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Condition monitoring and diagnostics of wind turbines —

Part 1: General guidelines

Surveillance et diagnostic d'état des éoliennes de production d'électricité —

Partie 1: Lignes directrices générales

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 5, *Condition monitoring and diagnostics of machine systems*.

A list of all parts in the ISO 16079 series can be found on the ISO website.

Introduction

General

This document is the first in a series of International Standards covering the application of condition monitoring to wind turbines. It is an application of the recommendations and best practices described in the generic standards developed under ISO/TC 108.

Background

Power production from wind turbines is growing exponentially on the global energy market. As a consequence, predictability of the production from wind power plants has become as crucial as predictability of power production from conventional power plants. As for conventional power plants, an efficient maintenance programme for wind power plants adds significant value to the reliability and predictability of the supply of energy. An efficient condition monitoring system is an important part of such a programme in order to achieve the following:

a) obtain predictability in power production, thus avoiding penalties from grid authorities if the quoted amount of power is not delivered;

b) maintain the confidence of investors by providing a stable power production, thus motivating future investments;

c) lower turbine maintenance costs by

   1) avoiding development of failures to a serious state,

   2) avoiding consequential or subsequent failures, and

   3) being able to plan service months ahead;

d) reduce the through life cost by

   1) avoiding loss of availability,

   2) allowing continued operations under fault conditions (perhaps with appropriate restrictions), and

   3) supporting failure investigations to prevent repetitive events.

Condition monitoring, in general, requires:

— Reliable alarms. An alarm is triggered only when the confidence level of the diagnosis and prognosis is high. Wind turbines are placed in remote locations and many wind turbines are located offshore where access is limited and costly.

— An estimated time to failure. This is for supporting efficient maintenance planning and utilization of cranes, staff, ordering of spare parts, etc.

— Reliable descriptor measurements. In addition to self-excited forces, a wind turbine is also subject to environmental occurrences. The compact structure can cause measurement readings from one machine part to be affected by other machine parts.

— Detection of faulty monitoring. A working data acquisition system is the basis of a reliable monitoring systems. Any equipment can fail. It is essential that faulty equipment is detected to ensure a reliable condition monitoring process.

— Complex IT landscape. A monitoring system is required to monitor thousands of wind turbines connected to a central server via complex worldwide data networks. (This requirement is outside the scope of this document.)

Condition monitoring of wind turbines presents some challenges compared to condition monitoring of other machinery.

— Access to the nacelle is difficult and potentially dangerous and in many countries is not allowed during operation, so online systems are likely to be required for measurements which have traditionally used hand-held methods.

— Wind turbine loading varies significantly with time and cannot be influenced; some extra measures need to be taken to ensure repeatability of measurements.

— Self-excitation of the structures, extremes of ambient temperature and the likelihood of lightning strikes present a severe test of the robustness of all systems.

— Since wind turbines are often in remote locations, the monitoring systems need to be able to function in the face of loss of network connectivity.

Aims of the ISO 16079 series

This document and subsequent documents in the ISO 16079 series have the following aims:

a) to allow manufacturers of wind turbines, operators of wind turbines and manufacturers of condition monitoring systems for wind turbines to share common concepts and terminology;

b) to provide a methodology whereby users of this document can prioritize and select which components shall be monitored and which failure modes shall be detected, in order to obtain the most efficient condition monitoring system with regard to

   1) cost,

   2) detection capability,

   3) complexity of monitoring system and methods, and

   4) available resources and skill level of staff in the monitoring body.

It is NOT the intention of this document or subsequent documents in the ISO 16079 series to cover any aspects of safety monitoring systems.

Time-proven experience

The monitoring strategies presented in the ISO 16079 series are based on time-proven experience. Only conservative, well-proven methods and best practices are applied. This means that detection of certain failure modes may be left out if the behaviour of the failure modes and their related symptoms are not well-documented. As new monitoring techniques mature, this document will be updated accordingly.

Relation to the generic standards of ISO/TC 108

ISO 17359 is a parent standard of this document. It presents an overview of a generic procedure recommended to be used when implementing a condition monitoring programme and provides further details on the key steps to be followed. It introduces the concept of directing condition monitoring activities towards root cause failure modes and describes the generic approach to setting alarm criteria, carrying out diagnosis and prognosis and improving confidence in diagnosis and prognosis, which are developed further in other documents. Particular techniques of condition monitoring are introduced briefly.

The concept of condition monitoring itself and the measurement techniques involved are presented in other generalized condition monitoring guidelines such as ISO 13373 (all parts), ISO 13374 (all parts) and ISO 13379-1. Those guidelines are considered as foundations of this document. Figure 1 illustrates how this machine-specific document is linked to other generic guidelines of condition monitoring and measurement techniques.

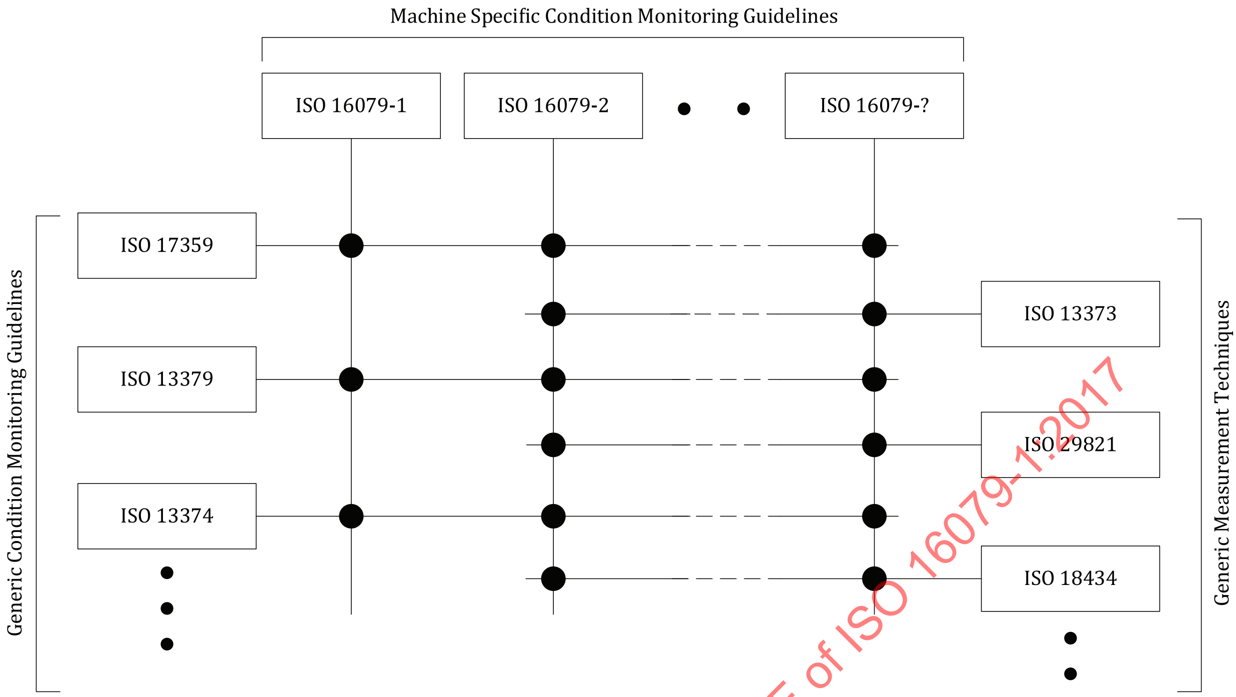


Figure 1 — Links between the machine-specific International Standards and the generic International Standards

Other documents and guidelines for wind turbines

The documents and guidelines listed here are not within the scope of this document. However, a brief introduction is relevant as they are often referenced.

— ISO 10816-21[1] specifies broadband measurements to be applied for the evaluation of mechanical vibrations of wind turbine using zone boundaries. Examples of zone boundaries for onshore wind turbines below 3MW are provided in an annex. The aim of ISO 10816-21 is to standardize vibration measurements, to assist in their evaluation and to make possible a comparative evaluation of the vibration measured in wind turbines and their components. For long-term condition monitoring and diagnostics, more advanced techniques are required which are outside the scope of ISO 10816-21.

— IEC 61400-25-6[10] in the IEC 61400-25 series specifies the information models related to condition monitoring for wind power plants and the information exchange of data values related to these models. The purpose of the ISO 16079 series is to define the descriptors for detection of various failure modes. IEC 61400-25-6 complements this document by specifying how to organize these descriptors in a data model.

  A data model organizes data elements and standardizes how the data elements relate to one another. The data model allows a single computer program to retrieve wind turbine data from several different condition monitoring systems where the data model is implemented. IEC 61400-25-6 describes notation for identifying sensors and sensor locations, sensor types, operational states and proposes a systematic naming of descriptor types.

— The DNV·GL guideline[11] specifies requirements for the certification of condition monitoring systems for wind turbines and the associated monitoring bodies. The guideline specifies requirements to the documentation of the condition monitoring system and requirements to associated procedures which are applied by the staff of the monitoring body. The guideline specifies sensor location and required frequency ranges as well as requirements to the presence of certain analysis procedures. The guideline does not propose any requirements to which failure modes shall be detected, nor to the capability of measuring related descriptor types.

Relation to the ISO 55000 series

The requirement of the ISO 55000 series is straightforward and has a direct link to condition monitoring. An organization, a company, a wind power plant, etc. has a portfolio of assets. It has a corporate strategy that provides overall objectives for the entire organization. Those assets are intended to deliver part of those objectives. Effective control and governance of assets by organizations is essential to realize value through managing risk and opportunity, in order to achieve the desired balance of cost, risk and performance.

For a wind power plant, condition monitoring is a key risk-handling element of the asset management program by avoiding that wind turbines fail unexpectedly, keeping the cost of operation under control and ensuring a high performance.

Condition monitoring and diagnostics of wind turbines —

Part 1:
General guidelines

1 Scope

This document gives guidelines which provide the basis for choosing condition monitoring methods used for failure mode detection, diagnostics and prognostics of wind power plant components.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2041, *Mechanical vibration, shock and condition monitoring – Vocabulary*

ISO 13372:2012, *Condition monitoring and diagnostics of machines — Vocabulary*

ISO 13379-1:2012, *Condition monitoring and diagnostics of machines — Data interpretation and diagnostics techniques — Part 1: General guidelines*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 and ISO 13372 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
alarm
operational signal or message designed to notify personnel when a selected *anomaly* (3.2) or a logical combination of anomalies, which requires a corrective action is encountered

[SOURCE: ISO 13372:2012, 4.2, modified — "requiring" has been replaced by "which requires".]

3.2
anomaly
irregularity or abnormality in a system

[SOURCE: ISO 13372:2012, 4.4]

3.3
component
sub-component
component part
part of a geared wind turbine, typically the main bearing, gearbox and generator

Note 1 to entry: Each of these components in the strictest sense of the definition can also contain several sub-components or component parts such as a generator bearing or a planet gear.

3.4
consequential damage
phenomena whereby degradation of one *component* (3.3) can cause *failures* (3.7) in other components

Note 1 to entry: This is also often referred to as secondary damage or subsequent damage.

3.5
descriptor
data item derived from raw or processed parameters or external observation

Note 1 to entry: Descriptors are used to express *symptoms* (3.15) and *anomalies* (3.2). The descriptors used for monitoring and diagnostics are generally those obtained from condition monitoring systems. However, operational parameters, like any other measurement, can be considered as descriptors.

Note 2 to entry: Descriptors are also referred to as “condition monitoring descriptors”.

[SOURCE: ISO 13372:2012, 6.2, modified — the admitted term "feature" has been deleted and the Notes to entry have been added.]

3.6
estimated time to failure
ETTF
lead time
estimation of the period from the current point in time to the point in time where the monitored machine has a *functional failure* (3.8)

[SOURCE: ISO 13381-1:2015, 3.8, modified — the term "lead time" has been added.]

3.7
failure
termination of the ability of a *component* (3.3) or a machine to perform a required function

Note 1 to entry: Failure is an event as distinguished from *fault* (3.10), which is a state.

[SOURCE: ISO 13372:2012, 1.7, modified — “item” has been replaced with "component" and “machine”.]

3.8
functional failure
F
point in time when the machine stops performing its required function

3.9
failure mode
manner in which an equipment or machine *failure* (3.7) can occur

Note 1 to entry: A machine can have several failure modes such as rubbing, spalling, unbalance, electrical discharge damage, looseness, etc. A failure mode produces *symptoms* (3.15) indicating the presence of a *fault* (3.10).

3.10
fault
<of a component of a machine, in a machine> occurs when one of its *components* (3.3) or assembly degrades or exhibits abnormal behaviour, which can lead to *functional failure* (3.8) of the machine

Note 1 to entry: See also *potential failure* (3.12).

Note 2 to entry: Fault can be the result of a *failure* (3.7), but can exist without a failure.

[SOURCE: ISO 13372:2012, 1.8, modified — the scope of application has been added, "failure" has been replaced by "functional failure" and the Notes to entry have been changed.]

3.11
P-F interval
estimate of the period from the detection of a *fault* (3.10) [*potential failure*, P (3.12)] and *functional failure* (F) (3.8)

Note 1 to entry: *ETTF/lead time* (3.6) is equal to or less than the P-F interval.

Note 2 to entry: See also *estimated time to failure* (3.6).

Note 3 to entry: For efficient planning of a maintenance action, it is useful to know the P-F interval of a specific *failure mode* (3.9). Refer to Annex A for further explanation of P-F interval, *ETTF/lead time* (3.6) and *RUL* (3.13).

3.12
potential failure
P
point in time when a *fault* (3.10) becomes detectable

Note 1 to entry: This is sometimes also called "potential for failure".

3.13
remaining useful life
RUL
remaining time before system health falls below a failure threshold defined by the confidence level of the *ETTF* (3.6) and the acceptable risk

Note 1 to entry: The capability to predict RUL is the goal of the prognostic process.

Note 2 to entry: Refer to Annex A for further explanation of *P-F interval* (3.11), *ETTF/lead time* (3.6) and *RUL*.

3.14
root cause
set of conditions and/or actions that occur at the beginning of a sequence of events that result in the initiation of a *failure mode* (3.9)

[SOURCE: ISO 13372:2012, 8.9, modified — the term "and" has been added.]

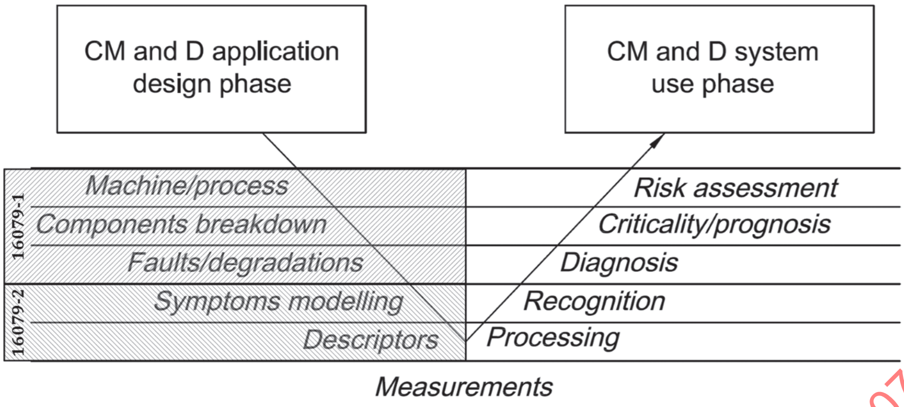
3.15
symptom
<of a fault> perception, made by means of human observations and measurements [*descriptors* (3.5)], which can indicate the presence of one or more *faults* (3.10) with a certain probability

[SOURCE: ISO 13372:2012, 9.4, modified — the scope of application has been added and the term "with a certain probability" has been added.]

4 Overview of condition monitoring procedure implementation — Set-up and diagnostics requirements

In order to implement condition monitoring and diagnostic procedures according to the faults that can occur in the wind turbine, this guideline recommends following the V-model as illustrated in ISO 13379-1.

An overview of this procedure is shown in Figure 2. The left branch corresponds to the preliminary study which prepares the necessary data for condition monitoring and diagnostics for a particular machine. The right branch of the diagram corresponds to the condition monitoring and diagnostics activities that are normally undertaken after the machine has been commissioned. Data reduction is a big issue for condition monitoring systems. Note that the data reduction process starts in the phase of the preliminary study as an outcome of the analysis process where it is prioritized which kind of failure modes it is relevant to monitor. The scopes of this document and subsequent documents such as ISO 16079-2 are indicated in Figure 2.



NOTE Source: ISO 13379-1:2012, Figure 1.

Figure 2 — Condition monitoring and diagnostics (CM and D) cycle: Design and use of the application on a machine

In accordance with ISO 13379-1, it is recommended that the preliminary study is carried out using the following, see Figure 3.

a) A FMECA (failure modes, their effects and criticality analysis) procedure. The purpose of this document is to facilitate this FMECA procedure.

b) A FMSA (failure mode and symptoms analysis) procedure, which shall be facilitated in subsequent component specific standards such as ISO 16079-2.

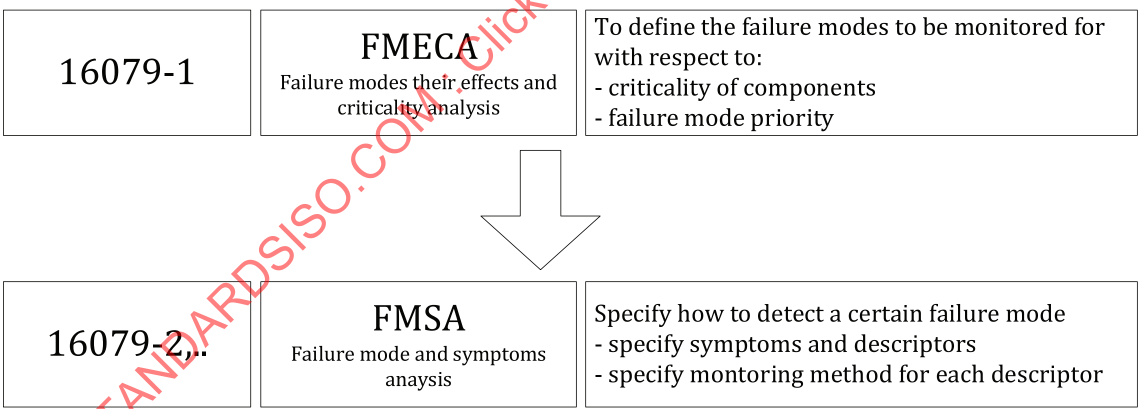


Figure 3 — Necessity of using FMECA before FMSA

The steps in this document's FMECA are as follows.

a) List the major wind turbine components.

b) Determine the criticality factor for each component, taking into account how critical the component is for the process, the ease of repair, availability and cost of spares, repair time, the risk of consequential damage, the location of the turbine and the failure rate of the component if such knowledge is available.

c) Identify the failure modes for each component. Prioritization of each failure mode to be monitored for, with respect to detectability and lead time.

d) Decide which failure modes shall be detected and diagnosed by taking into account the criticality of the component and the cost efficiency of monitoring for the different failure modes.

NOTE Annex D provides a brief introduction to the concept of FMECA analysis.

Steps in the FMSA such as described in ISO 16079-2 are as follows.

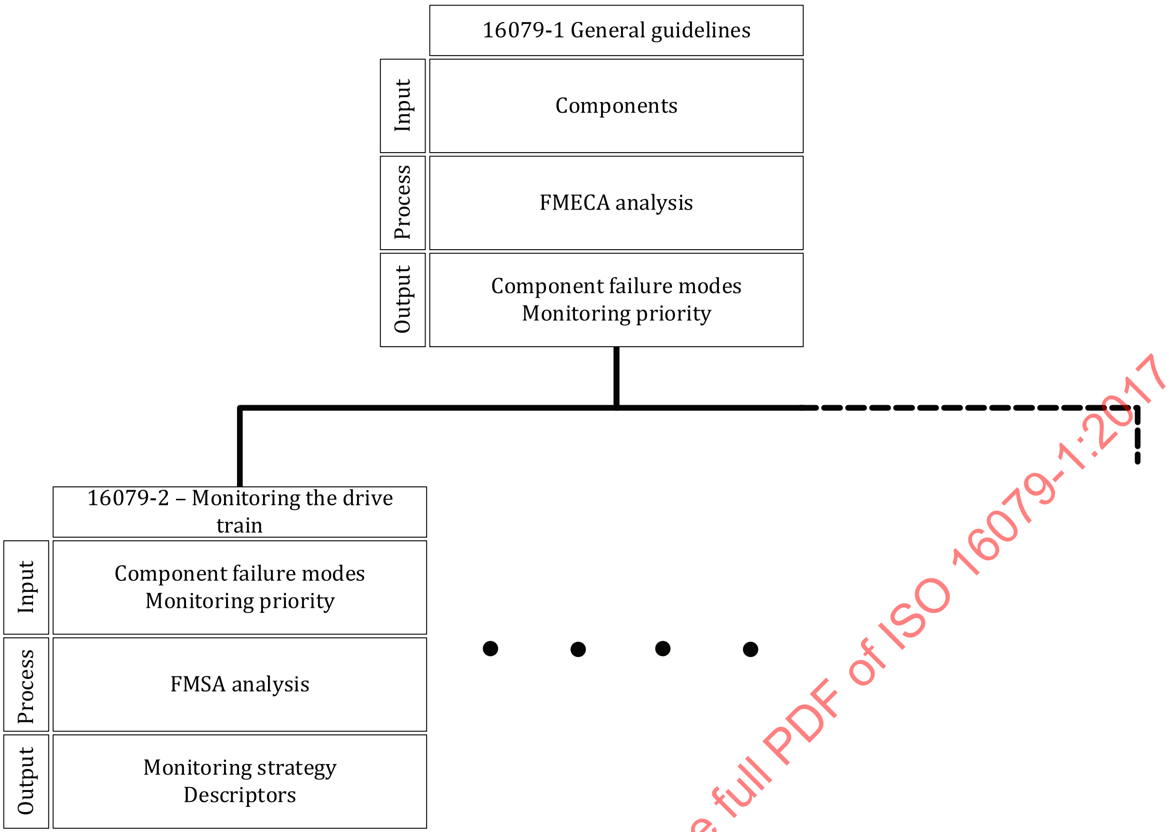
a) Decide under which operating conditions the different faults can be best observed and specify reference conditions.

b) Identify the symptoms that can serve in assessing the condition of the machine and that will be used for diagnostics.

c) List the descriptors that will be used to evaluate (recognize) the different symptoms.

d) Identify the necessary measurements and transducers from which the descriptors will be derived or computed.

Figure 4 shows the relation between this document and a subsequent guideline such as ISO 16079-2.



NOTE The output of the FMECA analysis is used as an input to the FMSA analysis.

Figure 4 — Relationship between this document and ISO 16079-2

5 FMECA: Identification of failure modes, their effects and criticality

5.1 Overview

The purpose of this clause is to provide an overview of the FMECA procedure. The result of the FMECA is a monitoring priority number (n_{MP}) for each of the wind turbine components. The n_{MP} allows the users of this document to focus their condition monitoring effort where it is most cost beneficial and by combining it with a FMSA analysis for each turbine component, use the results to specify requirements for the wind turbine condition monitoring system.

The monitoring priority number is defined as shown by Formula (1):

$$n_{MP} = f_{CR} \times f_{FMP} \quad (1)$$

where

n_{MP} is the monitoring priority number;

f_{CR} is the criticality factor, i.e. the criticality of each wind turbine component;

f_{FMP} is the failure mode priority factor, i.e. the prioritization of each failure mode with respect to detectability and lead time.

In order to have a uniform reference for the FMECA assessment and to guide the procedure, f_{CR} and f_{FMP} shall be assessed using criteria specified in two tables:

a) Table 1;

b) Table 2.

Using these two tables, the procedure for the FMECA is as follows.

a) List the components to be included in the FMECA.

b) Use Table 1 to identify the criticality factor, f_{CR}, for each component.

c) Use Table 2 to identify the failure mode priority factor, f_{FMP}, for the failure modes of each component.

d) Finalize the FMECA by combining f_{CR} with f_{FMP} into the monitoring priority number, n_{MP}.

Figure 5 presents the process overview.

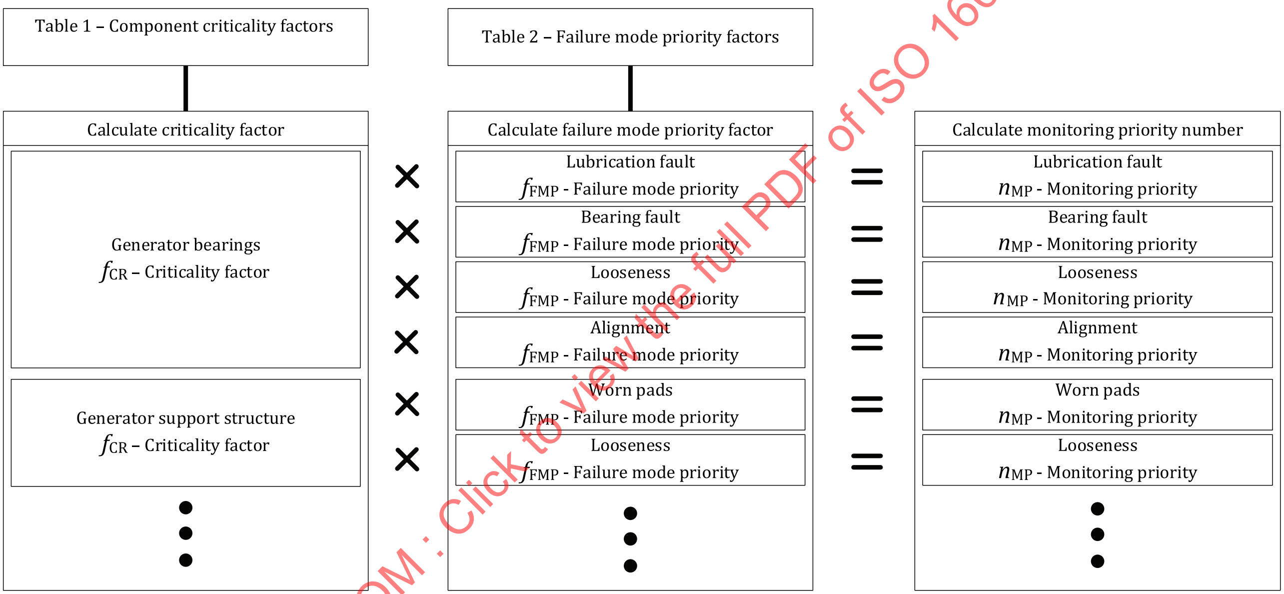


Figure 5 — Overview of the FMECA process

5.2 Identification of wind turbine components criticality factor, f_{CR}

There are four criteria which are combined into the criticality factor, f_{CR}, as shown by Formula (2):

$$f_{CR} = f_{LP} + f_{RE} + f_{CD} + f_{FR} \quad (2)$$

where

f_{LP} is the loss of production;

f_{RE} is the repair effort;

f_{CD} is the consequential damage;

f_{FR} is the failure rate.

Each of the four criticality criteria is assessed using Table 1.

NOTE Refer to Annex B for a practical example of assessing f_{CR} for a wind turbine drive train.

When assessing the criticality factor for a component, it is advised to split each component, such as the generator, into as many component parts as possible and assess a criticality factor for each component part. Some component parts, such as a generator bearing, can be repaired up-tower; other component parts can require an exchange of the major component such as the gearbox. Loss of production (f_{LP}) in Table 1 is used to state the influence of component functional failure on production. It is important to note that a functional failure does not necessarily mean the machine has failed catastrophically, but rather, it is no longer functioning in its intended state (e.g. production capacity). Not all functional failures of a component part have an immediate impact on production, some might not have at all.

Table 1 — Wind turbine component criticality factor, f_{CR}

Criteria	Explanation	Criticality rating
Criterion 1: Loss of production (f_{LP})		
CRITICAL	Immediate loss of production on functional failure. The component failure has immediate consequence for production. Either due to production stop or derating of the turbine.	3
IMPORTANT	Could cause loss of production on functional failure. The component failure could affect production. Derating of the turbine might become necessary.	2
NON CRITICAL	Causes no loss of production on functional failure. The component failure does not affect production.	1
Criterion 2: Repair effort (f_{RE})		
HIGH	Repair is either too difficult to carry out on site or is too difficult to carry out with normal equipment and staff. Spares might not be available due to uniqueness or obsolescence and will need to be manufactured. Thus, high cost of repair, long downtime due to repair and high cost of spare part.	3
MEDIUM	Repair is either difficult or involves complex and lengthy stripdown of machinery. Spares might not be held on site and will need to be ordered from the manufacturer and therefore cause some delay.	2
LOW	Typically up-tower repair. Repair is possible using standard techniques available on site and does not involve significant stripdown of machinery. Spares are readily available on site.	1
Criterion 3: Consequential damage (f_{CD})		
SEVERE DAMAGE	Failure of the component is certain to cause considerable damage to associated components.	3
LIMITED DAMAGE	Failure of the component is unlikely to cause major failures of associated components, but will cause limited damage.	2
NO DAMAGE	Experience of the plant has shown that little or no damage occurs following component failure.	1
Criterion 4: Failure rate (f_{FR})		
HIGH FAILURE RATE	Experience has shown that the component has an average lifetime of less than 20 % of the normal turbine lifetime.	3
MEDIUM FAILURE RATE	Experience has shown that the component has an average lifetime more than 20 % but less than 80 % of the normal turbine lifetime.	2
LOW FAILURE RATE	Experience has shown that the component has an average lifetime of more than 80 % of the normal turbine lifetime.	1

5.3 Identification of failure mode priority factor, f_{FMP}

There are six criteria which are combined into the failure mode priority factor, f_{FMP}, as shown by Formula (3):

$$f_{FMP} = f_{FMT} + f_{EFD} + f_{RFMS} + f_{EA} + f_{EDA} + f_{P\text{-}F} \quad (3)$$

where

f_{FMT} is the failure mode type;

f_{EFD} is the ease of fault detection;

f_{RFMS} is the repeatability of failure mode symptoms;

f_{EA} is the ease of automatic monitoring;

f_{EDA} is the ease of detailed analysis;

$f_{P\text{-}F}$ is the P-F interval.

Each of the six criteria for a wind turbine failure mode type shall be assessed using Table 2. Table 2 reflects the viewpoint that a correct assessment of a failure mode brings most value to the investment in a condition monitoring system. Therefore, it is most beneficial to prioritize the monitoring of failure modes which are the easiest to detect with simple means and which match the training level of the surveillance staff. Trying to detect non-trivial failure modes will often lead to many false alarms causing expensive and wasted service visits leading to increased service costs.

The lead time (P-F interval) influences the failure mode priority factor. Short lead time requires more attention in order to avoid component failure which in many cases also causes consequential damage.

NOTE Refer to Annex B for a practical example of assessing f_{FMP} for a wind turbine drive train.

Table 2 — Wind turbine failure mode priority factor, f_{FMP}

Criteria	Explanation	Priority rating
Criterion 1: Failure mode type (f_{FMT})		
STANDARD	Fault is well-documented and understood.	3
UNUSUAL	Fault is not well-documented or is specific to a single turbine.	2
NON STANDARD	Fault is not well-understood or not applicable to the turbine in question.	1
Criterion 2: Ease of fault detection (f_{EFD})		
CLEAR SYMPTOMS	Fault produces clearly defined symptoms.	3
LIMITED SYMPTOMS	Fault produces some defined symptoms, but also some unrelated symptoms.	2
NO RELATED SYMPTOMS	Fault produces no related symptoms.	1
Criterion 3: Repeatability of failure mode symptoms (f_{RFMS})		
HIGH	Symptoms are repeatable and are unaffected by changes in operating conditions.	3
SOME	Symptoms are repeatable but show variations with changes in operating conditions.	2
POOR	Symptoms are not consistently repeatable and show significant variations with changes in plant conditions.	1
Criterion 4: Ease of automatic monitoring (f_{EA})		
GOOD	The symptoms are well-suited for automatic monitoring using trending of descriptors.	3
MODERATE	The symptoms shows variations and some degree of randomness which makes trending difficult. Can be mixed with other failure modes.	2
POOR	The symptoms indicating the fault are not applicable for trending.	1
Criterion 5: Ease of detailed analysis (f_{EDA})		
GOOD	The symptoms are easy to reveal by further detailed analysis, e.g. by analysis of the time wave form with simple spectral techniques.	3
MODERATE	The symptoms requires the use of complex analysis techniques. Can be mixed with other failure modes.	2
POOR	The symptoms cannot be revealed by detailed analysis, e.g. by analysis of the time wave form. Very low signal, difficult to extract signal from surrounding noise. Requires special sensor installation.	1
Criterion 6: P-F interval (f_{P-F})		
SHORT	The P-F interval is normally less than 14 days.	3
MEDIUM	The P-F interval is normally more than 14 days but less than 2 months.	2
LONG	The P-F interval is normally more than 2 months.	1

5.4 Calculating the monitoring priority number, n_{MP}

The monitoring priority number, n_{MP}, for a particular wind turbine component failure mode is the combination of the evaluation of the criticality of a certain wind turbine component and the evaluation of the capability of detecting the different failure modes related to the wind turbine component. The monitoring priority number expresses the cost benefit of monitoring a certain wind turbine component failure mode. That is, it indicates where a condition monitoring system will provide the highest value.

The monitoring priority number is calculated as shown by Formula (1).

EXAMPLE 1 Monitoring priority number for a critical component causing immediate loss of production upon functional failure, repair effort high, with high risk of consequential damage and low failure rate but with easily identifiable, measurable and repeatable symptoms and a long P-F interval.

Table 1: $f_{CR} = 3 + 3 + 3 + 1 = 10$

Table 2: $f_{FMP} = 3 + 3 + 3 + 3 + 3 + 1 = 16$

$n_{MP} = f_{CR} \times f_{FMP} = 10 \times 16 = 160$

The number can be normalized by calculating the relative monitoring priority number:

$f_{CR\_max} = 12$ (from Table 1)

$f_{FMP\_max} = 18$ (from Table 2)

$$n_{MP\_rel} = \frac{n_{MP}}{f_{CR\_max} \times f_{FMP\_max}} = \frac{160}{216} = 0,74$$

The relative number makes it easier to assess and compare the monitoring priority numbers.

EXAMPLE 2 Monitoring priority numbers for a critical component causing immediate loss of production where repair effort is low with a risk of severe consequential damage and high failure rate but with easily identifiable, measurable and repeatable symptoms which are easy to monitor and make detailed analysis on, monitoring technique is standard, but with a short lead time.

Table 1: $f_{CR} = 3 + 1 + 3 + 3 = 10$

Table 2: $f_{FMP} = 3 + 3 + 3 + 3 + 3 + 3 = 18$

$n_{MP} = f_{CR} \times f_{FMP} = 10 \times 18 = 180$

$$n_{MP\_rel} = \frac{180}{216} = 0,83$$

Annex A
(informative)

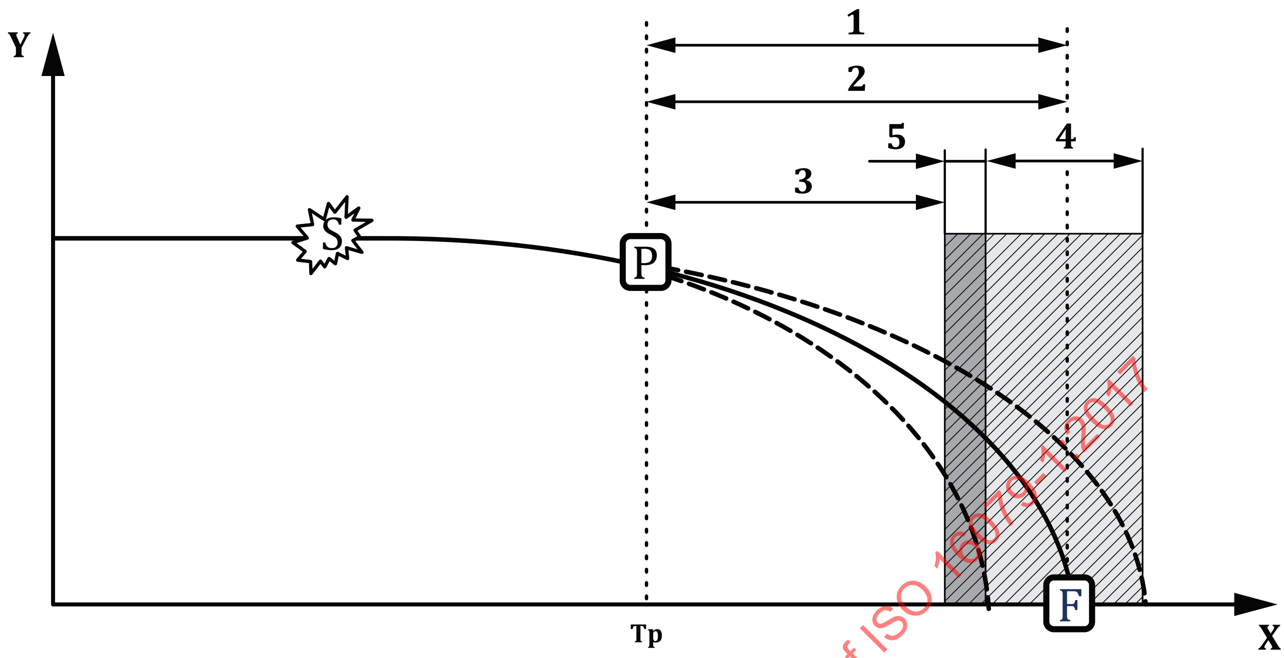
P-F interval, ETTF and RUL

A.1 General

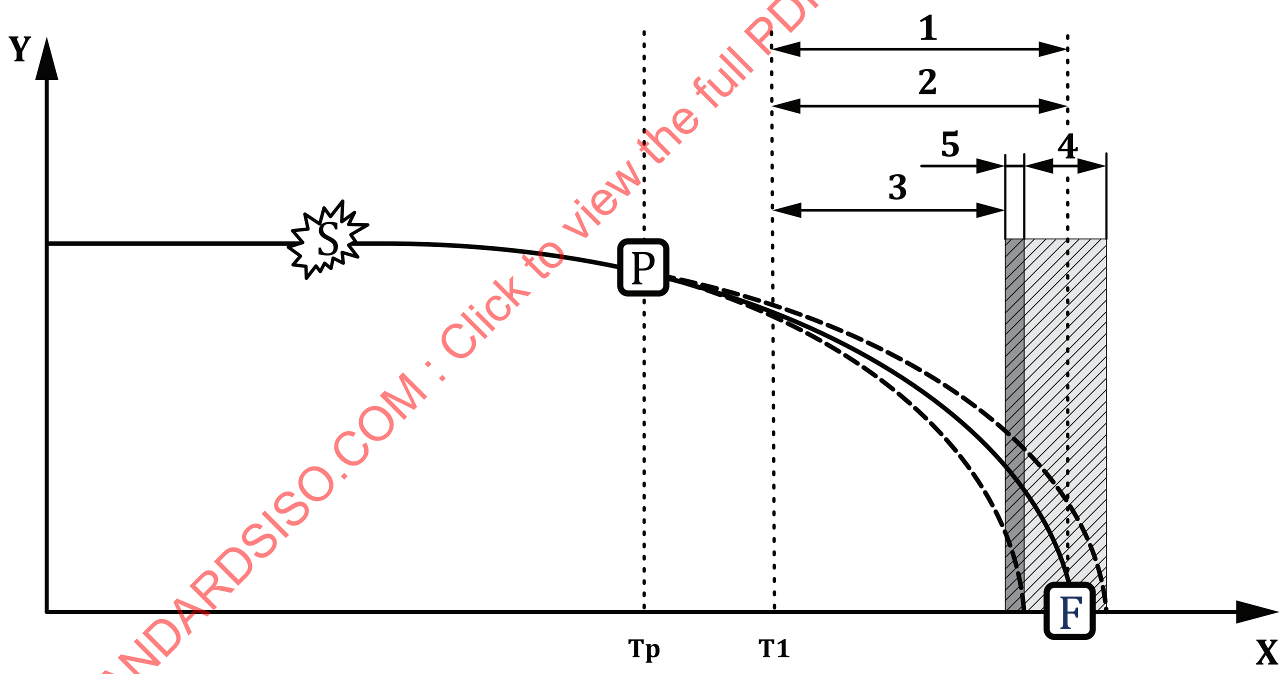
A model used to describe the path to failure of a component is the P-F interval. P-F stands for potential for failure. The P-F interval is the estimate of the period from the detection of a fault [potential failure (P)] and functional failure (F). Figure A.1 illustrates the deterioration of the condition of the machine as time goes on and the fault gets worse. A functional failure does not necessarily mean the machine has failed catastrophically, but rather, it is not long functioning in its designed state (e.g. production capacity).

A.2 Explanation

Figure A.1 illustrates the concepts of P-F interval, ETTF/lead time and RUL. The example could illustrate an outer race defect in a rolling element bearing. This type of defect typically has a very long P-F interval of between six months and one year.



(a) Bearing fault: Fault detected (Tp)



(b) Bearing fault: Fault has progressed (T1)

Key

S	fault starts to develop	1	P-F interval
P	point where fault is detectable (potential failure)	2	ETTF (lead time) (= P-F interval)
F	point where functional failure occurs	3	RUL – remaining useful lifetime
X	time	4	confidence of prognosis
Y	machine condition	5	risk

Figure A.1 — Simplified illustration of P-F interval, ETTF, RUL and risk

The example in Figure A.1 a) illustrates a point, Tp, where the fault is initially detected. In Figure A.1 a) the ETTF (lead time) is equal to the P-F interval. RUL is less than the ETTF as it takes into account the confidence level of the diagnosis/prognosis and a risk evaluation where the consequence of a functional failure is taken into consideration. The dashed curves indicate points in time where functional failure can occur when the confidence of the diagnosis/prognosis is taken into account.

The example in Figure A.1 b) illustrates a point, T1, after the fault has initially been detected. At point T1, ETTF and RUL have been reassessed by using information from the condition monitoring system. As the fault has progressed, it is possible to make a diagnosis/prognosis with a higher confidence, resulting in a more accurate ETTF. This lowers the risk and results in an updated RUL, thus stretching the remaining life of the component.

Using regular assessment of the confidence level by condition monitoring after a fault has been detected can contribute significantly to control risk and extend the component's lifetime.

Annex B
(informative)

Example of FMECA analysis for a wind turbine drive train

B.1 General

This example performs a FMECA analysis by using the evaluation factors in Table 1 and Table 2.

B.2 Calculation of criticality factor

The procedure is as follows.

a) List the wind turbine components and the related parts which shall be included in the FMECA analysis (see Table B.1). The selection of components and parts in the example can be extended with other components and parts. Refer to Annex C for further proposals.

b) Use Table 1 to assess the criticality factor for each part.

Table B.1 — Calculation of criticality factors, f_{CR}, for each turbine component

Component	Part	f_{LP}	f_{RE}	f_{CD}	f_{FR}	f_{CR}
Generator rotor – mechanical	Bearing system	3	1	3	2	9
	Shaft	3	2	3	1	9
	Bandage	3	2	2	1	8
	Fan	2	1	2	1	6
	Support structure	2	1	1	1	5
Generator rotor – electrical	Winding	3	3	3	1	10
	Slip ring	2	1	1	3	7
Coupling		3	1	2	1	7
Gearbox	Casing	3	3	3	1	10
	Suspension	3	1	2	1	7
Gearbox stage – helical	Helical part, gear	3	1	2	2	8
	Helical part, bearing	3	1	2	2	8
	Helical part, pinion	3	1	2	2	8
	Helical part, shaft	3	1	3	1	8
Gearbox stage – epicyclic	Planet carrier	3	2	2	1	8
	Planet bearing	3	2	2	1	8
	Planet gear	3	2	2	1	8
	Ring gear	3	2	2	1	8
	Sun gear	3	2	2	1	8
Main bearing		3	2	2	1	8

B.3 Calculation of failure mode priority factor and monitoring priority number

The procedure is as follows.

a) List the wind turbine components, the related parts and their failure modes (see Table B.2).

b) Use Table 2 to assess the failure mode priority factor for each failure mode. If there is no knowledge about a certain failure mode, the f_{FMP} and n_{MP} fields are left open. The open fields are also important information as they document the failure modes not to be considered in the subsequent FMSA analysis and thus cannot be detected by the condition monitoring system. The open space can also be a motivation factor for investigating how these failure modes are detected. Likewise, failure modes for components with a high f_{CR} but a low n_{MP} also motivate for further investigation.

c) Calculate the monitoring priority number by multiplying the criticality factor from Table B.1 and the failure mode priority number. Calculate n_{MP_rel} by normalizing with the maximum possible n_{MP} = 216.

Table B.2 — Failure mode priority (FMP) and monitoring priority (n_{MP})

Component	Part	Failure mode	f_{FMT}	f_{EFD}	f_{RFMS}	f_{EA}	f_{EDA}	f_{P-F}	f_{FMP}	f_{CR}	n_{MP}	n_{MP_rel}
Generator – mechanical	Bearing system	Bearing fault	3	3	3	3	3	1	16	9	144	0,67
		Lubrication failure	2	2	2	2	2	3	13	9	117	0,54
		Alignment	3	3	3	3	3	1	16	9	144	0,67
		Looseness	3	3	3	3	3	1	16	9	144	0,67
	Shaft	Crack	3	3	3	2	3	2	16	9	144	0,67
	Bandage	Broken	—	—	—	—	—	—	—	8	—	—
	Fan	Fracture	—	—	—	—	—	—	—	6	—	—
	Support structure	Looseness	3	3	3	3	3	1	16	5	80	0,7
		Worn pads	3	3	3	3	3	1	16	5	80	0,37
Generator – electrical	Winding	Lost wedges	—	—	—	—	—	—	—	10	—	—
		Looseness	—	—	—	—	—	—	—	10	—	—
		Shorted turns	—	—	—	—	—	—	—	10	—	—
	Slip ring	Wear	—	—	—	—	—	—	—	7	—	—
Coupling		Misalignment	3	3	3	3	3	1	16	7	112	0,52
		Looseness	3	3	3	3	3	3	18	7	126	0,58
		Wear	3	3	3	3	3	1	16	7	112	0,52
Gearbox	Casing	Crack	1	1	1	1	1	3	8	10	80	0,37
	Suspension	Looseness	3	3	3	3	3	1	16	7	112	0,52
Gearbox stage – helical	Gear	Tooth fault	3	3	3	3	3	1	16	8	128	0,59
	Bearing	Bearing fault	3	3	3	3	3	1	16	8	128	0,9
	Pinion	Tooth fault	3	3	3	3	3	1	16	8	128	0,59
	Shaft	Crack	2	2	2	1	1	3	11	8	88	0,41
Gearbox stage – epicyclic	Planet carrier	Bearing fault	3	2	1	2	2	1	11	8	88	0,41
	Planet bearing	Bearing fault	2	2	2	2	2	2	12	8	96	0,44
	Planet gear	Tooth fault	3	2	3	3	3	2	16	8	128	0,59
	Ring gear	Tooth fault	3	2	3	3	3	2	16	8	128	0,59
	Sun gear	Tooth fault	3	2	3	3	3	2	16	8	128	0,59
Main bearing		Bearing fault	2	2	2	2	2	1	11	8	88	0,41

As an example, the FMECA can be used to decide that only failure modes with a relative $n_{MP\_rel} \geq 0{,}5$ shall be carried over to the next step: the failure mode and symptoms analysis. Including the failure modes with lower n_{MP} can increase the initial cost of the condition monitoring system as well as the cost of operation of the monitoring system. The failure modes selected by using the FMECA documents the detection capability of the condition monitoring system.

The example shown in this annex is mainly based upon utilizing the experience with cheap vibration sensors like accelerometers. The result of the analysis might have another outcome if additional specialized sensor types are considered. However, the cost of additional sensors and equipment shall always be considered. It is recommended to make a cost benefit calculation for each failure mode based upon the calculated n_{MP}.

The FMECA also shows that n_{MP} could not be calculated for some components and failure modes even if f_{CR} is high. This can be due to lack of appropriate sensors or condition monitoring methods. This can be a motivation to perform further investigations in order to design monitoring methods which have a high f_{FMP} for the particular failure modes.

