rare events that represent the tail in the statistical distribution is too weak to be given a probabilistic measure, we construct an extra safety distance based on *engineering judgement*.

The magnitude of this extra factor must be very specific for each application and should be based on 1) the expected consequences of failure, with the largest values for structural designs that put human life in hazard and 2) the engineering judgement of the likelihood of rare detrimental events like human mistakes and environmental catastrophes. Table 5.6 gives extra safety distances, δ_E, and corresponding factors, γ_E, for strength/load that can be used as an overall guideline. The table is inspired by the Joint Committee on Structural Safety, (JCSS, 2001), that gives guidance on determining the required safety index, β_{req}.

Table 5.6: Extra safety distance/factor.

Likelihood of detrimental rare events	*Consequences of failure*					
	Minor		*Moderate*		*Large*	
	dist.	***factor***	*dist.*	***factor***	*dist.*	***factor***
Small	0.41	**1.5**	0.47	**1.6**	0.59	**1.8**
Normal	0.59	**1.8**	0.74	**2.1**	0.83	**2.3**
Large	0.74	**2.1**	0.83	**2.3**	0.92	**2.5**

Example 5.12 (Reliability of metal bar, continued).

For the metal bar, its application was judged to represent a small likelihood of rare events but a moderate consequence of failure, thus, using Table 5.6 as a guideline, the extra safety distance becomes $\delta_E = 0.50$ *, and extra factor becomes becomes* $\gamma_E = \exp(0.5) = 1.65$ *. The requirement of the total safety margin is*

$$\delta_{req} = \delta_S + \delta_E = 0.877, \tag{5.43}$$

which is larger than the actual margin of 0.632 from Example 5.8, and thus some improvement actions are needed.

If the target function is formulated by means of fatigue life, the distances in Table 5.6 need to be multiplied by a factor corresponding to the Wöhler exponent, which can be assumed to be three in the case of pure crack growth and larger otherwise.

The formula for converting the extra safety factor in load to extra safety factor in life is based on the Wöhler curve. More precisely, assume a log-log relation between stress and life (Basquin equation):

$$N = \alpha \cdot S^{-k}. \tag{5.44}$$

where k is the Wöhler exponent. Say that the safety factor in stress is

$$\gamma_{E,stress} = \frac{S_\gamma}{S}, \tag{5.45}$$

and the safety factor in life is defined as

$$\gamma_{E,life} = \frac{N}{N_\gamma}. \tag{5.46}$$

Then using the Basquin equation we get

$$\gamma_{E,life} = \frac{N}{N_\gamma} = \frac{\alpha \cdot S^{-k}}{\alpha \cdot (\gamma_{E,stress} S)^{-k}} = (\gamma_{E,stress})^k, \tag{5.47}$$

and by taking the logarithm the extra safety distance for life becomes

$$\delta_{E,life} = k \cdot \delta_{E,stress}. \tag{5.48}$$

5.7.2.3 In Summary

The extra safety factor approach adjusts the Cornell approach by demanding that the *safety distance*, the difference between log strength and log load, should be larger than the sum of two safety distances, 1) 1.64 times the estimated standard deviation and 2) an extra distance based on engineering judgement. By taking anti-log of this criterion we arrive at a *safety factor* that is the

product of the anti-logs of the two safety distances.

5.8 Improvement Process

An important part in the design process is the improvement stage, where the VMEA can be of help for identifying areas of improvement and evaluating their potential effects. Typical improvement measures involve:

- **Tolerances:** A part of the detailed design phase is to set the tolerances. The VMEA can help to identify tolerances that give a large impact on the total uncertainty, and thus are aspirants for improvements by tightening the tolerance. On the other hand, there may be tolerances that are set too tight and could be relaxed without giving an impact on the total uncertainty. A systematic process for tolerance design is given by (Taguchi, 1986).
- **Strength models and testing:** If the uncertainty in the strength is large, it can be motivated to perform tests on the specific material or component or system. One such typical case is when the material data is obtained from literature of a similar material compared to the one that is used. This can be especially valuable for reducing the uncertainty in the fatigue evaluation, where empirical model need to be used. Often fatigue data are taken from standards, literature or data sheets, and the conditions typically does not exactly match the actual situation. Therefore, especially for safety critical component, a targeted test is often performed to assess the fatigue properties. To get the best results, tests should be performed on component level rather than on material level, and the load conditions should reflect a real load condition rather than being a constant amplitude load.
- **Numerical modelling and calculations:** The calculation from environmental loads to local loads involve numerical modelling by simplifying the physical system and and to numerically solve the mathematical problem. These two problems should be separated.
    - The numerical modelling is a simplified representation of the physical phenomenon that are under study, and thus there is a need for model validation. This can involve a validation experiment where the local loads are measured for known environmental loads. The validation tests can be a way to assess the modelling uncertainty, but of cause also a help in the improvement process of the numerical modelling.
    - The numerical calculations often involve dynamic simulation and/or FEM to assess the local loads. An option can be to improve the numerical calculations by refining the numerical calculations. By making an experiment the numerical calculations can be verified and calibrated
- **Suppliers:** Sometimes the uncertainty source representing the batch or supplier variation is large. A way to reduce the batch variation can be to set higher demands on specification or quality of the supplier. Another possibility can be to limit the allowed suppliers to ensure a stable quality. This would reduce the between supplier variation.
- **Load measurements:** Often the loads constitute a large part of the uncertainty. There are typically three levels of loads: 1) environmental loads, 2) forces on systems or components, and 3) local stresses on hot spots of the components. Depending on where the weakest link in the uncertainty analysis is, different load measurements need to be performed. If the wave climate at the site (or potential sites) has not been assessed in detail, site measurements of the wave, current and tidal can be an option. Measuring forces and local stresses on systems or components can be of much help to establish the actual load response on systems and components. This is especially important for validation of numerical models and calibration of numerical calculations, as described above.

- **Operational conditions:** If the loads are generally too high or if the variation in loads are too high, it could be motivated to control the loads in some way. There can be a substantial variation the environmental load conditions depending on the site where the MECs are placed. In order to reduce this variation it could be motivated to limit the allowed use of the MEC. Another possibility would be to adjust the control of the MEC to reduce the load on the system or component.

5.9 Application to a Mooring Line

A mooring rope for a buoy must withstand the largest possible wave in service. The model for the limit state is given by modelling the force on the rope caused by a certain significant wave hight and compare this with the ultimate strength of the rope. The limit state is given as the dimension of the rope that makes the largest wave force equal to the ultimate tensile strength of the rope. For the mathematical description of the limit state we use the logarithms of load and strength and intend to find a proper *safety distance* between 'log strength' and 'log load'. This distance corresponds to a *safety factor* representing the dimensionless quotient between strength (Newton) and load (Newton).

A mooring rope for a buoy must withstand the largest possible wave in service. Uncertainties that have to be taken into account are

- uncertainty in the assessment of the largest significant wave height that will occur in service,
- random variation in rope strength,
- possible model errors in the transfer model between significant wave height and rope force,
- possible difference between specified and true rope strength,
- possible environmental effects on the rope strength, not covered in the reference tests,
- possible model error in the degradation model for the rope.

5.9.1 Evaluate Sensitivity and Size

The next step is to evaluate the sizes of the uncertainties and their sensitivities to the limit state function (or target function), which is often performed in parallel. Here, exemplified by the case study.

A study was performed 2014 for a typical critical wave power component, namely the rope that connect the buoy with the energy converter, see (Svensson & Sandström, 2014) . The steel wire rope solutions was evaluated in certain detail and a probabilistic VMEA was evaluated. The limit state is here defined as the difference between the natural logarithm of equivalent strength[4] and the natural logarithm of equivalent load. The result is seen in the table below, where the median load and strength are calculated based on nominal estimated values and uncertainty contributions from different sources can be seen in the blue area to the right. Since the limit state is defined as a natural logarithm, the standard deviations can be directly interpreted as relative uncertainties, i.e. the standard deviation of 0.1 in strength corresponds to the uncertainty of 10% in MPa. The result in Table 5.7 will serve here as a demonstration of the VMEA procedure and each number be shortly explained below.

4 Equivalent load and strength are defined according to a theory for variable amplitude fatigue, see details in the references.

Table 5.7: Probabilistic VMEA for steel wire.

Load-Strength Evaluation for a wave power component

Steel wire connection between buoy and energy converter — Thomas Svensson, 2013
Target life: One year.

Evaluation of Uncertainties

Input						Result		
Uncertainty components	Scatter	Uncert.	Sensitivity coeff cient c	t-correction factor t	standard deviation s	Scatter	Uncertainty	Total
Strength								
Strength scatter	x		0,208	1,060	0,540	0,119		
Statistical uncert. strength		x	0,208	1,000	0,200		0,042	
Adjustment uncertainty CA/VA		x	0,208	1,000	0,100		0,021	
Reference data relevance		x	1,000	1,000	0,100		0,100	
Mean value influence		x	1,000	1,000	0,050		0,050	
Labaratory uncertainty		x	1,000	1,000	0,029		0,029	
Total Strength uncertainty						**0,119**	**0,125**	**0,172**
Load								
Pool measurements, scatter	x		1,000	1,300	0,040	0,052		
Scaling		x	1,000	1,000	0,012		0,012	
Distribution of Hf		x	1,000	1,000	0,014		0,014	
Model uncertainty		x	1,000	1,000	0,023		0,023	
Friction		x	1,000	1,000	0,029		0,029	
Total Load uncertainty						**0,052**	**0,041**	**0,066**
Wöhler Exponent		x	0,200	1,000	0,500		0,100	
Total Exponent uncertainty						0,000	0,100	**0,100**
Total uncertainty						**0,130**	**0,165**	**0,210**

Reliability Evaluation

wire diameter (mm) 110

Input		Result	
Median strength [MN]	2,25	Safety factor	1,41
Median Load [MN]	1,60		

Result (log-scale)	
Strength, mS	0,81
Load, mL	0,47
Distance	0,34

Evaluation - Extra safely factor		Variation safety factor	1,41
Required extra safety factor	1	Extra safety factor	1,00

Variation dist.	0,34
Extra dist.	0,00

The strength uncertainty is represented by the first six rows,

1. ***Strength scatter*** is a measure of the expected scatter of fatigue strength in steel wire ropes. A numerical estimate of the life scatter was found in literature to be 54%, which is found in the column for standard deviation in the table. This estimate was based on a limited number of observations (24), which add some uncertainty to the estimate, evaluated as a *t-correction factor*[5](1.06), given in the preceding column. The scatter is measured by means of fatigue life and the sensitivity for fatigue strength is then the reciprocal of the S-N curve slope: 0.208, see the reference for details.
2. ***Statistical uncertainty*** is the the uncertainty of the nominal value for fatigue strength. The uncertainty of such a nominal value is usually calculated by means of standard statistical theory and is typically equal to the scatter uncertainty divided by the square root of the number of experimental observations. However, in the actual case the nominal fatigue life

5 The statistical t-distribution is here used in a standardised way: the correction value is chosen as the ratio between the 5% quantile in the t-distribution for the actual number of observations and the quantile for infinitely many observations.

was found from another source and its uncertainty judged to be 20%.

3. ***Adjustment uncertainty CA/VA*** is an estimate of the possible model error that is introduced by using the Palmgren-Miner damage accumulation rule when using a Constant Amplitude (CA) Wöhler curve to predict Variable Amplitude (VA) life. The given number is a rough judgement based on consideration of common adjustments for this model uncertainty in engineering practice.
4. ***Mean value influence*** is another possible model error source. For steel this is usually not a serious source of uncertainty and is here judged to be around 10%.
5. ***Reference data relevance***. The data for the steel wire fatigue strength was found in the open literature and may deviate for the specific wire to be chosen. An uncertainty of 10% was therefore added here.
6. ***Laboratory uncertainty*** is the possible difference between the service environment and the reference test laboratory environment. The components under study will be used in salt water and parts of the rope will be used in the vicinity of the sea surface, which could be expected to be a very aggressive environment. The strength curves that we have used are established in laboratory for sea conditions and should to a certain extent reflect the aggressive environment. Still there is an uncertainty for the equivalence between laboratory conditions and service which was judged to be maximum 5% in load. This judgement is regarded as representing the limits for a uniform random variable and its standard deviation is calculated by the division by the square root of three.

The load uncertainty components are summarised in the next five rows:

1. ***Pool measurements, scatter***. No load measurements in service were available at the time for the investigation, but scaled experiments had been performed by artificial waves in a tank. Assuming that the observed scatter in these experiments corresponds to the scatter in service environment we found the scatter to be 4%. Since this is based on only a few experiments it is multiplied with at quite large t-factor.
2. ***Scaling and experimental equivalence***. The scale factors used, the Froude scale factors, are judged to be sufficiently accurate, but the artificially generated waves differ of course from waves in service. The uncertainty in load due to this influence is judged to be max 2%, which by assuming uniform distribution corresponds to the standard relative uncertainty 1.2%.
3. ***Distribution of significant wave heights***. The estimate of future service environment may be in err, judged to add 1.4% uncertainty.
4. ***Model uncertainty***. In order to calculate the equivalent load for other sea states than the ones measured, we used a simple linear model with an calculated model error of 17%. However, since our overall equivalent load is based on a large range of sea states, this model is assumed to be averaged out to a large extent. An indication of how large it could be is found by calculating the error if only the observed cells are used. We then find a deviance between model overall load and actual overall load of 4%, which we use directly as a maximal uncertainty component.
5. ***Friction***. The force measurements in the experiments are not taken immediately next to the buoy, but a wheel influenced by friction disturb the measures. The influence of this is not available at this stage. Therefore we must add an uncertainty for the frictional influence, which is roughly judged to be max 5%.

Since both the equivalent load and the equivalent strength used here depends on the estimated Wöhler exponent, the uncertainty of this property is treated separately. The nominal value of the

exponent was found in the DNV standard to be 4.8 which was judged to be uncertain within an interval [4.35;5.25] and the corresponding standard deviation is calculated assuming a uniform distribution within this interval. The sensitivity coefficient is calculated based on the theory of equivalent strength/load, see the reference for details.

5.9.2 Evaluate Prediction Uncertainty and Reliability

For the case study shown in the table above, the total uncertainty is calculated by first adding the uncertainty measures from all source quadratically and then take the square root of the result. In the actual case this total uncertainty is estimated to 0.210. The statistical safety distance is then calculated as 1.64 times this number giving the distance 0.34.

The nominal estimates of strength and load, are 2.25 MPa and 1.60 MPa, respectively. The natural logarithms of these two values are 0.81 and 0.47. The difference is 0.34 and equals the statistical safety distance. Thus, in this case there is no extra safety distance and the design is not safe enough.

The next step is to study the table above in order to find uncertainty sources that may be reduced by further investigations. It can be seen that the three dominating sources are 1) the strength scatter and uncertainty due to 2) the reference data relevance and 3) the Wöhler exponent. Since the Wöhler exponent is also reference data, it can be seen that the total uncertainty can be reduced by specifying wire rope quality and perhaps arrange laboratory wire tests. Once the uncertainty sources are reduced enough to make the unavoidable scatter dominating, the VMEA analysis can be regarded as finished.

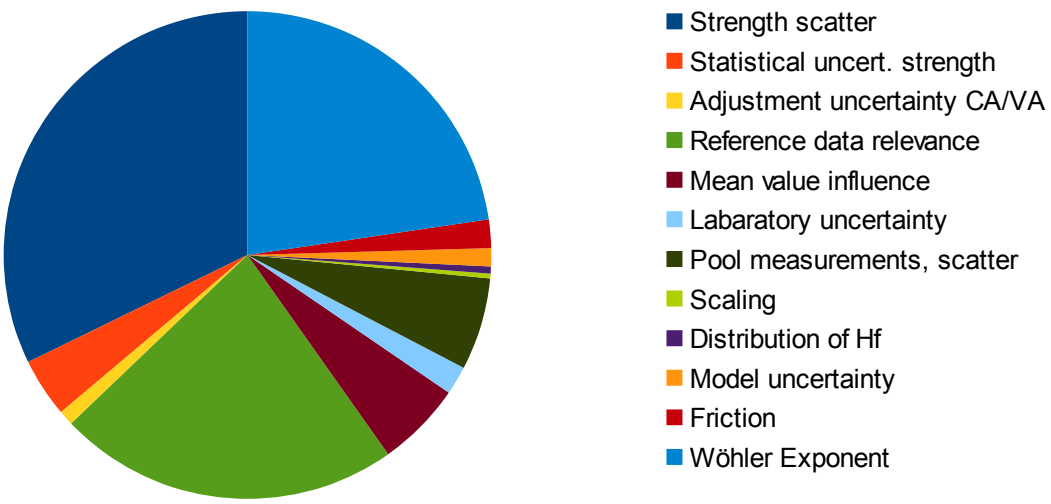


Figure 5.2: Probabilistic VMEA for steel wire; Pie chart of uncertainty contributions.

6 VMEA in Structural Methodology Analysis

The harsh conditions at the ocean surface where WECs and TECs are deployed lead to many irregular large load cycles being placed on their primary structures. The reliability target for developers is a design that can withstand environmental conditions during the lifespan of the device. These unusual load conditions, combined with novel technologies, lead to a high degree of uncertainty in the design process and associated variability in durability calculations.

6.1 Failure Mechanisms and Critical Structural Members

Possible failure mechanisms that need to be considered are

- *Immediate failure* caused by exceedance of material ultimate strength
- *Fatigue failure* caused by repeated mechanical loads below the ultimate material strength

Both mechanisms depend on 1) material strength in hot spots in the structure and 2) external forces caused by the intended conversion of wave or tidal water movements to energy.

The strength may change during usage by

- *corrosion*, changing load carrying material content and geometry,
- *wear*, changing load carrying material content and geometry,
- *marine growth*, reducing strength and causing changed mechanical behaviour.

Both mechanisms must be subjects to reliability investigations.

For the immediate failure case the ultimate strength of critical members must be investigated against the largest expected force. This largest force should be quite well known for tidal based energy devices, but for wave based devices it is difficult. Approximate assessments of extreme events must be considered.

For the fatigue failure case there are mainly two actual methodologies: 1) Design against the fatigue limit, where critical members are designed against external loads so as to guarantee that the outer forces do not cause stresses or strains that exceed the actual fatigue limit. 2) Design against fatigue life, i.e. against a predefined life for the device, possibly combined with inspection intervals. In both cases the reliability issue may be formulated by means of a load/strength formulation:

$$Strength > Load\ , \tag{6.1}$$

where both the strength and load are not known exactly at the design stage and the uncertainty regarding their values must be taken into account in the design by introducing a safety factor when determining the required strength

$$Strength \geqslant Load \cdot SF\ . \tag{6.2}$$

6.2 The Probabilistic VMEA Procedure

The probabilistic VMEA methodology is one method to calculate a proper safety factor which is a probabilistic approach that regards “Strength” and “Load” as random properties. In order to take advantage of powerful mathematical/statistical tools these random properties are usually transformed to their logarithms, the random variables $\ln(S)$ for the strength and $\ln(L)$ for the load. The reliability target then transforms to

$$\ln(S) - \ln(L) \geqslant \delta_{req}\ , \tag{6.3}$$

where δ_{req} is the logarithm of the safety factor, i.e. $\delta_{req} = \ln(SF)$. The difference in the left hand side of this inequality is then studied as a random variable in the VMEA analysis. Its expected (or nominal) value is found as the result of the ordinary engineering analysis, using nominal values as inputs. Its uncertainty is calculated by means of its standard deviation in a statistical sense by pooling the uncertainties caused by all input variations and possible errors. This standard deviation is multiplied by the number 1.64 to obtain the statistical safety margin:

$$\delta_S = 1.64 \cdot \tau, \tag{6.4}$$

where δ_S is the statistical part of the safety margin to be completed by an extra margin based on other considerations than statistics, and τ is the uncertainty (by means of a standard deviation) calculated from all input variations and possible errors. This margin is constructed to represent approximately 95% survival probability and an extra safety margin must be added as a complement:

$$\ln(S) - \ln(L) \geqslant \delta_S + \delta_E, \tag{6.5}$$

where δ_E is the extra safety margin.

6.3 The Basic and Enhanced VMEA Procedure

In order to get an overall picture of the uncertainty sources in the design process it may be useful to prepare the detailed probabilistic analysis by performing a *basic VMEA*. The result from such an analysis is a qualitative picture of the influence of different uncertainty sources which points out sources that must be further investigated and put priorities to different subject for further analysis.

When a preliminary design is established, the basic VMEA can be transformed to an *enhanced VMEA*. Then the comparison scores from the basic VMEA are translated to approximate percentage variation in strength and load respectively. These percentage variation should represent standard deviations, and can then be pooled to the overall uncertainty to get a preliminary safety margin. This enhanced VMEA should be seen as an initial probabilistic VMEA, and after possible design changes, it can be refined to a probabilistic one for reliability assessments.

6.4 The Structural Strength Application

For the case of designing for *immediate failure* or *fatigue limit* the strength is usually the ultimate tensile stress or the fatigue limit stress, measured in the unit MPa. The load is the expected stress in a hot spot in the structure caused by constraints of wave and tidal movements. Typical structural members that need to be designed for immediate failures include mooring members, such as, chains, wires or lines, and connecting members, such as, shackles. Members that typically need to be designed against fatigue limit are bearings, gears and other parts with smooth surface finish.

For the case of fatigue life design the *strength* must be related to a specified life for the device in question. This life, often measured in years of usage, must be translated to load cycles and then, by using a fatigue strength diagram, such as a Wöhler curve, transformed to a fatigue strength, measured in the unit MPa. The *load* is varying during the life and must therefore be transformed to an equivalent load, usually by using the Palmgren-Miner rule for fatigue damage summation. Structural members that typically are subjected to fatigue life design includes, as for immediate failures, chains, wires lines, and shackles, but also welded parts and structural members with sharp notches or with possible detrimental internal defects.

A schematic description of a typical life assessment for a MEC is demonstrated in Figure 6.1, where it is exemplified for fatigue life evaluation. The steps are:

1. *Marine loads assessment* – Evaluate the input loads to the device, typically it is environmental loads such as waves, currents and wind, but it can also be internal loads from the drive train or electrical system.
2. *Hydrodynamic model: Loads to forces* – Evaluate forces on systems or components from the input loads, typically this involves a hydrodynamic model for simulating the motions of the device, preferably in combination with measurements of input loads and forces to validate the simulation model.
3. *Structural model: Forces to stress* – Evaluate local loads and identify hot spots of the construction, for mechanical stresses typically using FEM, preferably in combination with measurements of forces and stresses to validate the numerical model.
4. *Fatigue life model: Life assessment* – Evaluate the life of the component or system under investigation, e.g. using a Wöhler curve model and damage accumulation in the case of fatigue life evaluation, preferably in combination with fatigue tests to validate the model.

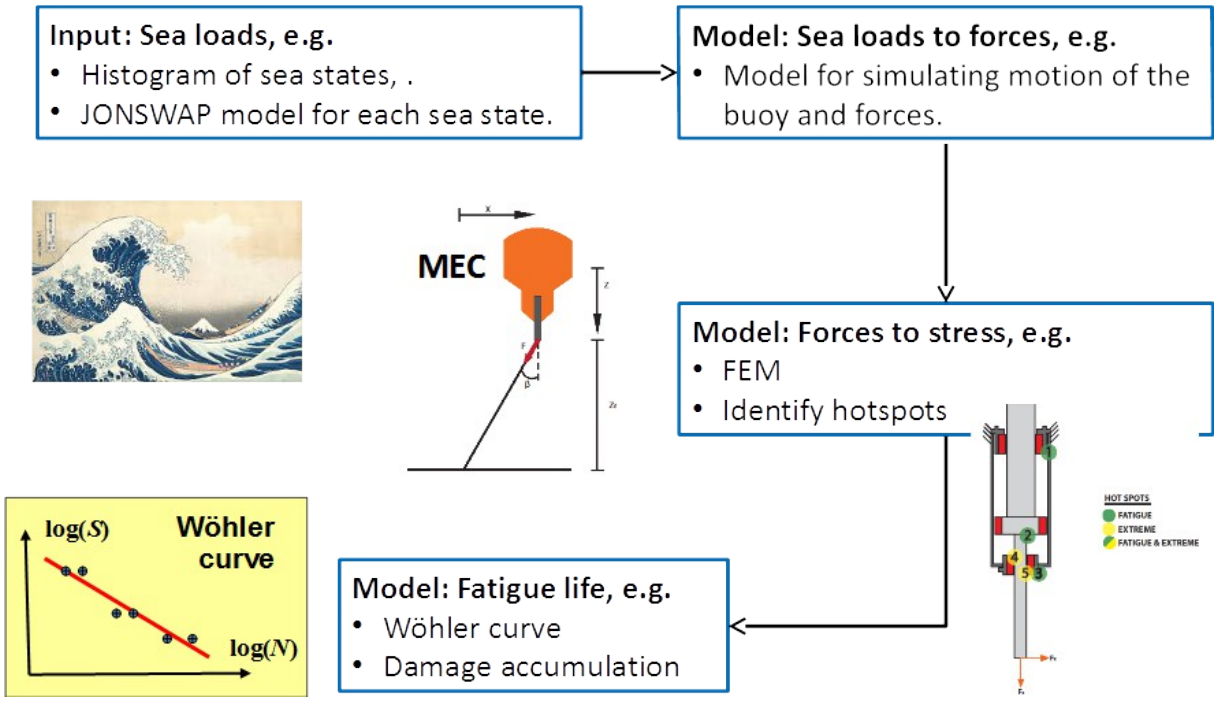


Figure 6.1: Typical life assessment for MECs.

6.5 Check List of Uncertainties

All steps in the life assessment involve scatter sources (random variation) or introduce uncertainties in terms of, for example, estimation of parameters or possible model errors. Based on the scheme in Figure 6.1, a list of typical uncertainty sources, that usually need to be considered in the VMEA work, is presented in Table 6.1. Of course, for each specific design case there may be other sources that need to be considered.

Table 6.1: Check List of Uncertainties

Uncertainty components	Scatter	Uncertainty
Marine Loads:		
- Between and within site variation	x	
- Load estimation uncertainty		x
Hydrodynamic model:		
- Hydrodynamic model errors		x
- Hydrodynamic model parameter uncertainties		x
- Geometric tolerances	x	
- Marine growth		x
Structural model:		
- Structural model errors		x
- Structural model parameter uncertainties		x
- Geometric tolerances	x	
Fatigue life model:		
- Strength/life scatter	x	
- Life model error		x
- Life model estimation uncertainty		x
- Damage accumulation model error		x
- Multi-axial effects		x
- Corrosion effects		x

6.6 Case Study: VMEA for a Piston Rod in a Wave Energy Device

We study a case taken from the early development process of a a wave energy device from CorPower Ocean. This specific device contains a piston rod mounted inside a buoy and mechanical wave induced forces are expected to cause severe stresses at some critical hot spots in the piston rod. In Figure 6.2 a principal sketch is given to illustrate the case. The piston rod connects the mooring line with the energy transformation device and the movements of the buoy induce tensile and bending forces through the connection to the mooring line.

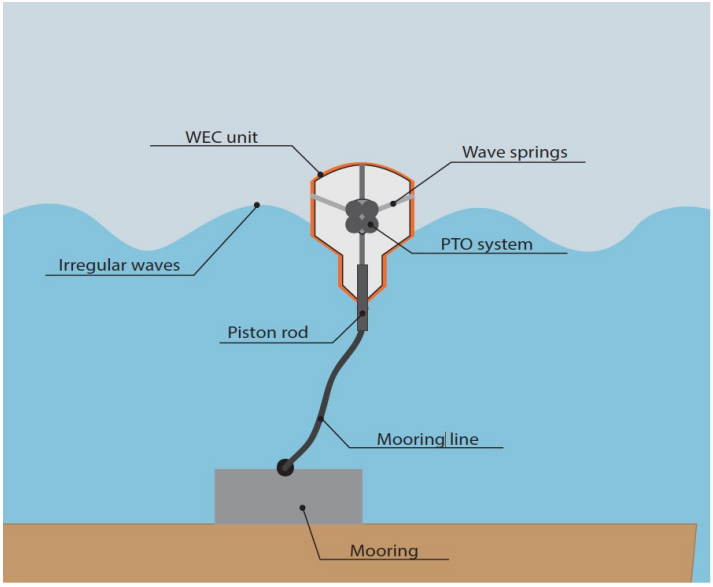


Figure 6.2: Illustration of the position of the critical piston rod.

In (Gustafsson, 2016), an analysis is performed to find the nominal fatigue life of the piston rod. The main engineering tools in this analysis are 1) a hydrodynamic numerical tool, 2) a finite element numerical tool and 3) a fatigue model. Here we will review this analysis in order to find proper safety factors for the design.

In order to analyse the nominal fatigue assessment with regard to safety we use the VMEA methodology, in this case starting with a basic VMEA for identifying the largest uncertainty contributions. This analysis is in the next step refined and quantified to a enhanced VMEA, which can be used to find a first preliminary assessment of the reliability of the device.

6.6.1 A Strength Calculation Overview

Figure 6.3 illustrates the engineering calculation procedure. Standard tools are used to reduce the expected service wave behaviour to significant wave heights and wave periods. These number are then used to generate synthetic JONSWAP wave spectra that should represent future external service waves. A hydrodynamic numerical tool, implemented in Matlab/Simulink, is used to get the corresponding time series of forces in horizontal and vertical directions, see Figure 6.4.

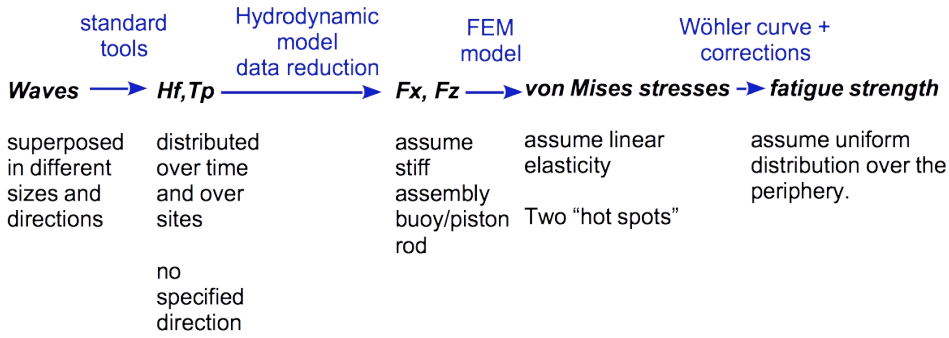


Figure 6.3: The evaluation procedure for fatigue strength and the piston rod.

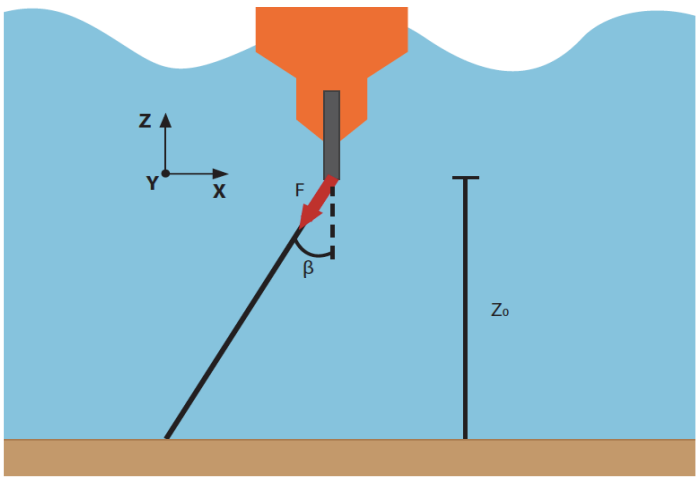


Figure 6.4: Schematic picture of the external forces acting on the piston rod.

In the next step a finite element model of the piston rod is used to find the internal stresses in hot spots. The multidimensional stresses at each spot are transformed to one, using the "von Mises" transformation. See Figure 6.5 for the location of the two hot spots found for possible fatigue failure.

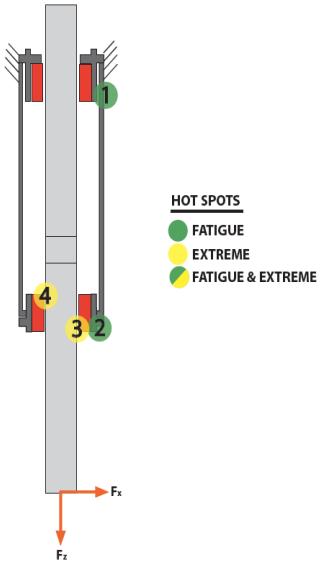


Figure 6.5: Schematic picture of the piston rod with fatigue hot spots in green.

6.6.2 Uncertainty Sources

A discussion related to the procedure described in Figure 6.3 points out the possible sources of error and scatter.

In the first step, the wave reduction to significant wave numbers, the complex wave behaviour superimposed from different directions, shapes, periods and heights are measured and simplified. And these simplifications are then transformed to synthetic wave spectrum to be used as input to the hydrodynamical model. This means that measurement and model errors are introduced that need to be considered.

Also, sampling errors are introduced, since measurements have been performed at specific places at certain specific times at sea, while the future locations of the energy device and future weather conditions are unknown.

One may also expect a variation of wave behaviour both within a site and between different sites.

In the second step, the synthetic wave spectrum is transformed to a time series of forces, using a numerical hydrodynamical model. Apart from the wave spectrum also the outer geometry of the buoy and the mooring line constraint are necessary inputs, both with possible errors. Also, future marine growth may change geometry and friction to new unknown conditions.

A large uncertainty in this specific case is the connection between the piston rod and the mooring line. This detail is not yet fully developed for the device, and has a large influence on the force distributions.

Another possible error introduced in this specific case is data reduction bias. Namely, to reduce the computational timed in the finite element program, the force time series must be reduced in length.

The third step, transforming the forces to stresses in critical locations, introduces new possible model errors. The finite element model is a quite rough simplification in this case, in particular since items like bearings and threads are approximated as solid elements.

Also, interpolation errors may be present, since the finite element calculations are performed only at three different positions of the piston rod. Namely, the vertical movement of the piston rod changes

the bending moment caused by the horizontal forces. This dynamics is not included in the finite element simulation, but found by interpolation of the high, low and mid positions.

In the fourth step the fatigue damage is assessed from the von Mises stresses at the critical positions. This is done by comparing the calculated von Mises stresses with a material specification by means of a Wöhler curve. Since the stresses are given as a time series the comparison is done using the Palmgren-Miner damage rule: the time series is transformed to a spectrum of stress reversals by the rain flow count algorithm. The reversals are combined by the Palmgren-Miner rule to an equivalent stress which can be compared to the material specification.

Possible error sources in this step are the relevance of using the von Mises stress for the hot spot, the relevance of the material specification, and possible model errors introduced by using the Palmgren-Miner rule and the Wöhler fatigue strength representation.

Regarding the relevance of the material specification, the available reference curve does not represent a corrosive environment or a thread. In the analysis the effect of corrosion has been taken into account by adjustment with a factor 0.9, which of course may be erroneous.

For the material there is also a scatter in the fatigue strength which must be taken into account.

6.6.3 Basic VMEA

The large number of uncertainty sources makes it relevant to start the VMEA analysis with a basic variant. This type is of a format which is appealing for people who may are experienced with FMEA analyses and minimise the use of statistical and mathematical concepts. The aim of the basic VMEA is to point out which uncertainty sources that should be prioritised in the refinement to an enhanced VMEA.

At a meeting at the CorPower company office, a group of five people “brainstormed” to find the uncertainty sources in the actual design case. After listing the sources, the variation of these sources were judged by scoring 1-10 and their sensitivity to fatigue load or strength was judged also by scoring on the scale 1-10.

As a result, a basic VMEA table could be calculated where the most important uncertainty sources could be identified and be subjects to further investigations, see Table 6.2 below.

The dominating uncertainties can be seen by inspecting the last column in the table:

- Uncertainty in the design (connection solution), 23%
- Model error in hydrodynamic model, 16%
- Variation between sites, 12%
- Influence of threads (stress concentration factor), 12%
- Simplification in the finite element model, 9%
- Fatigue strength specification, 9%.

The basic VMEA can only be used for this type of identifying the most important sources of uncertainty. In order to make reliability conclusions the uncertainties must be quantified, the scores cannot be related to probability of failure. The first step for such a quantification is to make an enhanced VMEA.

Table 6.2: Basic VMEA table.

Input			Result		
	Sensitivity	Uncertainty	Resulting uncertainty	Variation contribution	
Uncertainty components	(1-10)	(1-10)	Uncertainty	VRPN	Propor-tion
Sea loads					
- Estimation of sea states	5	3	15	225	2%
- JONSWAP model	5	3	15	225	2%
- Variation within site	5	2	10	100	1%
- Variation between sites	5	7	35	1225	12%
- Neglected loads (wave direction, current, ...)	2	4	8	64	1%
Total Sea loads			**43**	**1839**	18%
Sea loads to forces					
- Model error, calculation	5	8	40	1600	15%
- Marine growth (increase loads?)	5	4	20	400	4%
- Connection (flexible?)	7	7	49	2401	23%
- System degeneration (may increase forces)	0	3	0	0	0%
Total Sea loads to forces			**66**	**4401**	42%
Forces to stress					
- FEM, stiffness	5	3	15	225	2%
- FEM, simplified model	5	6	30	900	9%
- FEM, mesh	5	2	10	100	1%
- Position (low-mid-high)	5	3	15	225	2%
Total Forces to stress			**38**	**1450**	14%
Fatigue model					
- Fatigue strength, scatter	5	3	15	225	2%
- Fatigue strength, uncertainty	5	6	30	900	9%
- Wöhler slope	2	5	10	100	1%
- Stress concentration factor	5	7	35	1225	12%
- Multiaxial effects	2	4	8	64	1%
- Equivalent load sequence	5	3	15	225	2%
Total Fatigue model			**52**	**2739**	26%
Total uncertainty			**102**	**10429**	100%

6.6.4 Enhanced VMEA

The aim is to find a safety factor for fatigue design of the actual piston rod. The target life is two years in service (730 days). We first formulate the reliability target in logarithmic form:

$$\ln(N_{nom}) - \ln(N_{target}) \geqslant \delta_S + \delta_E, \tag{6.6}$$

where N_{nom} is the nominal calculated fatigue life measured in days, $N_{target} = 730$ is the target life, $\delta_S = 1.64 \cdot \tau$ is the logarithm of the statistical safety factor, the statistical safety distance, and δ_E is the logarithm of an extra safety factor.

From (Gustafsson, 2016), we find the calculated nominal life to be 183 days for point one and 1560 days for point 2. This means that not even the nominal life fulfils the target of 730 days for the most critical point.

6.6.5 Adjustments of Calculated Nominal Life

There are two apparent adjustments that should be done to the first calculated nominal life.

Firstly, the critical points appear in threads but the Wöhler curve used represents the material strength. Using some results from literature we have found that the expected fatigue strength is reduced by factor 2.1, as described below.

Secondly, the three-dimensional effect is not accounted for. Namely, in reality the critical point is not a point, but rather a circumferential line. Assuming a uniform distribution of load along this line reduces the severity at each point with a factor of 0.64, as described below.

Together, these two adjustments give an even worse situation, the nominal lives are adjusted to

$$\frac{183}{(2.1\cdot 0.64)^3} = 75 \text{ days and } \frac{1560}{(2.1\cdot 0.64)^3} = 640 \text{ days, respectively.}$$

These nominal lives are uncertain and in the next section we use the enhanced VMEA procedure to assess the statistical uncertainty in these values.

6.6.5.1 Adjustments of the Fatigue Strength

The fatigue strength used in (Gustafsson, 2016) is a standard curve specified in the used finite element program. This curve represents the actual specified material at tensile load, but in the actual case the critical components are threaded and subjected mainly to bending loads. In order to adjust for this we use a recent experimental study of fatigue strength of threaded fasteners (Wentzel & Huang, 2015). This study was performed on 10.9 M14 bolts. The size of the actual thread is not known, so we simply assume that it is comparable with these M14 bolts.

The results for the threaded bolts gives a Wöhler curve with slope around 3 and the bending fatigue strength at 1 million cycles was 70 MPa. The reference curve used in (Gustafsson, 2016) has the slope 4.1 and the fatigue strength 210 MPa at 1 million cycles. We therefore must adjust the strength with a factor of 3 because of the weakness due to the thread.

In addition the different slopes gives different results for a variable amplitude load and by using one of the reference force signals we find that the Palmgren-Miner equivalent load for the two slopes differs by a factor of 0.7 with the lower value for the slope 3 case.

In total we can conclude that the bending thread case lowers the strength while the lower slope in the thread case gives a somewhat higher equivalent strength. The total adjustment becomes:

The nominal fatigue strength is lowered by a factor 2.1.

6.6.5.2 Random Peripheral Load Distribution

In the CorPower application we study fatigue in a piston rod placed in the centre of the buoy. The most severe contribution to the fatigue stress in the two critical hot spots is the bending stress caused by horizontal forces. These bending stresses are critical at the periphery of the rod which rotates according both to the main wave directions and to internal random rotation within the piston. This means that each stress cycle in the spectrum will act at a random peripheral position and the fatigue damage be spread around the periphery.

We calculate the mean effect of this damage spread by assuming that the angle is random and uniformly distributed. Since we base our fatigue calculations on cycles we only study half the periphery. When the buoy bend in a certain direction each point at the hot spot periphery will obtain

the stress cycle magnitude $F_{max} \cdot \cos(\alpha)$, where F_{max} refers to the stress at the angle zero from the actual direction. We now assume that alpha is uniformly distributed from $-\pi/2$ to $+\pi/2$ and calculate the expected stress:

$$E[F] = \int_{-\pi/2}^{\pi/2} F_{max} \cos(\alpha) \frac{1}{\pi} d\alpha = \frac{2}{\pi} F_{max} = 0.64\, F_{max}. \tag{6.7}$$

This means that the moment generating spectrum that is transformed to a stress spectrum at the periphery of a hot spot should be reduced by the factor 0.64 to account for the distribution of loads over the periphery.

6.6.6 Uncertainty Assessments

The enhanced VMEA analysis is used to find the statistical safety factor by estimating the overall uncertainty τ by means of a standard deviation.

The enhanced VMEA is a first rough approximation of the probabilistic one, where we don't have detailed knowledge about the variation of each source, nor the sensitivity to the target function. Most of the uncertainty components must be based on engineering judgements, which preferably are done directly on the assumed percentage variation in the target function.

In some cases it may be easier to judge about percentage variation in load and then we need a sensitivity coefficient. In case of fatigue, this sensitivity coefficient is simply the Wöhler exponent, which in the present case is assumed to be 3.

First, the sources judged as the most important in the basic VMEA are considered.

Uncertainty in design. The most important source of uncertainty according to the Basic VMEA analysis is in the design, namely the design of the connection between the mooring line and the piston rod. This uncertainty is here left to the future developments and our reliability analysis based on the solution of the rigid connection as used in the reference master thesis work.

Model error in hydrodynamic model. So far, we have no access to measurements for assessments of how large this error could be. Based on the initial discussions we judge that the error in the calculated forces could be as large as 15%, which under the assumption of a uniform distribution gives a relative standard deviation of $0.15/\sqrt{3} = 0.087$. Since the stress in the hot spot is proportional to the external force, the sensitivity to log life is 3.

Variation within and between sites. The scatter within sites is judged to be 2% and between sites 20% by means of load. Using the uniform distribution as above, this gives the relative standard deviations 0.012 and 0.12, respectively.

Simplification in the Finite Element Method. The main concerns here are the modelling of bearings that in the model are defined as rigid objects with no mechanical losses in the contact areas. This may introduce errors in the stress calculation and the possible error is judged to be up to 5%, which divided by the square root of three gives the value 0.029.

Influence of threads and fatigue strength specification. The original calculation was performed without considering the threads in the fatigue hot spots. The nominal life was therefore adjusted according to existing knowledge. These adjustments includes some rough assumptions and the uncertainty due to the adjustments is judged to be up to 20% in fatigue strength giving the standard deviation for log strength: 0.12.

Next, a few additional sources are added after further considerations:

Fatigue scatter. From visual inspection of the scatter diagram in the paper (Wentzel & Huang, 2015), the scatter in life for bending fatigue of threads is approximated to 0.25 in log life.

CA/VA conversion. For the evaluation of the nominal life, the Palmgren-Miner cumulative damage rule is used, which may introduce an error. We assume that it at most is 17% in life giving 10% standard deviation.

Mean value influence. The reference fatigue strength used refers to a laboratory test performed at alternating load, i.e. with zero mean stress. In our application the mean value will vary and its influence is not taken into account in the life calculation. We assume that this also could introduce an error of at most 17% in life, giving 10% standard deviation.

Marine growth. Marine growth on the equipment may cause the properties to change, making the hydrodynamic calculation out of date. This is judged to influence the calculated load at most 5% in load, giving the standard deviation 0.029.

Additional uncertainty sources, such as the used adjustment for corrosion and the simplification of load sequence are judged to be negligible at this stage, but may be considered in a refined design when some of the present uncertainties have been decreased.

In the VMEA table (Table 6.3), the assessments are summarised and evaluated for hot spot number 2. In Figure 6.6, the uncertainty components are illustrated in a pie chart for comparison of their severities.

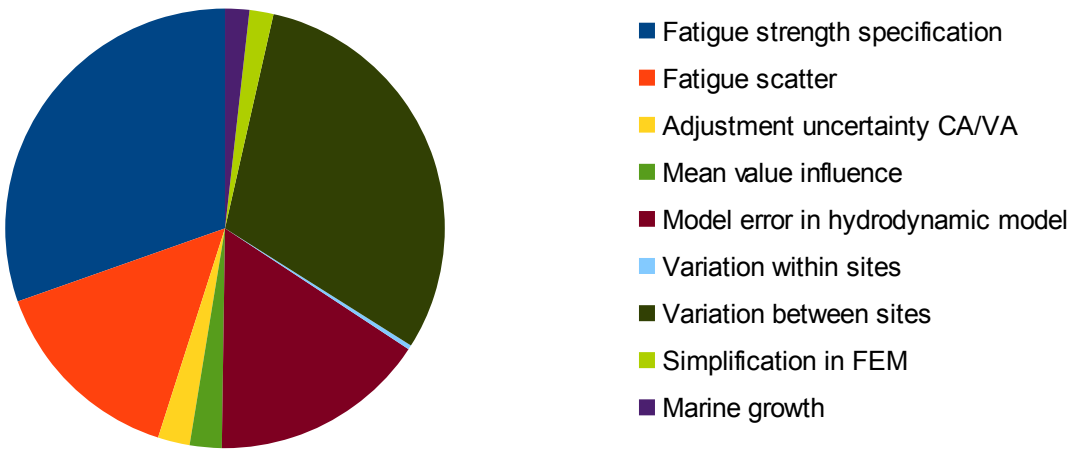


Figure 6.6: Uncertainty contributions for the hot spot fatigue evaluation.

Table 6.3: Enhanced VMEA reliability evaluation.

Input						Result		
	scatter	uncert.	Sensitivity coefficient	t-correction factor	standard deviation			
Uncertainty components			**c**	**t**	**s**	**Scatter**	**Uncertainty**	**Total**
Strength								
Fatigue strength specification		x	3,000	1,0	0,120		0,360	
Fatigue scatter	x		1,000	1,0	0,250	0,250		
Adjustment uncertainty CA/VA		x	1,000	1,0	0,100		0,100	
Mean value influence		x	1,000	1,0	0,100		0,100	
Total Strength uncertainty						**0,250**	**0,387**	**0,461**
Load								
Model error in hydrodynamic model		x	3,000	1,0	0,087		0,261	
Variation within sites	x		3,000	1,0	0,012	0,036		
Variation between sites	x		3,000	1,0	0,120	0,360		
Simplification in FEM		x	3,000	1,0	0,029		0,087	
Marine growth		x	3,000	1,0	0,029		0,087	
Total Load uncertainty						**0,362**	**0,289**	**0,463**
Total uncertainty						**0,440**	**0,483**	**0,653**

Reliability Evaluation

Input		Result	
Median life (days)	640	Safety factor	0,88
Target life (days)	730		

Result (log-scale)	
Life	6,46
Target life	6,59
Distance	-0,13

Evaluation - Extra safely factor		Variation safety factor	2,92
Required extra safety factor	2	Extra safety factor	0,30

Variation dist.	1,07
Extra dist.	-1,20

6.6.7 Reliability Evaluation and Improvements

Since even the calculated nominal life is less than the target it is clear that the design does not fulfil the reliability target. Still we can evaluate the uncertainties to see to what extent the design needs improvement.

The evaluation of the uncertainties results by quadratic summation in a total statistical uncertainty of 0.653 (65% in life), and to be safe to 95% probability of survival the log distance to the target life needs to be $1.64 \cdot 0.653 = 1.07$. This distance is transformed to the statistical safety factor $e^{1.07} = 2.92$. The actual nominal total safety factor is $640/730 = 0.88$.

Since the design not even is reliable to 95% probability, the extra safety is far less than one showing that the design is far from reliable.

The corresponding analysis of the second fatigue hot spot, number 1, is not shown here. It has the same uncertainty and the same required statistical safety factor. The actual safety factor in that case is only 0.1.

The enhanced VMEA suggests that the design is far too weak for the assumed conditions. This is of course an important result in the ongoing design process which probably now must find a design that diminish the bending stresses caused by the horizontal forces at the connection.

Still, the large uncertainties may also be subjects to consideration at this stage since some of them probably will remain in a new design.

The largest contribution is the assumed variation between sites. This is an important source that will demand large safety margins if the wave energy device is designed for any possible sea location. One possibility is to make measurements at many locations and possibly obtain a more accurate estimate of the true variation than the actual rough guess. Another possibility to make this contribution smaller could be to have a flexible design that can be adapted to different locations. For example, say that we classify the sites in terms of the severity of the wave climate. Then it is reasonable that the scatter between sites within a class can be reduced from 12% to 4%, which in turn will reduce the total uncertainty from 0.653 to 0.558.

The second largest contribution is the possible error in the hydrodynamic model. This may be reduced by measurements in service for calibrating the model and diminish model errors.

The fatigue strength specification is also an important uncertainty contribution in this case mainly due to lack of knowledge about the stress concentration because of threads at the hot spots. This uncertainty can be diminished by refinement of the analysis in combination with proper strength specifications.

Simplifications in the finite element analysis, beyond the threads considered above, are mainly the lack of proper modelling of bearings that by refined analysis could be less uncertain.

The strength scatter is probably not possible to reduce, but should rather be seen as an unavoidable source of uncertainty that ideally should be the dominating one.

6.6.8 Conclusions

The assessment of the fatigue life of this piston rod in service showed that the design is too weak and improvements are necessary. The basic VMEA analysis pointed out the most important sources of uncertainty in this assessment and the enhanced VMEA analysis refined and quantified these uncertainties to a reliability measure in terms of total uncertainty that was converted into a safety factor for design.

Clearly, the design needs large improvements in terms of reduced stresses at hot spots and/or increased strength. However, also the knowledge on, for example, wave load input, hydrodynamic models, FE models and fatigue models, needs to be increased in order to decrease the demand for large safety factors.

7 Electrical Methodology

7.1 Introduction

A typical marine energy converter can largely be split into four sections:

- Energy capture section
- Energy conditioning section
- Electrical generation section
- Power conditioning section

Figure 7.1 shows a simplified tidal turbine functional block diagram. The main components in the energy capture section are blades, pitch system and hub in this case, which transforms primary wave or tidal energy into kinetic motion. In non-direct drive configurations of Figure 7.1, gearboxes are used in the energy conditioning section. The aim of this energy conditioning system is to increase the slow rotor angular velocity to a sensibly high rotating speed for rotary generator within the electrical generation section in the rotary drivetrain configuration.

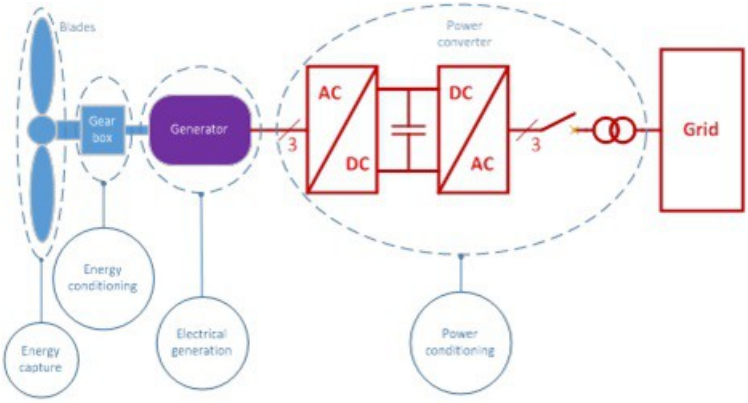


Figure 7.1:Sections defined in a conventional tidal energy converter.

Considering the intermittence and variable nature of wave and tidal, energy production will have fluctuating profile which eventually would result in voltage and frequency fluctuations in the generator outputs. In the direct grid connected systems, such fluctuations would cause the electrical generator toggling between “overload” and “motoring” modes. Therefore, a power conditioning state is required for the turbine interfacing to the grid.

Most widely used power converters are the three-phase four quadrant converters. These converters are configured with an AC/DC generator side rectifier, a DC/AC grid side inverter and a DC coupling. The first AC/DC rectifying variable voltage and current from the generator into the DC link in conjunction with the pitch control system to maximise the power tracking and minimises overall turbine loading. The DC/AC grid side inverter mainly is to regulate DC link voltage level and to ensure reproducing grid compatible AC outputs, satisfying grid requirement in power quality, fault rid through feature, etc.

In general, compared to wind energy converter, tidal energy converter technology is currently an immature technology and is developing towards industrial scale developments. Key components of both medium scale wind and tidal turbines, based on the above mentioned configuration, are very similar (Delorm et al., 2012) . Hence, it is possible and reasonable to apply experiences gained from

the wind industry to improve reliability level of tidal turbines (Karikari-Boateng et al., 2013).

Figure 7.2 shows a distribution of components affected by failures for two power groups of wind turbines (Boettcher & Fuchs, 2011). In a power range between 1 MW and 1.5 MW, the share of failures in the electrical systems is 20% compared to 35% for the power group above 1.5 MW.

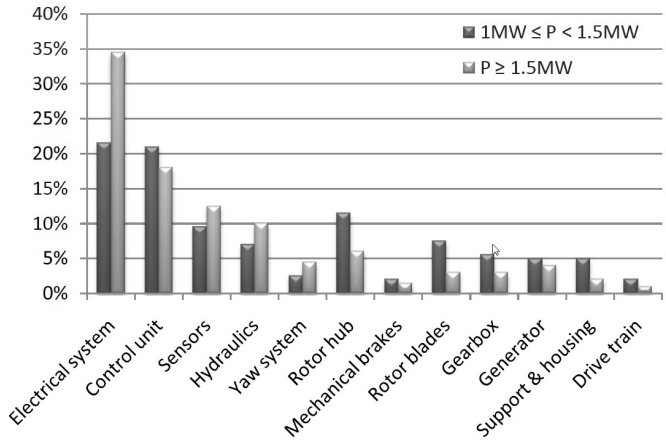


Figure 7.2: Distribution of affected components of wind turbines of two power groups in WMEP during 1997-2005 (Boettcher & Fuchs, 2011).

Figure 7.3 indicates that the failures in power electronic converters (i.e. IGBT, Chopper, Diodes, Rectifier and Inverter) account for almost half (48%) of the failures in the electrical system of the wind turbines so far (Lyding et al., 2010).

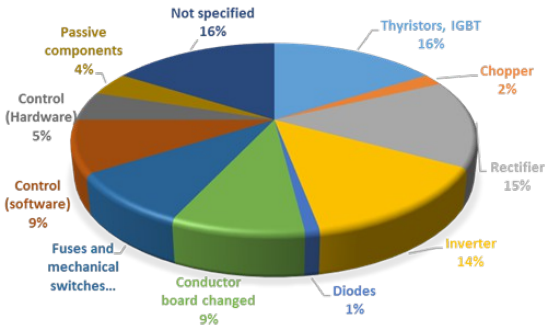


Figure 7.3: Failure mode breakdown for failures in electrical systems of wind turbines in WMEP (Lyding et al., 2010).

Therefore, a typical component, IGBT (Insulated-Gate Bipolar Transistor), is chosen from the electrical system of marine energy converters to apply the VMEA.

7.2 IGBT Module

An IGBT module is a three-terminal power semiconductor device primarily used as a power switch in converter design. Figure 7.4 displays a picture of IGBT module and its position inside a three-phase AC/DC/AC converter schematic diagram. This is a six-pack IGBT module with EconoPack package outline, manufactured by Infineon. It interfaces DC and 3-phase AC terminals and can be used in either side of AC/DC/AC converter.

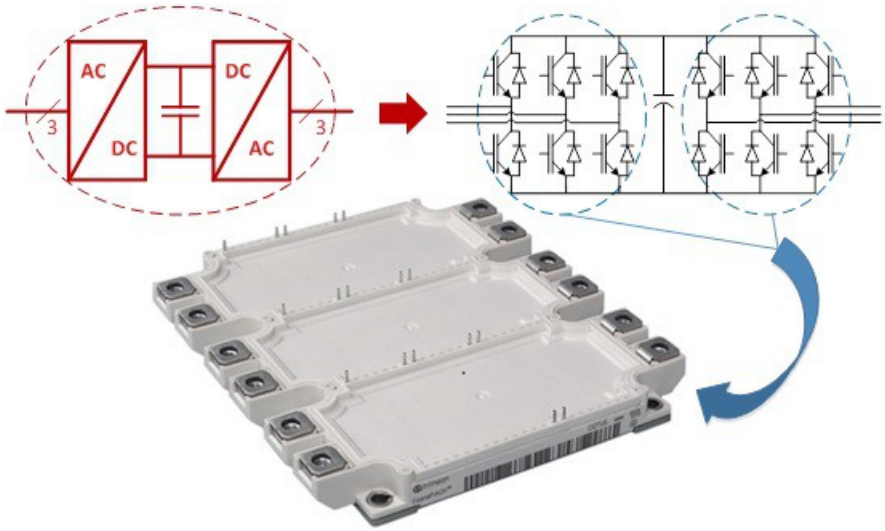


Figure 7.4: IGBT module in three-phase AC/DC/AC converter.

The internal layout of the module is illustrated in Figure 7.5, one phase only, after removal of cover and gel. Two DC terminals, DC+ (up) and DC- (low), are located on the right hand side, and two AC terminals are connected together on the left hand side. There are three half-bridge sub-modules paralleled to boost power capability. A diode, square chip of smaller area, is parallel-connected with an IGBT chip of gate wire in centre, each having 4 bond wires. Each bond wire has two soldering points with chip in order to reduce current density.

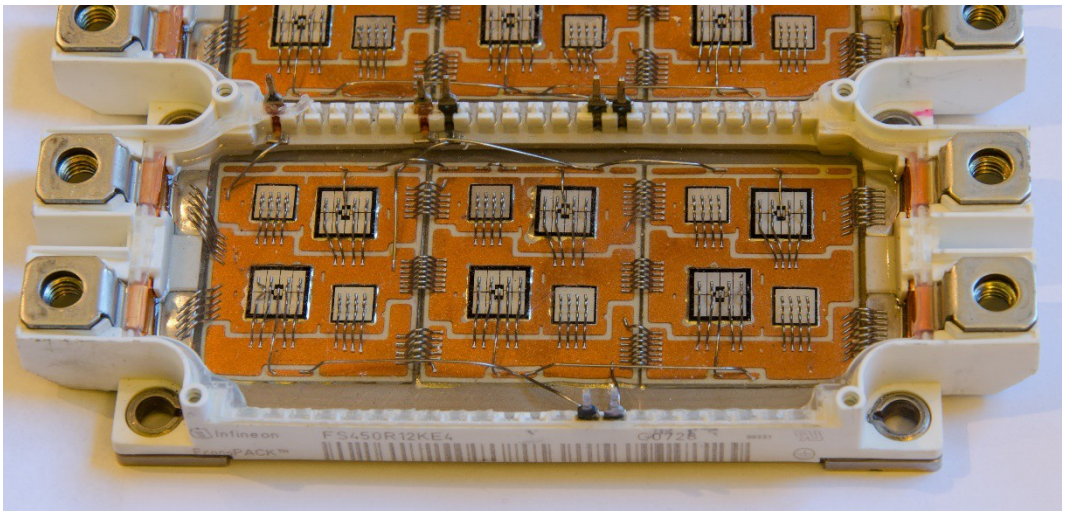


Figure 7.5: Internal layout of IGBT module (Infineon FS450R12KE4).

The structure of one half-bridge sub-module is explained briefly in Figure 7.6. In this figure the relative circuit diagram is shown and layer explanations are listed as well. The thickness of each layer is exaggerated and not scaled proportionally in order to have better illustration of IGBT structure and fatigue mechanism thereafter. For the sake of simplicity, only one representative bond wire is connected with IGBT/diode chip instead of 4 wires in Figure 7.6. Also gate wire connection has been moved from centre to edge.

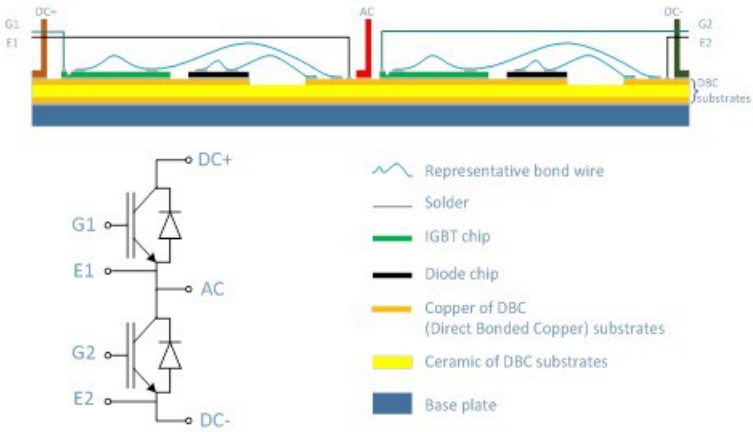


Figure 7.6: Half-bridge IGBT module structure.

Vertically from top to bottom, bond wires are soldered to IGBT/diode chips, and these chips are soldered to copper layer of DBC (Direct Bonded Copper) substrates. DBC substrates consist of a ceramic isolator sandwiched by copper layers. These substrates are then soldered with copper base plate. Finally the whole IGBT module is bolted on top of heatsink, and thermal paste is usually applied in between to achieve better thermal conductivity. The last two layers are only shown in Figure 7.7 where the whole thermal path is displayed.

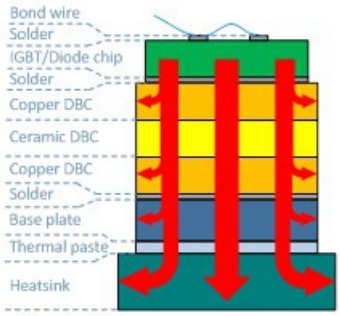


Figure 7.7: Thermal path inside module layers.

Once current is fed into IGBT/diode chip via DC and AC terminals and bond wires, heat will be generated in the centre of the chip. The majority of the generated heat will go vertically through the thermal path displayed in Figure 7.7 due to high thermal conductivity and temperature differential. Only small amount will spread laterally through layers and dissipate via DC and AC terminals and bond wires as well. However, different layers in the thermal path have different CTEs (Coefficient of Thermal Expansion) due to different material used in each layer. The related information is listed in Table 7.1.

Table 7.1: Material and CTE of layers in IGBT structure.

Layers	Material	CTE (ppm/K)
Bond wire	Aluminium	22
IGBT/diode Chip	Silicon	3
Copper DBC	Copper	16.5
Ceramic isolator DBC	Alumina (Al_2O_3)	7
	Aluminium Nitride (AlN)	4
Base plate	Copper	16.5
	Aluminium silicon carbide (AlSiC)	8

These layers will expand in different scale even at same loading current. Under a set of wind profile, this phenomenon will accumulate. As a result soldering integration between bond wire and chip, between chip and copper and between DBC and base plate will suffer from this accumulation. As time goes by such accumulation will cause failure inside IGBT module in the form of bond wire lift-off and solder delamination.

The whole process is pretty much the same as fatigue in materials in which the weakening of a material is caused by repeatedly applied loads. In reliability engineering, the bathtub curve is widely used to describe failure rate of this process. An example of the bathtub curve of life time failure rate is plotted in Figure 7.8, in which rising failure rate caused by fatigue locates in the wear out stage. The high failure rate in the early stage is usually introduced by immature design rather than fatigue.

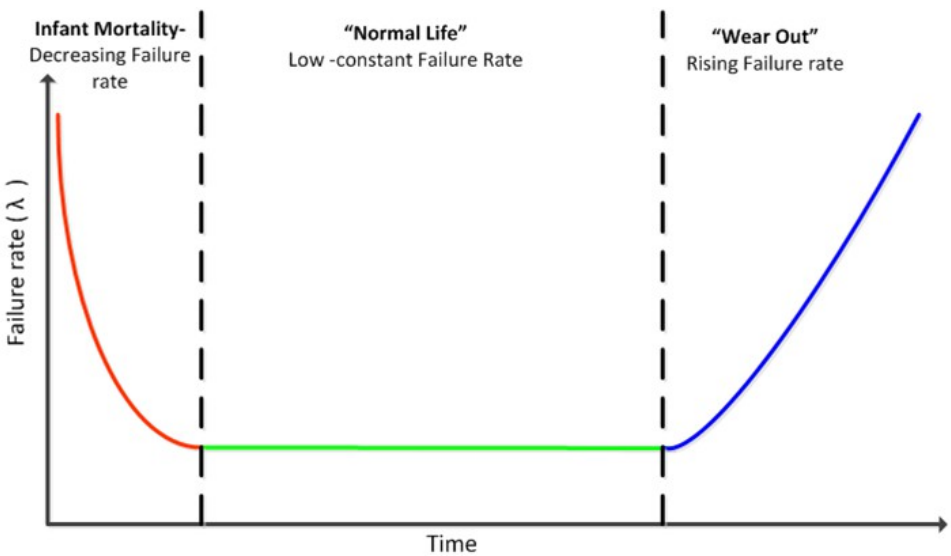


Figure 7.8: Bathtub curve of life time failure rate.

7.3 Reliability Design Criteria and Process

Since there is no specific standard available, life time of IGBT module in a turbine converter is usually based on custom requirement. Once a particular site is chosen, wind speed history will be

analysed statistically to derive its distribution. At each wind speed the relative power output can be simulated by turbine design engineering software (FAST, Bladed, etc.). After conversion circuit is setup and a type of IGBT module is chosen, this IGBT power loss can be calculated according to manufacturer's datasheet. Then the junction temperature of the IGBT can be predicted based on the thermal mode in the datasheet at specific ambient temperature and cooling condition.

After applying the aforementioned process the time varying junction temperature will be predicted for 10 minutes which is the time window of average wind speed. Then the range of junction temperature variation (ΔT_j) and the number (n_i) of ΔT_j cycles are recorded within this 10 minutes window. The nominal number (N_i) of ΔT_j cycles can be read from the power cycling capability curves provided by manufacturers. After considering wind speed distribution and arbitrary 10 years requirement, accumulated damage can be calculated and a rough guideline is given in Equation (7.1) The whole process is illustrated in Figure 7.9,

$$D=\sum_i \frac{n_i}{N_i}, \quad D<1. \tag{7.1}$$

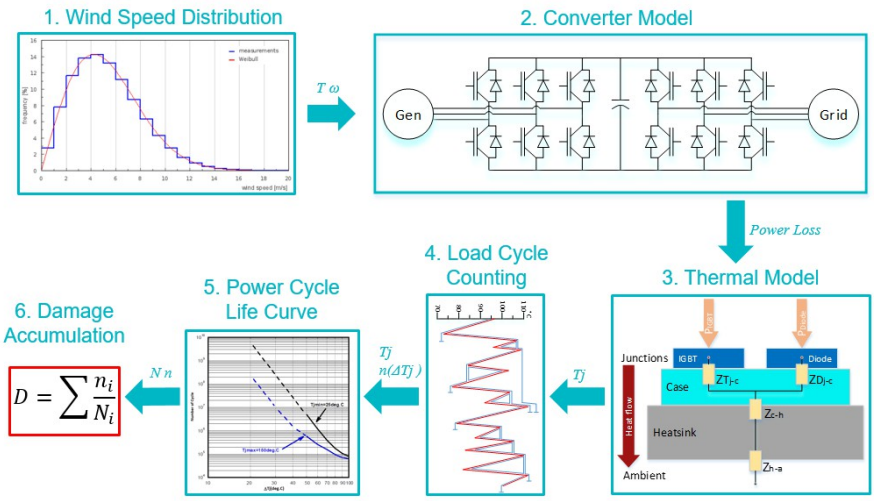


Figure 7.9: IGBT reliability design process.

Practically the 10-minute accumulated damage (D_{10}) is converted into lifetime (L_{dgn}) in years according to Equation (7.2). This designed lifetime should be larger than the 10-year requirement,

$$L_{dgn}=\frac{10\cdot 60}{D_{10}\cdot 60\cdot 60\cdot 24\cdot 365}=\frac{1}{D_{10}\cdot 6\cdot 24\cdot 365}. \tag{7.2}$$

A design margin is conventionally added, covering model error, tolerances, calculation error, etc. The size of design margin is usually based on engineers' experience. It cannot be either too high or too low. Being too high means loss of IGBT useful lifetime and cost increase, and being too low indicates possible failure before the end of lifetime.

The probabilistic VMEA, proposed in this document, can analyse both strength and load uncertainties and provide a quantified design margin, which could be a good engineering tool to understand design margin.

7.4 Strength Assessment

Like S-N curve for materials, power cycling curve, usually provided by manufactures, is used to

describe IGBT lifetime capability. Figure 7.10 shows an example of power cycling curve for certain Infineon IGBT modules (Infineon, 2010). Both axes are in logarithmic scale. The x axis is range of junction temperature variation (ΔT_{vj}) in Kelvin, and the y axis is the nominal number of power cycles the module may survive under different maximum junction temperatures ($T_{vj,max}$). The dashed lines in Figure 7.10 are estimated values. As ΔT_{vj} increases the number of cycles drops. At certain ΔT_{vj} the number of cycles also decreases as maximum junction temperature increases.

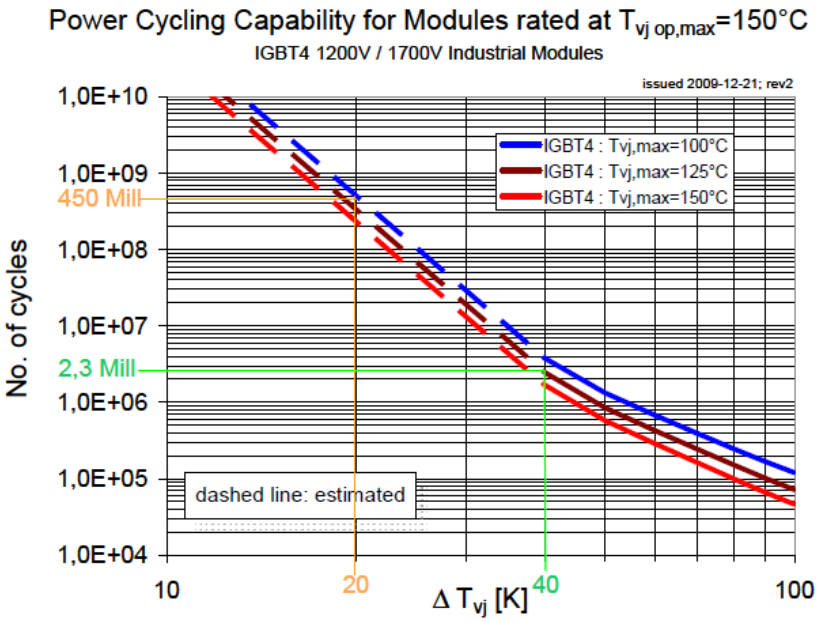


Figure 7.10: IGBT power cycling curve.

These three curves in Figure 7.10 are almost paralleling with each other and have three distinct ratios roughly at intervals of 20-40K, 40-50K and 50-100K. Apparently these are supposed to be under low, medium and high load respectively. Commonly the high load decides the IGBT lifetime in great majority. This part will be later referred in case study.

In (Fuji, MT5Z02525c), the manufacturer Fuji points out the number of cycles is a percentile value, 1% failure rate in Weibull analysis. From (Infineon, 2010), it is suggested that the number of cycles in Figure 7.10 is a mean value. However, neither the shape parameter of Weibull distribution nor the deviation of normal distribution is available from these manufactures. Infineon IGBT power cycling curve in Figure 7.10 is used later in case study due to relatively more information contained.

7.5 Load Assessment

The fundamental load of IGBT module comes from the variation of junction temperature which is a combined result of power loss and thermal characteristics of the module. Once the converter design is setup, thermal characteristics, ambient temperature, cooling condition etc. have been decided. Therefore, the junction temperature variation is mainly determined by the power loss which has originated from the primary wind condition.

Weibull distribution is usually employed to describe wind speed distribution. The probability density function is calculated in Equation (7.3), where c is the shape parameter and a is the scale parameter. An example of wind speed distribution is plotted in Figure 7.11, where the shape parameter equals to 2 and the scale parameter is 11.287 m/s. For wind speed distribution the shape

parameter is usually about 2, which is also called Rayleigh distribution,

$$f(x;c,a)=\frac{c}{a}\left(\frac{x}{a}\right)^{c-1}\exp\left(-\left(\frac{x}{a}\right)^{c}\right). \tag{7.3}$$

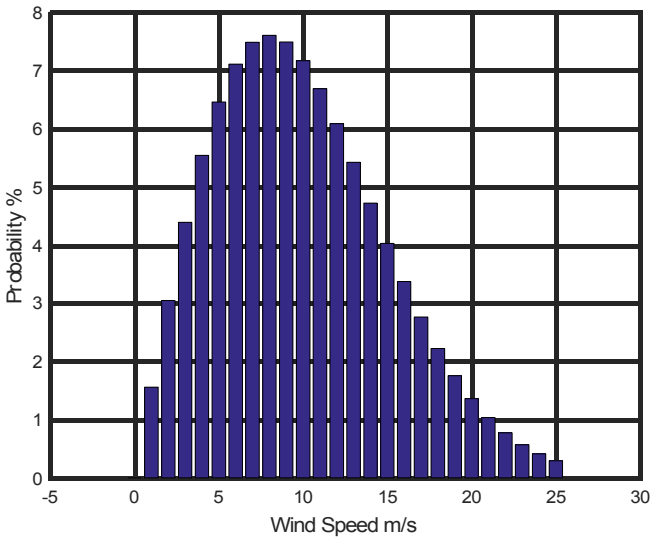


Figure 7.11: Wind speed distribution, c=2, a=11.287m/s.

7.6 Check List of Uncertainties

All uncertainties involved in VMEA for IGBT module analysis can be categorised into two groups accordingly, strength and load. In each group these uncertainties can be discriminated by scatter and uncertainty. The scatter here describes the nature of randomness, which cannot be reduced as the number of tests increase. The latter can be decreased by more designed tests in order to have better understanding of objects. Table 7.2 summarises all these uncertainties.

Table 7.2: Uncertainties of IGBT module VMEA.

Uncertainty components	Scatter	Uncertainty	Comments
Strength			IGBT power cycling capacity
Strength scatter	x		From Power cycling life time curve, Weibull or normal distribution
Statistical uncertainty strength		x	Assuming ten reference tests, 1/sqrt(10-1)
Palmgren-Miner model		x	Model uncertainty due to PM-rule
Extrapolation & interpolation error		x	Extrapolation below ΔT_{vj}=40°C, interpolation between $T_{vj,max}$ of 100-125-150°C
Mean value influence		x	Judgement from Power cycling life time curves
Reference data relevance		x	E.g. batch variation
Laboratory vs. Operative environment		x	E.g. environment, temperature, humidity...
Load			Loading generation
Wind speed scatter within site	x		Wind speed scatter within sites
Wind speed scatter between sites	x		Wind speed scatter between potential sites
Wind speed distribution uncertainty		x	Uncertainty in wind distribution estimation
FAST simulation uncertainty		x	Uncertainty in torque and angle speed estimation using FAST
Converter model uncertainty		x	Uncertainty in power loss calculation using converter model
Thermal model uncertainty		x	Uncertainty in junction temperature using thermal model
Rainflow counting uncertainty		x	Uncertainty in rainflow counting

7.7 Case Study: VMEA for IGBT Module

An example of a probabilistic VMEA for IGBT module in wind power converter is going to be illustrated in this chapter. The wind speed distribution in Figure 7.11 has been applied, and at each wind speed FAST software is used to simulate the torque and the speed of shaft. A converter topology of traditional two-level three-phase AC/DC/AC converter has been chosen to condition the output voltage and frequency before connecting with power grid. Infineon IGBT module, FZ600R12KP4, has been employed to realise the power conversion. Its thermal model has been used to derive the junction temperature. In order to convert 3MW rated power, eight of this module are connected in parallel satisfying other requirements like 50°C ambient temperature and 100°C case temperature. Figure 7.12 plots the view of the whole process. Rainflow counting is then applied to count the range of junction temperature variation (ΔT_{vj}) and relative number. Finally, 43 years of lifetime has been derived based on the wind profile, the converter topology, the case and the ambient temperatures.

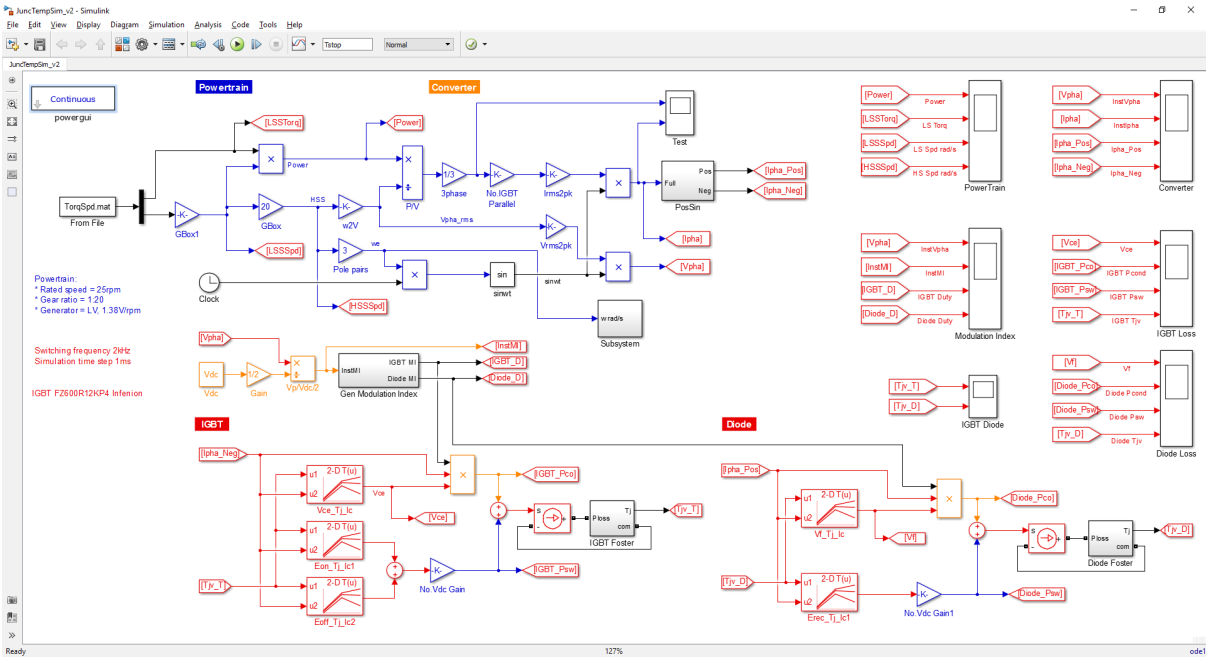


Figure 7.12: Schematic view of junction temperature simulation in Simulink.

The 43 years designed lifetime (L_D) will be evaluated in VMEA incorporating all the uncertainties from Table 7.3 with the target life of 10 years (L_T). The detailed values of uncertainties and the load-strength analysis result are plotted in Figure 7.13.

Component: Power converter with IGBT module

Target function: 43 years — Reliability Assessment Tool (RAT)

Target life: 10 years

Probabilistic VMEA – Evaluation of Uncertainties

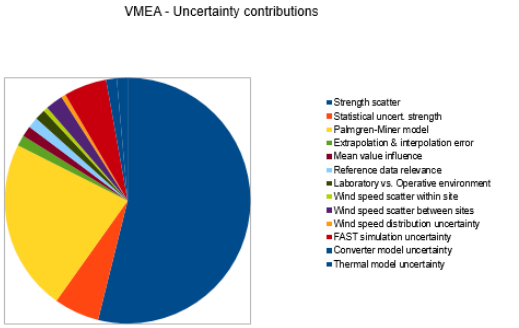
Input						Result				
Uncertainty components	scatter	uncert.	y coefficient c	t-correction factor t	rd deviation s	Scatte	Uncertainty	Total	Variance	Comments
Strength										IGBT power cycling life capacity
Strength scatter	x		1.000	1.000	0.309	0.309			0.095	From Power cycling life time curve, Weibull exponent 3-4 gives s=0.3 (see below)
Statistical uncert. strength		x	1.000	1.000	0.103		0.103		0.011	Assume ten reference tests, 1/sqrt(10-1)
Palmgren-Miner model		x	1.000	1.000	0.200		0.200		0.040	Model uncertainty due to PM-rule
Extrapolation & interpolation error		x	1.000	1.000	0.050		0.050		0.003	Extrapolation below DeltaT 40 dgC.
Mean value influence		x	1.000	1.000	0.050		0.050		0.003	Judgement from Power cycling life time curves
Reference data relevance		x	1.000	1.000	0.050		0.050		0.003	E.g. batch variation
Laboratory vs. Operative environment		x	1.000	1.000	0.050		0.050		0.003	E.g. environment, temp., humidity,...
Total Strength uncertainty						**0.309**	**0.246**	**0.395**		
Load										Load calculation
Wind speed scatter within site	x		0.032	1.000	1.000	0.032			0.001	Wind speed scatter within sites
Wind speed scatter between sites	x		0.032	1.000	2.000	0.064			0.004	Wind speed scatter between potential sites
Wind speed distribution uncertainty		x	0.032	1.000	1.000		0.032		0.001	Possible uncertainty in wind distribution estimation
FAST simulation uncertainty		x	1.000	1.000	0.100		0.100		0.010	Uncertainty in torque and angle speed estimation using FAST (wind simulation software)
Converter model uncertainty		x	1.000	1.000	0.050		0.050		0.003	Uncertainty in power loss calculation using converter model
Thermal model uncertainty		x	1.000	1.000	0.050		0.050		0.003	Uncertainty in junction temperature using thermal model
Rainflow counting uncertainty		x	1.000	1.000	0.050		0.050		0.003	Uncertainty in rainflow counting
Total Load uncertainty						**0.072**	**0.136**	**0.154**		
Total uncertainty						**0.317**	**0.281**	**0.424**		

Reliability Evaluation

Input		Result (exp-scale)		Result (log-scale)	
Median life [Years]=T0/D	43	Safety factor	4.30	Median life	3.76
Target life [Years]	10			Target life	2.30
				Distance	1.46
Evaluation - Extra safely factor		Variation safety factor	2.00	Variation dist.	0.70
Required extra safety factor (SF)	1.96	Extra safety factor	**2.15**	Extra dist.	0.76
Required median life [Years]	39.3	This value should be less than Median life!			

Alternativelg: calculate L5 and adjust for the extra safety factor.

Median life [Years]=T0/D	43	
L5, life with 95% reliability [Years]	21	
L5 & extra SF [Years]	10.3	This value should be larger than Target life!



P-VMEA, v1 (SP) | P-VMEA, v2 (OREC)

Figure 7.13: IGBT module probabilistic VMEA.

The strength scatter (τ_{ss}) in Figure 7.13 is derived from Equation (7.4) assuming that the Weibull shape factor (c) is equal to 3.5,

$$\tau_{ss}=\sqrt{\ln\left(\Gamma\left(1+2/c\right)\right)-2\cdot\ln\left(\Gamma\left(1+1/c\right)\right)}. \tag{7.4}$$

The statistical uncertainty (τ_{su}) is calculated according to Equation (7.5) with the assumption that there are ten reference tests ($N=10$),

$$\tau_{su}=\frac{\tau_{ss}}{\sqrt{N}}. \tag{7.5}$$

The other uncertainties are assessed based on engineering judgement. In the Result column, Figure 7.13, of scatter and uncertainty, these uncertainties are products of co-efficiency, correction factor and standard deviation. For example, Palmgren-Miller model uncertainty of 0.2 is the product of co-efficiency (1), correction factor (1) and standard deviation (0.2), which means Palmgren-Miller model may introduce 20% relative deviation in lifetime estimation based on engineering judgement. In case of wind speed uncertainties of Load, (i.e. Figure 7.13), pure standard deviations are given with the co-efficient of 0.032. The co-efficient, c, of wind speed uncertainties to lifetime estimation is calculated in Equation (7.6), where L1 is the lifetime at wind speed V1 and L2 is the lifetime at wind speed L2,

$$c=\left|\frac{L1-L2}{V1-V2}\right|. \tag{7.6}$$

The lifetime here is derived in logarithmic scale by the aforementioned method, and the wind speed here could be referred to scale parameter. The calculated coefficient is listed in Table 7.4.

Table 7.3: Wind speed co-efficient calculation result.

Scale parameter, m/s	Lifetime, years	Ln(Lifetime)	Coefficient, *c*
11.287	43.8	3.78	-
15	39.0	3.66	0.032

The total uncertainty (τ) is calculated by root sum squared of all uncertainties according to Equation (7.7),

$$\tau = \sqrt{\sum_i \tau_i^2}. \tag{7.7}$$

It is calculated to be 0.424 from Figure 7.13. Lx life, pdf and statistical safety distance are listed in with assumption of 1-tailed end. In this case L5 life is selected, and the statistical safety distance will be set to 1.64τ. The extra safety factor in the load scale is for this application chosen to be as low as 1.2, since consequences of failure is only related to economic risks; compare Table 5.6 in Chapter 5. This factor in load scale is in Table 7.5 converted into the corresponding extra safety factor in life, depending on the exponent of the life curve. Considering the IGBT strength analysis above, the extra safety factor (γ_E) is chosen to 1.96, corresponding to high load conditions with exponent 3.7, due to its dominance in fatigue.

Table 7.4: Lx life, pdf and statistical safety distance with total uncertainty τ.

Lx life	pdf	Statistical safety distance
L10	90%	1.28τ
L5	95%	1.64τ
L2	98%	2.05τ
L1	99%	2.33τ

Table 7.5: Extra safety factor in life.

Exponent, x	Extra safety factor, $\gamma=(1.2)^x$	Comment
1	1.20	
2	1.44	
3	1.73	
3.7	1.96	High load: 50-100 K
4	2.07	
4.2	2.15	Medium load: 40-50 K
5	2.49	
6	2.99	
7	3.58	
7.2	3.72	Low load:20-40 K
8	4.30	

The judging criteria of VMEA is then expressed in Equation (7.8),

$$\ln(L_D) > \ln(L_T) + 1.64\tau + \ln(\gamma_E). \tag{7.8}$$

The design margin in logarithmic scale consists of two parts, the statistical safety distance (L5 life, 1.64τ) and the extra safety factor (γ_E). This equation may also be expressed in Equation (7.9) after transformation,

$$L_D > L_T \cdot \exp(1.64\tau) \cdot \gamma_E. \tag{7.9}$$

After applying all the values into Equation (7.8), the judgement is satisfied, namely,

$$43 > 10 \cdot \exp(1.64 \cdot 0.424) \cdot 1.96 = 39.3, \tag{7.10}$$

or in logarithmic scale,

$$\ln(43) > \ln(10) + 1.64 \cdot 0.424 + \ln(1.96). \tag{7.11}$$

The 10 years target life can be guaranteed by the 43 years design life after considering all these uncertainties, statistical safety factor and extra safety factor.

8 Mooring and Foundation Methodology

8.1 MEC Moorings and the Associated Application of VMEA

Marine energy converters (MECs) come in many different shapes, sizes and configurations, as detailed in Section 2.1.

The marine energy sector has developed and morphed over time, with the tidal devices moving away from utilising devices mounted on foundations, and towards a philosophy of using floating devices held in place with moorings. Wave devices have also been moving universally towards a moored solution, compared to some early devices that were solidly attached to the seabed. This section will primarily look at moorings, although the analysis methodology is also applicable to foundations.

There are many different styles and types of mooring in use in other industries, as shown in the diagram below. Beyond these recognised mooring types are the very specific ones used by certain wave energy converter developers, who are designing mooring systems that work with the device to maximise power output. They are in effect part of the power take-off system, rather than just a means of holding the device on location.

The traditional mooring systems as shown above tend to have three main components: anchor, riser and buoy. They sometimes also have additional mid riser buoys, secondary surface buoys and mid riser weights.

Different component configurations and materials of each component lead to different behaviours, and different suitability for seabed types. For example, a chain tension leg system will provide a very stiff, unmoving mooring point, whereas a synthetic mooring with mid riser buoys will provide a compliant mooring point that won't provide sharp shock loadings. Either exemplar systems could be adapted to different seabed conditions, using a range of drag, gravity or vertical load anchors.

The ability to mix and match components is a strength, but also a weakness when designing mooring systems. In theory, it provides a much wider array of systems to address a large set of requirements. However, the risk that has been seen in the wave and tidal sector is that many configurations haven't been used in the energetic wave and tidal environments before, and the uncertainties of adapting them from other industries lead to much larger safety factors, and expensive systems.

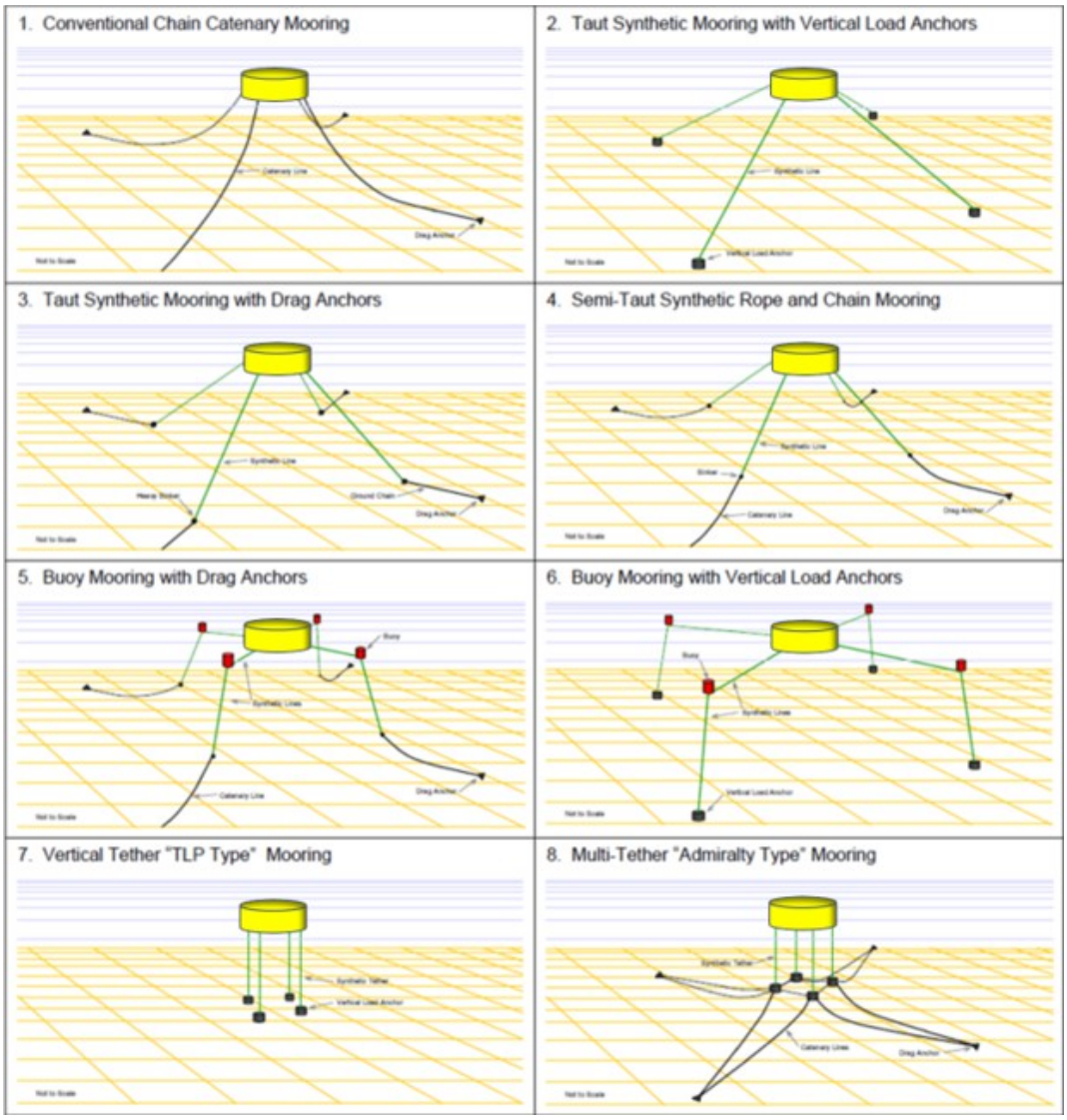


Figure 8.1. Some examples mooring configurations.

8.1.1 VMEA and Moorings

The move towards moored floating devices is driven primarily by the overall cost of operating the device. The marine operations for towing buoyant devices versus lifting very heavy devices during the installation and maintenance phases of the device lifecycle provide a noted cost differential, which has led to the greater use of moorings in the sector.

The drive for cost efficiency will continue to shape the sector, and the cost of the moorings required for a successful device deployment will become a new focus for cost reductions. VMEA analysis can be used to identify the cost drivers of the mooring design process, as identified by two factors: total cost of component, and the level of safety factor applied to said component. Safety factors will be the focus of this section, and of the VMEA analysis of moorings in this guideline, as they are the common feature between easily quantifiable measurements, and much less specific assumptions and models.

As detailed in Section 5.1, there is a step change in the levels of VMEA analysis as you go from basic to probabilistic analysis. Determining the levels of uncertainty in the mooring design process is currently at the basic level, but will be developed to embrace the greater quantitative value of probabilistic analysis as more detail is made available from field campaigns.

8.2 Mooring Design, and Uncertainty

The design process for MECs is based around the use of computer models to simulate the movements of the device in the deployment environment, and while under the forces of simulated tide/wave interaction. These simulations are used to tailor the moorings to their desired function, whether that is simply to hold the device against the forces, or to be in tune with the device to magnify the reaction with incoming waves. They also provide an idea of the forces that the moorings must resist, thus allowing for the procurement process to begin at suitable scales and strengths. There are several programs, offered by several providers to carry out these simulations.

The design process can be represented by this flow diagram, although it's worth noting this is a simplified illustration, and doesn't show all the iterative cycles and interdependencies that the process involves. The aim of the process is to find the minimum costs for a mooring system that can provide a safe and reliable means of holding a MEC in place, although it will also identify the characteristics and behaviour of the mooring system and device together in various conditions. This can lead to an iterative system where the mooring designer increases or decreases the size of a given component to work towards more satisfactory behaviour.

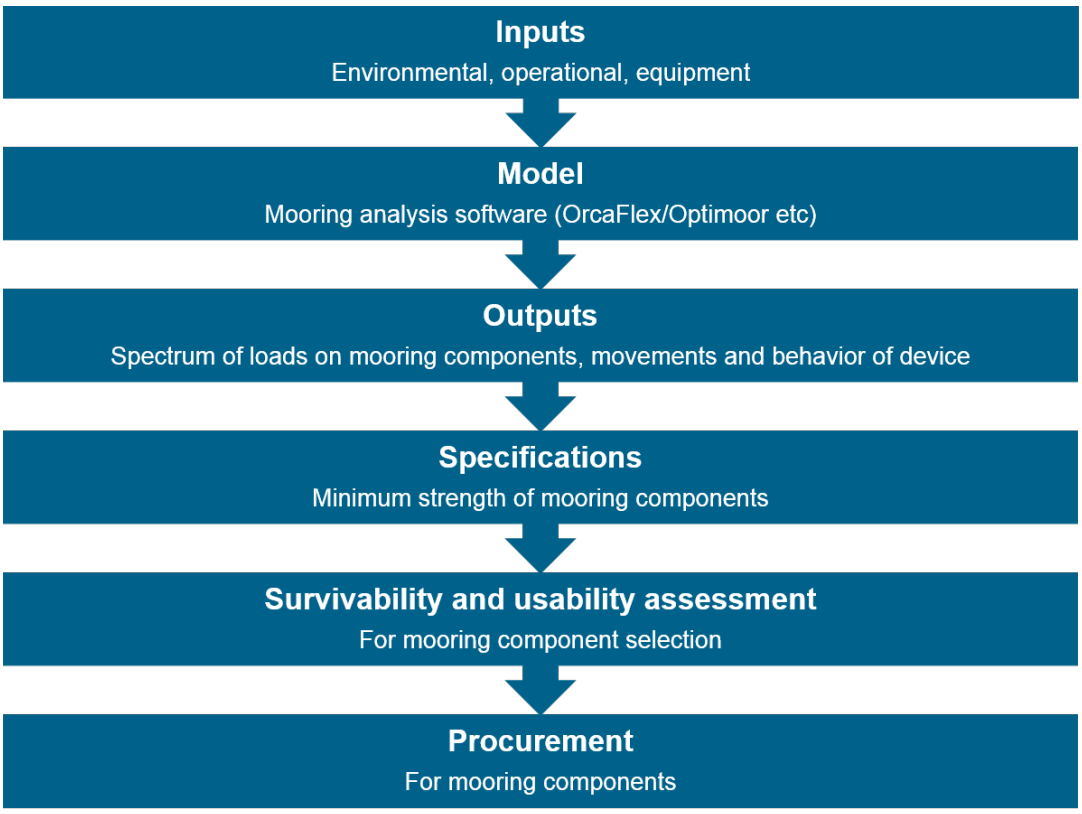


Figure 8.2: Flow diagram of the design process.

The results/outputs that the computer model can give are strongly dependant on the quality and detail of the inputs, which come from various sources, such as environmental, operational and equipment suitability. Examples of these are provided in the following table.

Type of input	Factor	Variable
Environmental	Tidal flow	Maximum flows seen by device
		Quality of measured/modelled tidal data - time (number of cycles)
		Quality of measured/modelled tidal data - proximity to final location
	Waves	Maximum wave height measured/modelled
		"Wave rose" accuracy of measured vs modelled conditions
		Interaction between wave and tide (rarely modelled)
		What is the water depth, and how does it change locally - shoaling waves?
	Seabed	Seabed type
		Is any overburden stable, or does it move with storm action
		Is there sufficient overburden to use embedment anchors
		Is the rocky substrate suitable for drilling
		What is the measured/assumed friction coefficient for the seabed type
Operational	Ultimate loads	What is the drag profile of the device
		Will the device always weathervane, or are there multiple drag profiles
		How well modelled is the device - simple shape with assumed characteristics or very detailed model with measured hydrodynamic behaviour
		Does the device have any active or passive storm protection systems
		Does any storm protection system fail safe, or fail unsafe?
	Fatigue loads	Expected life of device
		Anticipated maintenance items within mooring spread
		Anticipated natural frequencies of device, and impact upon moorings, and vice versa for thrumming moorings, especially in tidal areas
Mooring suitability	Life expectancy	Have the proposed components been used before in this environment
		What level of corrosion has been assumed
		Are items in contact with seabed sufficiently over specified to allow for abrasion
		How compliant/stiff must the mooring system be
		Are all connectors suitable for repeated connection/disconnection cycles

Each input will have either a quantifiable degree of uncertainty based on direct measurements, or a less specific degree of uncertainty based on industry knowledge. These uncertainties will result in a safety factor, which can then be used as a point of comparison. It is the influence upon the cumulative safety factor that this methodology exploits. The limits of model accuracy will also impart a degree of uncertainty into the results of the model, and the results can be altered accordingly.

8.3 Case Study: Pelamis Moorings

This best practice guide uses a case study of the Pelamis P2001 wave energy converters mooring design to illustrate the application of basic VMEA to the moorings design process.

8.3.1 Executive Summary

The European Marine Energy Centre (EMEC) in collaboration with SP Research and the Offshore Renewable Energy Catapult participated in the Reliability in a Sea of Risk (RiaSoR) project. The RiaSoR project adapted, evaluated and demonstrated the value of utilizing a reliability methodology called Variation Mode and Effect Analysis (VMEA) for ocean energy sector.

The RiaSoR project received funding from the Ocean Energy ERA-NET, a network of 15 national and regional funders, of which InnovateUK, Swedish Energy Agency and Scottish Enterprise are contributors.

The aims of the RiaSoR project is captured in the following core objectives for the project:

1. European Ocean Energy test sites will acquire the competence in the VMEA methodology tailored towards the ocean energy sector. The method will be designed to work across as many technology variations as possible.

2. A specific process for analysing the results from reliability testing will be established. This will provide support in drawing conclusions from the testing programme and set out a clear path for TRL advancement.

3. The approach of reliability testing with VMEA will be transferred to the WEC/TEC companies. This is accomplished through training and ensures close cooperation is maintained during the testing campaign, thereby creating a culture of testing and validation when moving from one TRL stage to the next.

   The overall outcome of the project is to provide a reliability guidance for ocean energy technologies, educational training on the VMEA methodology and uptake across the sector, to increase the reliability and performance of ocean energy devices.

The EMEC deliverables focus the adaptation of the VMEA methodology for mooring and foundation subsystems. The case study subject chosen was the application of the basic VMEA methodology as illustrated in the guidance, to the mooring design process. The VMEA analysis helped identify the main sources of uncertainty and thus the potential areas for further design development.

Using this information, EMEC progressed VMEA analysis on a set of bespoke tethers (from a Pelamis P2001 device)[6] by recovering them from their deployed state, inspecting them in detail, and finally testing strength through destructive testing through a collaboration with Tension Technology International. A separate report will be made available on results of these tests to inform future mooring designs.

This case study has been an effective means of demonstrating the value of basic VMEA as a reliability tool, allowing engineers to make a qualitative judgement on where to focus design efforts. The conclusions demonstrate a need for the sector to contribute to an industry wide accessible database for reliability, based on robust condition monitoring.

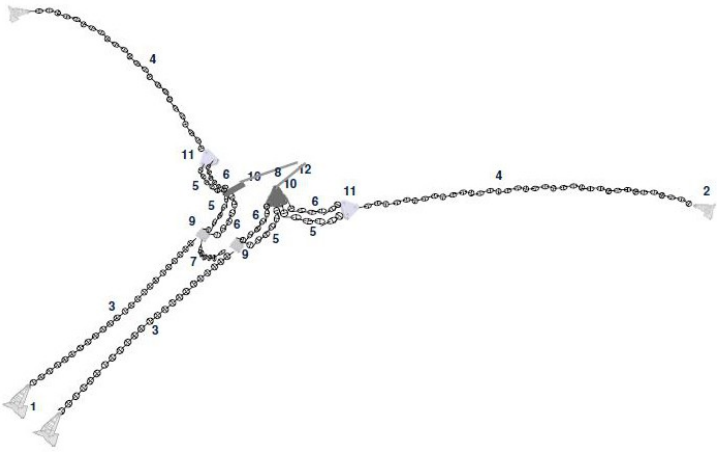
6 Owned by EMEC post December 2014.

8.3.2 Introduction – History of P2001

The Pelamis P2001 device (see Figure 8.3) was owned by E.ON Energy, and built and tested by Pelamis Wave Power from 2010 until 2014. The primary converter is a linear attenuator device that produced power through the differential movement of floating compartments, reacting to the curve of the waves rather than the significant wave height.

Figure 8.3: P2001 Device deployed on EMEC test site.

The P2001 device was decommissioned in late 2014, with EMEC taking ownership of the device and the mooring subsystem. The P2001 was secured to the seabed using a combination of standard and bespoke equipment. The ground tackle (the metalwork lying flat on the seabed) was fairly standard: drag anchors, heavy wire and heavy chain, connected into a central pair of bespoke 5 way brackets fabricated from heavy plate (see Figure 8.4).



1	Font Anchors (2 x 3.5Te Stevpris)
2	Rear Anchors (2 x 2Te Stevpris)
3	Front chains (2 x 119m long 76mm chain)
4	Rear chains (2 x 109m long 76mm chain)
5	Primary chains (4 x 21m long 76mm chain)
6	Back-up chains (4 x 25m long 76mm chain)
7	Cross link chain (1 x 8m long 76mm chain)
8	Tethers (2 x 96mm polyester x 27m long)
9	Front chain connection (2 x 4-way 'Quad' plate)
10	Tether/chain connection (2 x 5- way 'Quin' plate)
11	Rear chain connection (2 x 3-way 'Tri' plates)
12	Tether top connection (2 x universal joints)

Figure 8.4: Ground tackle for P2001 device.

The links between the ground tackle and the device comprise of a set of bespoke hooks, some heavy chain and then a pair of synthetic tethers leading into the base of a mid water column buoy (Tether Latch Assembly, TLA), where the mechanical and electrical connections to the device were made (see Figure 8.5).

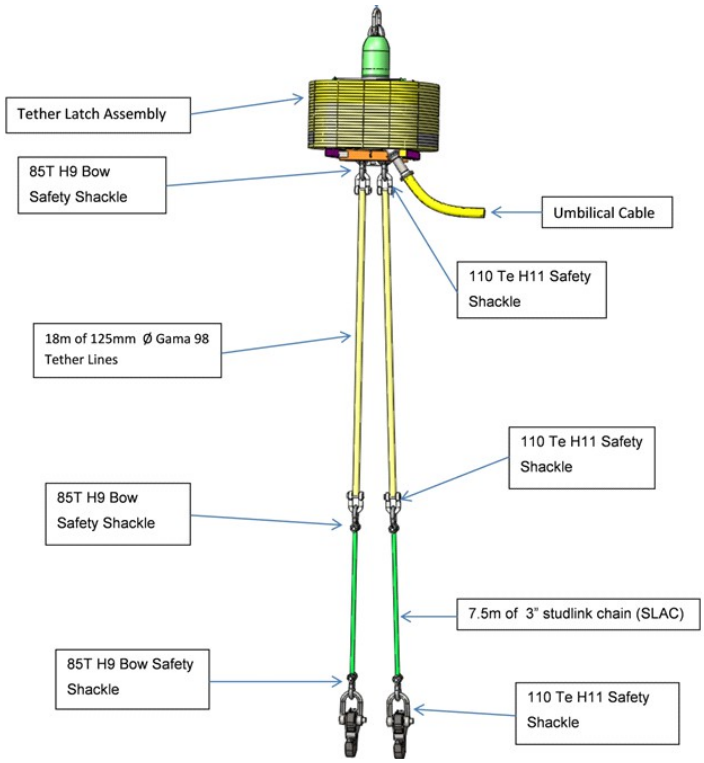


Figure 8.5: Midwater buoy and risers, including bespoke tethers.

The Pelamis P2001 moorings were scheduled for inspection early in 2016, and were removed to that effect in July 2016. The recovery was done using local contractors, with multicat vessels and divers. The pictures below (i.e. Figure 8.6, Figure 8.7 and Figure 8.8) demonstrate the operational recovery of the mooring

Figure 8.6: Tether and riser chains mid recovery.

Figure 8.7: Drag anchor winched over bow of a MultiCat.

Figure 8.8: One of two sets of riser chain, tether and shackles.

8.3.3 Motivation for P2001 within RiaSoR

The use of synthetic materials in the tethers used to secure the P2001 device to the seabed was a wave industry first, which has proved to be a valuable first step in providing confidence towards the future use of similar systems. The use of the tethers was chosen by Pelamis Wave Power despite there being a large degree of uncertainty in the longevity of the materials in this harsh environment compared to the use of traditional steel components such as wire or chain.

Innovative new technology and techniques such as synthetic tethers, have significant cost reduction potential, and could unlock survivability and reliability of these devices in targeted water depths due to the different mass and strength characteristics of the synthetic materials. With more information regarding reliability, longevity and strength available, future device developers would have greater confidence making a design choice to use these materials.

During the operation of the device, the tethers were swapped out as a planned maintenance activity, and load tested until failure. Knowing that one set of data was available, it became very apparent that carrying out further inspections and destructive testing would provide very valuable reliability data for the industry, and would demonstrate the use of basic VMEA.

8.3.4 Basic VMEA

The fundamental theory of a basic VMEA analysis is the ranking and weighting of variables in terms of their uncertainty, and analysing how that affects how the variables are used, and the impact of the uncertainty (see Figure 8.9 and Chapter 3).

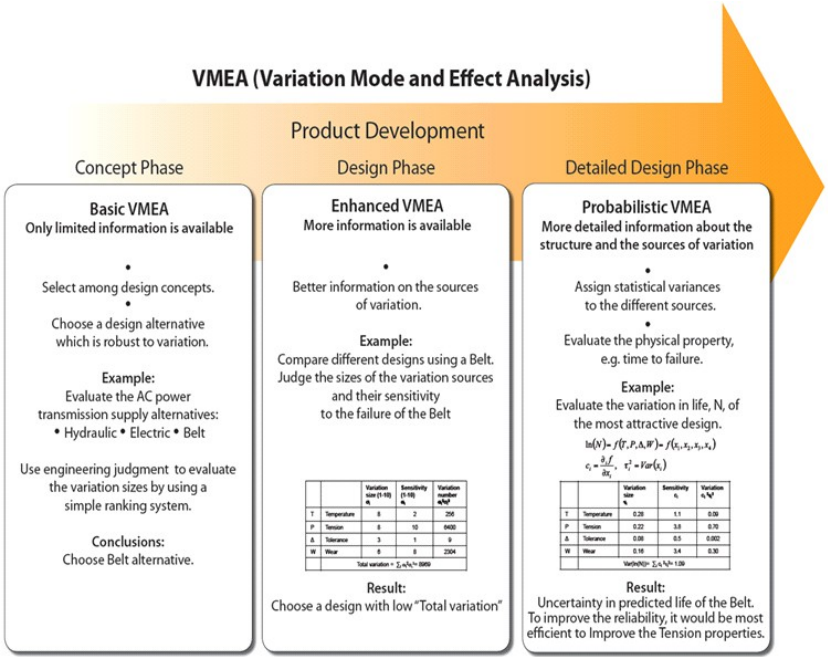


Figure 8.9: Outline of the different VMEA approaches.

In this case study, the variables were line items in the moorings design process, and the impact is largely upon the safety factor applied to the moorings on a component and system level.

As summarised in the flow sheet shown in Figure 8.2, the design process for moorings is focused round the use of modelling software, which requires a range of inputs upon which to base its calculations. The software then simulates the movement of a structure when external forces from the environment interact with it. This starts an iterative cycle where materials, masses and layouts are tweaked and played with until a mooring system has been developed that has the required compliance and strength. Safety factors are then put on items that are known, or suspected to have a reduced life due to corrosion, abrasion or other external influences. The modelled mooring system is reviewed, usually with a marine operational check that as well as being technically sound it also makes sense from a deployability point of view.

This case study replicates some of the top level inputs into the design process for the P2001 moorings, see Figure 8.10.

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling environmental data - wind	2	4	8	64	0
Accuracy of modelling environmental data - tide	3	5	15	225	2
Seabed conditions, and seabed stability	4	3	12	144	1
Design uncertainties					
Interation between moorings/foundation and seabed	4	8	32	1024	8
Ultimate loads seen by device (100 year storm)	5	8	40	1600	12
Fatigue loads seen by device (20 year working life at rated power)	5	9	45	2025	15
Measured metocean data not representative due to short sample period	1	5	5	25	0
Measured metocean data not representative due to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

Figure 8.10: Table showing weighted uncertainties in the mooring design process.

This table is filled with representative numbers from the design process. In this case it was completed based on the author's industry experience, however the preferred method would be to have a workshop between a device developer and a moorings design company to reach a joint assessment of uncertainty of the chosen techniques in the given environment. The two input columns (Sensitivity and Uncertainty) have been filled in based on a ranking system from 1-10 where 10 is the most significant and 1 the less significant.

The input columns comprise the two components that affect the safety factor for each line item – how sensitive each item is to uncertainty and how much uncertainty there is.

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling envi	2	4	8	64	0
Accuracy of modelling envi	3	5	15	225	2
Seabed conditions, and se	4	3	12	144	1
Design uncertainties					
Interation between mooring seabed	4	8	32	1024	8
Ultimate loads seen by device (100 year storm)	5	8	40	1600	12
Fatigue loads seen by device (20 year workin life at rated power)				2025	15
Measured metocean data not representative to short sample period				25	0
Measured metocean data not representative to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

The level of impact on safety factor that each line item has.

The uncertainty in measurement/modelling of each line item

Figure 8.11: Table of weighted uncertainties, detailing the inputs.

The results columns show the combination of the two inputs in the uncertainty column, followed by a second order weighting (squaring the uncertainty VPRN) and finally the proportion of the total uncertainty that each line represents. The second order weighting acts to magnify the difference between the different lines, allowing for clearer determination of the prime sources of uncertainty in the whole design.

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling environmental data - wind	2	4	8	64	0
Accuracy of modelling environmental data - tide	3	5	15	225	2
Seabed conditions, and seabed stability					
Design uncertainties					
Interation between moorings/foundation and seabed					
Ultimate loads seen by device (100 year storm)					
Fatigue loads seen by device (20 year working life at rated power)					15
Measured metocean data not representative du to short sample period					0
Measured metocean data not representative due to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

The combination of the input sensitivity and the input uncertainty. Gives a weighted uncertainty, showing how important it is to the overall design

The percentage of the total uncertainty that each line item represents.

Second order weighting

Figure 8.12: Table of weighted uncertainties, detailing the outputs.

A pie chart of the proportion of total uncertainty within the design process is shown below in Figure 8.13, with the two main sources outlined in black.

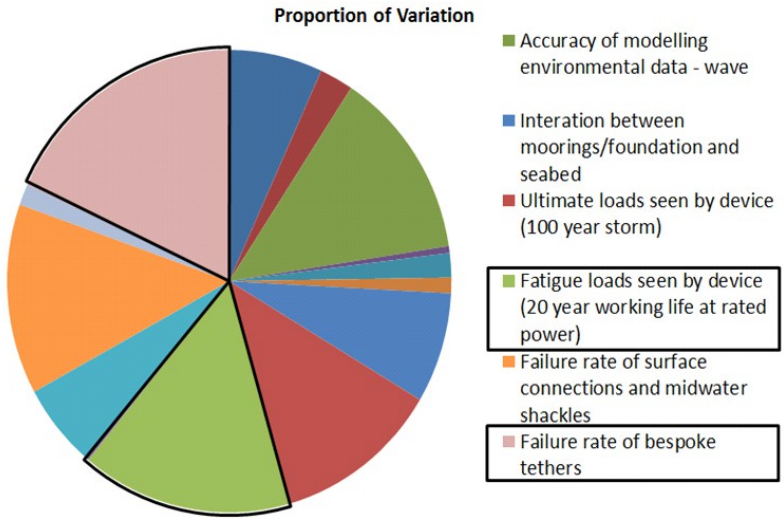


Figure 8.13: Pie chart showing proportion of total uncertainty by input. Two main inputs highlighted.

The two main improvement areas noted in the example are the fatigue loads seen by the device, and the failure rate of the bespoke tethers used. This helps drive the motivation to gather more information relating to the health and longevity of the tethers, in the form of detailed post recovery inspection and testing (see Figure 8.14).

Chosen improvement areas: Condition monitoring of deployed moorings, with a focus on bespoke tethers, surface connections, and midwater shackles

	Input		Results		
Modelling uncertainties	Sensitivity	Uncertainty	Uncertainty	VRPN	Proportion
Model detail of device	5	6	30	900	7
Model detail of mooring/foundation	3	6	18	324	2
Accuracy of modelling environmental data - wave	7	6	42	1764	13
Accuracy of modelling environmental data - wind	2	4	8	64	0
Accu					
Seab					
Desi					
Interation between moorings/foundation and seabed	4	8	32	1024	8
Ultimate loads seen by device (100 year storm)	5	8	40	1600	12
Fatigue loads seen by device (20 year working life at rated power)	5	9	45	2025	15
Measured metocean data not representative due to short sample period	1	5	5	25	0
Measured metocean data not representative due to distance from final site	4	7	28	784	6
In operation uncertainties					
Failure rate of surface connections and midwater shackles	6	7	42	1764	13
Failure rate of long term mooring shackles on seabed	2	7	14	196	1
Failure rate of bespoke tethers	7	7	49	2401	18
			380	13240	100

Figure 8.14: Table of weighted uncertainties, showing chosen improvement area.

8.3.5 Mooring inspection and test program

The inspection and test program was focused on the tethers, but also included the associated shackles and a few links of the riser chain, as these items were kept suspended and would have seen some light wear during the length of the deployment. The tests on each component were as follows:

- Metal items (shackles, chain)
  - Visual inspection both before and after light abrasive cleaning
  - Measurement of bearing surfaces to determine wear
  - Penetrative dye tests to highlight any cracking
  - Break testing on a test rig
- Tethers
  - Break testing of single tether (pull to failure after cycling the tether up to partial load 10 times)
  - Dissection of filters on second tether for visual inspection of tether inner structure

Break testing of subcomponents of the second tether (testing 3 out of 8 load bearing components gives a linear 3/8ths fraction of total tether capacity. Same cycling technique as full tether test).

8.3.6 Results

The full results of the inspection and testing will be delivered, with analysis and updates to this case study in January 2017. They will be appended to this case study as a standalone document when available.

8.3.7 Further work

This basic VMEA has used sensitivity and impact of uncertainty on a 1-10 scale to determine at a qualitative level where the main uncertainties lie within a design. Next steps to refine the process are initially thought to be twofold:

1. to gain a quantitative understanding of each uncertainty by linking them directly to safety factor and/or cost;
2. to reduce the uncertainties by creating and implementing a monitoring program for mooring components, in order to determine actual max loads vs modelled max loads, measure cumulative damage and associated reductions in longevity of components, and generally act to validate the models through measurements and inspections. This will be particularly key in situations where new materials or bespoke components are being used.

8.3.8 Conclusions

The use of basic VMEA analysis in this case study has allowed for the weighting of the different uncertainties in the design process, which in turn allowed for research efforts to be directed where it might have most effect – the post recovery testing of mooring components. Basic VMEA has proven to be a very useful first stage analysis tool for situations where there is limited data, and need to improve engineering qualitative assessments.

By reducing the uncertainty in the VMEA inputs (the mooring model or environmental data) within the mooring design, a designer could apply a lower safety factor, with improved confidence.

Lowering the safety factor is not the recommended practice until more data on reliability and component failures can be ascertained in the wave and tidal sector. However, in the drive for cost competitiveness, designing against a lower safety factor compared to safety factors applied from the O&G sector would improve CAPEX /OPEX costs including Levelised Cost of Energy (LCOE). The results of the RiaSoR project and industry workshop will be tested with the certification bodies in order to complete the uptake of the VMEA methodology.

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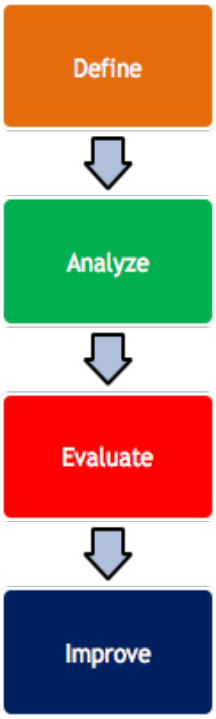
Appendix A: A Short VMEA Reference Guide

Here a short reference guide is presented for the evaluation of a probabilistic (or enhanced) VMEA. The guide follows the following steps:



1. **Target Function Definition.**
   For example, life of a component, maximum stress or largest defect.
2. **Uncertainty Sources Identification.**
   Identify all sources of uncertainty (scatter, statistical, model).
3. **Sensitivity Assessment.**
   Evaluate the sensitivity coefficients of the sources of uncertainty.
4. **Uncertainty Size Assessment.**
   Quantify the size of the different sources of uncertainty.
5. **Total Uncertainty Calculation.**
   Combine the contributions from all uncertainty sources.
6. **Reliability and Robustness Evaluation.**
   Find the dominating uncertainties or derive safety factors.
7. **Improvement Actions.**
   Identify uncertainties that are candidates for improvement actions.

1. Target Function Definition

The reliability target may be a specified life or the load/strength ratio.

In the life case the target function is defined as the difference between the logarithm of the calculated nominal life and the logarithm of the target life,

$$\ln(N) - \ln(N_{target}).$$

In the load/strength ratio case the target function is defined as the logarithmic difference between the estimated load and the estimated strength,

$$\ln(S) - \ln(L).$$

2. Uncertainty Sources Identification

The schematic description of the life assessment for a MEC is seen in the figure below, where the red and brown error bars represent *possible model errors (uncertainty)* and *variation (scatter),* respectively.

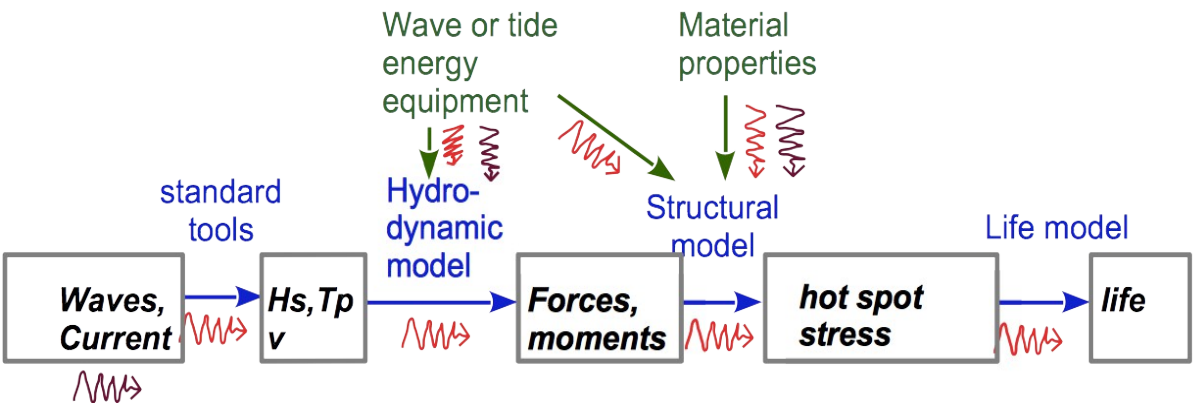


Figure: Schematic description of the life assessment for a MEC.

From this scheme one can list a number of typical uncertainty sources that usually need to be considered in the VMEA analysis:

- Marine Loads:
  - Between and within site variation (scatter)
  - Load estimation uncertainty (uncertainty)
- Hydrodynamic model:
  - Hydrodynamic model errors (uncertainty)
  - Hydrodynamic model parameter uncertainties (uncertainty)
  - Marine growth (uncertainty)
- Structural model:
  - Structural model errors (uncertainty)
  - Structural model parameter uncertainties (uncertainty)
  - Geometric tolerances (scatter)
- Strength/life:
  - Strength/life scatter (scatter)
  - Life model error (uncertainty)
  - Life model estimation uncertainty (uncertainty)
  - Damage accumulation model error (uncertainty)
  - Multi-axial effects (uncertainty)
  - Corrosion effects (uncertainty)

Of course, for each specific case there may be other sources that need to be considered.

3. Sensitivity Assessment

In case the uncertainty size is judged by means of variation in the target function, then the sensitivity coefficient is unity. This is also the case if the judgement is given in percentage variation of the anti-log of the target function.

If the target function is the difference between log strength and log load, then percentage variation by means of load or strength results in the sensitivity equal to unity.

In case the uncertainty size is measured in any other unit than the output of the target function, then the sensitivity is the partial derivative of the target function with respect to the uncertainty source in question.

This sensitivity can in most cases easily found by making two calculations of the target function. The factor of interest is varied while the others are kept fixed. It is recommended to choose the step in in the order of one or two standard deviations of the uncertainty source in question, then the two calculations can be:

1. one with nominal inputs, and
2. one where the uncertainty source in question is changed to a value two standard deviations closer to the more severe case.

The difference between the two calculated target functions is then divided by two standard deviations to get the actual sensitivity coefficient.

$$c_i = \frac{f(X_{i,nom}) - f(X_{i,nom} \pm 2 \cdot s_i)}{2 \cdot s_i}.$$

4. Uncertainty Size Assessment

Each source of uncertainty is given a measure of its size by means of a standard deviation. There are different ways to assess the uncertainty size:

1. If a set of observations of the variable of interest is available, the standard deviation is simply calculated by standard statistical tools. If the number of observations is less than 30, then the the calculated number is adjusted by a *t*-correction according to the table below.

$$s_1 = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2}, \qquad \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i.$$

2. In case the mean value of a set of observations is used to calculate the nominal strength or load, then its uncertainty is the standard deviation of the observations divided by the square root of the number of observations. The *t*-correction is chosen according to the table below.

$$s_2 = \frac{s_1}{\sqrt{n}} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2}.$$

3. If only the minimum and maximum values are available, then the standard deviation is approximated by the range (maximum minus minimum) divided by the square root of twelve and the t-correction is put to unity.

$$s_3 = \frac{\max - \min}{\sqrt{12}}.$$

4. If the uncertainty is a possible model error in the life, strength, or load calculation, then the possible error is judged from engineering experience, suitably a judgement by means of

percentage error, +/- *e*%, the standard deviation is then approximated by the percentage error divided by 100 and the square root of three,

$$s_4 = \frac{e}{100 \cdot \sqrt{3}}.$$

5. If a possible model error can be described as a set of possible alternative models, then the standard deviation of the model results can be used as the uncertainty measure, adjusted as above by a *t*-correction.
6. If the uncertainty is of any other origin, such as possible bias in sampling, possible equivalence error between test environment and service, then the judgement methods as described above can often be used for finding a proper standard deviation.

Table: Values for the t-correction factor.

n	2	3	4	5	6	7-10	11-26	27-
t_n	**6.5**	**2.2**	**1.6**	**1.4**	**1.3**	**1.2**	**1.1**	**1.0**

5. Total Uncertainty Evaluation

For each source of uncertainty, the standard deviation, the t-correction and the sensitivity coefficient are multiplied. These numbers are squared and added to the overall uncertainty variance of the target. The square root of this variance is the overall statistical uncertainty measure.

6. Reliability and Robustness Evaluation

This statistical uncertainty measure is multiplied by the number 1.64 for the *statistical safety distance.* If the nominal target function (the difference in logs) exceeds this number, then the design reliability should be at least 95%.

The amount of exceedance is a measure of the extra safety distance, which should fulfil the designers demand about extra safety for approvement.

7. Improvement Actions

In case the design is not approved, there are different possibilities:

- Change the design to increase the strength or to reduce the loads.
- Refine investigations to diminish the dominating uncertainties estimated as possible errors.
- Limit the allowed usage to diminish the load variation.

Using the Spreadsheet Tool

Each identified uncertainty source has a row entry in the sheet below. The uncertainty name, standard deviation, *t*-correction and sensitivity coefficient are filled in and it is defined as a scatter source or an uncertainty source by a cross in the chosen column.

The anti-log of the target function values are filled in in C23 and C24 and the required safety factor in cell C29.

The values in the blue cells are evaluated by the tool and the design is approved if the calculated extra safety factor in cell F29 is not lower than the required in cell C29.

	A	B	C	D	E	F	G	H	I
1	**Evaluation of Uncertainties**								
2									
3	**Input**						**Result**		
4		**scatter**	**uncert.**	**Sensitivity coefficient**	**t-correction factor**	**standard deviation**			
5	**Uncertainty components**			**c**	**t**	**s**	**Scatter**	**Uncertainty**	**Total**
6	**Strength**								
7									
8									
9									
10	**Total Strength uncertainty**								
11									
12	**Load**								
13									
14									
15									
16	**Total Load uncertainty**								
17	**Total uncertainty**								
18									
19									
20	**Reliability Evaluation**								
21									
22	**Input**			**Result**				**Result (log-scale)**	
23	Median strength			Safety factor				Strength, mS	
24	Median Load							Load, mL	
25								Distance	
26									
27									
28	**Evaluation - Extra safely factor**			Variation safety factor				Variation dist.	
29	Required extra safety factor			Extra safety factor				Extra dist.	