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Condition monitoring and diagnostics of machines — Prognostics

Part 1: General guidelines

National foreword

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Part 1: **General guidelines**

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 5, *Condition monitoring and diagnostics of machine systems*.

This second edition cancels and replaces the first edition (ISO 13381-1:2004), which has been technically revised.

ISO 13381 consists of the following parts, under the general title *Condition monitoring and diagnostics of machines — Prognostics*:

— *Part 1: General guidelines*

The following parts are planned:

— *Part 2: Performance based approaches*

— *Part 3: Cyclic-driven life usage techniques*

— *Part 4: Useful-life-remaining prediction models*

Introduction

The complete process of machine condition monitoring consists of five distinct phases:

— detection of problems (deviations from normal conditions);

— diagnosis of the faults and their causes;

— prognosis of future fault progression;

— recommendation of actions;

— post-mortems.

Machine health prognosis demands prediction of future machine integrity and deterioration so there can be no exactitude in the process. Instead, prognosis requires statistical or testimonial approaches to be adopted. Standardization in machine health prognosis therefore embodies guidelines, approaches, and concepts rather than strict procedures or standard methodologies.

Prognosis of future fault progressions requires foreknowledge of the probable failure modes, future duties to which the machine will or might be subjected, and a thorough understanding of the relationships between failure modes and operating conditions. This may require an understanding of the physics underlying the fault modes and demand the collection of previous duty and cumulative duty parameters, previous maintenance history, inspection results, run-to-failure data, trajectories and associated operational data, along with condition and performance parameters prior to extrapolations, projections and forecasts.

Prognosis processes need to be able to accommodate analytical damage models.

As computing power increases, and data storage decreases in cost, multiple-parameter analysis becomes more complex and modelling becomes more sophisticated. Thus, the ability to predict the progression of damage accumulation is achievable if the initiation criterion is known (expressed as a set of parameter values for a given mode) in addition to future behaviour for a given set of conditions.

Condition monitoring and diagnostics of machines — Prognostics —

Part 1: General guidelines

1 Scope

This part of ISO 13381 provides guidance for the development and application of prognosis processes. It is intended to

— allow developers, providers, users and manufacturers to share common concepts of prognostics,

— enable users to determine the data, characteristics, processes and behaviours necessary for accurate prognosis,

— outline appropriate approaches and processes to prognostics development, and

— introduce prognostics concepts in order to facilitate future systems and training.

Other parts will include the introduction of concepts of the following forms of prognostic approaches: performance changes (trending) approaches (ISO 13381-2), cyclic-driven life usage techniques (ISO 13381-3), and useful-life-remaining models (ISO 13381-4).

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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, *Condition monitoring and diagnostics of machines — Vocabulary*

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

ISO 17359, *Condition monitoring and diagnostics of machines — General guidelines*

3 Terms and definitions

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

3.1
prognosis
estimation of time to failure and risk for one or more incipient failure modes

[SOURCE: ISO 13372:2012, 10.2]

3.2
prognostics
analysis of the symptoms of faults to predict future condition and residual life within design parameters

[SOURCE: ISO 13372:2012, 1.15]

3.3
confidence level
figure of merit (e.g. percentage) that indicates the degree of certainty that the diagnosis/prognosis is correct

Note 1 to entry: This figure essentially represents the cumulative effect of error sources on the final certainty or confidence in the accuracy of the outcome. Such a figure can be determined algorithmically or via a weighted assessment system.

3.4
root cause
set of conditions or actions that occur at the beginning of a sequence of events that result in the initiation of a failure mode

[SOURCE: ISO 13372:2012, 8.9]

3.5
failure modes effects analysis
FMEA
structured procedure to determine equipment functions and functional failures, with each failure being assessed as to the cause of the failure and the effects of the failure on the system

Note 1 to entry: The technique may be applied to a new system based on analysis or an existing system based on historical data.

Note 2 to entry: A FMEA procedure is outlined in IEC 60812.[3]

[SOURCE: ISO 13372:2012, 8.2]

3.6
failure modes effects criticality analysis
FMECA
FMEA with a classification process based on the severity of the faults

Note 1 to entry: This is in comparison with the criticality thresholds.

Note 2 to entry: A FMECA procedure is also outlined in IEC 60812.[3]

[SOURCE: ISO 13372:2012, 8.3]

3.7
failure modes symptoms analysis
FMSA
process based on FMECA that documents the symptoms produced by each mode and the most effective detection and monitoring techniques in order to develop and optimize a monitoring programme

Note 1 to entry: This process is outlined in ISO 13379-1.

3.8
estimated time to failure
ETTF
estimation of the period from the current point in time to the point in time where the monitored machine is deemed to be in the failed condition

Note 1 to entry: Defined in Figure 2.

3.9
remaining useful life
RUL
remaining time before system health falls below a defined failure threshold

3.10
predictive horizon
threshold for prediction of lead time to failure as desired by the user

4 Data requirements

4.1 The general concepts for condition monitoring are outlined in ISO 17359 and form the basis for the prognostic process and its pre-requisites. Prognostics may require the collection of documented data covering

a) the total population of plant, machinery and components under observation along with original equipment specifications,

b) all monitored parameters and descriptors,

c) expert knowledge of baseline, commissioning, historical operation, maintenance, inspection and failure data,

d) current and future operating and maintenance environments, regimes, requirements and schedules,

e) initial diagnosis inclusive of identification of all existing failure modes,

f) failure models including single and multiple failure modes that can include statistics, existing and future failure mode influence factors, initiation criteria, and failure definition set points for all parameters, and descriptors,

g) curve fitting, projection and superimposition techniques,

h) alarm limits,

i) trip (shut-down) limits,

j) performance thresholds relating to system health,

k) failure investigation results,

l) reliability, availability, maintainability, cost and safety data,

m) damage initiation data,

n) damage progression data,

o) manufacturing configuration state (lot number, batch number, etc.), and

p) environmental data that has an impact on component health.

All this information may not be available in some applications and cases.

4.2 There are specific objectives for the collection of reliability data relating to current condition and field performance of machinery:

— survey the actual reliability and, hence, to enable the predicted reliability characteristics of an item to be made and compared with field data, and damage models and thereby to improve future predictions;

— provide data for improving the reliability of both the current item and future developments;

— provide data for verifying and validating models and algorithms.

4.3 There are specific objectives for the collection of data relating to current field duties and cumulative duties of machinery:

— survey the relationship between the actual reliability and the work done, hence, to enable the comparison of damage initiation and progression models with field data;

— provide data for improving the damage estimation models of both the current item and future developments;

— provide data for extending the range of applications for damage estimation models.

4.4 There are specific objectives for the collection of cost data relating to monitoring equipment and usage, production losses, secondary damage losses, maintenance activities and inventories of machinery:

— survey the benefit-to-cost ratios of various alternative maintenance actions;

— improve future maintenance decisions;

— provide data for reducing the operating and maintenance costs of both the current item and future embodiments;

— provide cost data (along with monitored data and performance data, and also field duty data, see 4.3) for the optimal organization and management of any maintenance operation (on-condition maintenance, scheduled preventive maintenance, corrective maintenance, service personnel, spare parts stores, etc.).

5 Prognosis concepts

5.1 Basic concepts

Prognosis is an estimation of time to failure and the probability of one or more existing and future failure modes. It is based on detailed knowledge and experience of the fault propagation process. The goal of prognostics is to provide the user with the capability to predict remaining useful life (RUL) with a satisfactory level of confidence. This information can be used to drive operators' decisions in order to avert the failure, extend life through appropriate operational changes, or simply to allow time to prepare for the impending failure. The effectiveness of prognosis is determined by the degree to which faults and failure modes have known, age-related, performance-related or progressive deterioration characteristics that are well-understood and supported by models.

A failure has to be defined in terms of the monitored parameters and descriptors. Monitoring data on its own is insufficient to produce a prognosis.

The general conceptual basics of a prognosis process are

a) define the end point,

b) determine or estimate the parameter or descriptor behaviours and the expected rate of deterioration,

c) estimate current state of deterioration,

d) estimate the expected remaining life or expected time to failure,

e) define level of confidence, and

f) establish the desired prognostic event horizon.

It is important to understand that diagnostics is retrospective in nature in that it focuses on existing data at a given point in time.

Prognostics, however, focuses on the future and so must consider

— existing single and multiple failure modes and deterioration rates,

— the initiation criteria for future failure modes,

— the role of existing failure modes in the initiation of future failure modes,

— the influence between existing and future failure modes and their deterioration rates,

— the sensitivity to detection and change of existing and future failure modes by the current monitoring techniques,

— the design and variation of monitoring strategies to suit all of the above,

— the effect of maintenance actions and/or operating conditions, and

— the conditions or assumptions under which prognoses remains valid.

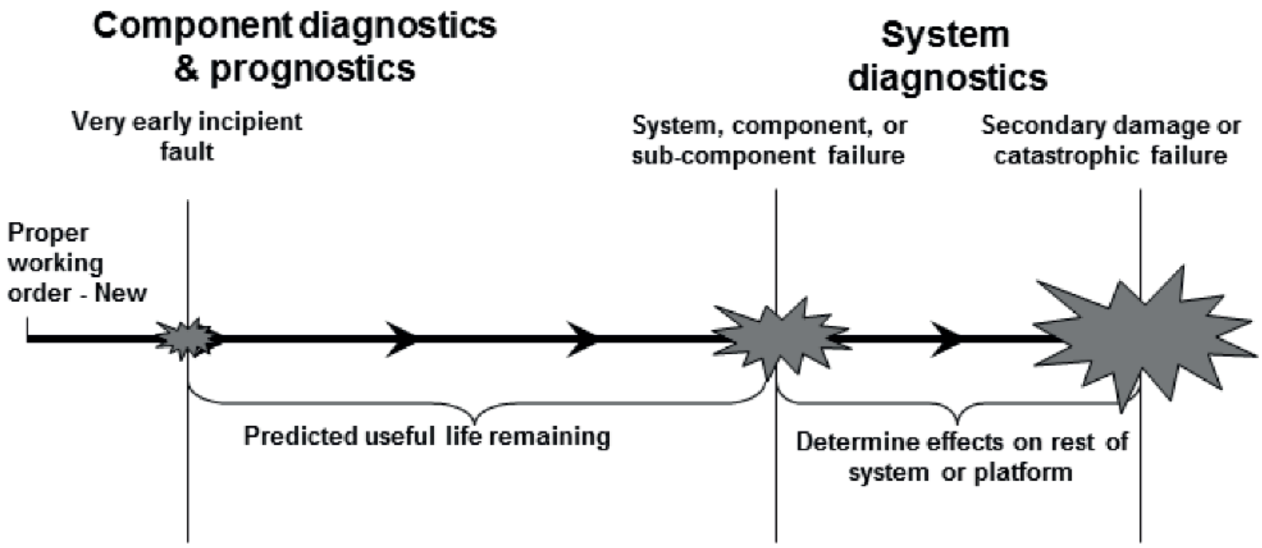
The sub-domains of interest are: performance degradation, cyclic usage and RUL prediction models.

Figure 1 a) shows the general relationship concepts between prognostics and diagnostics across the failure progression timeline. Figure 1 b) shows another perspective of the relationship between diagnostic and prognostic processes.

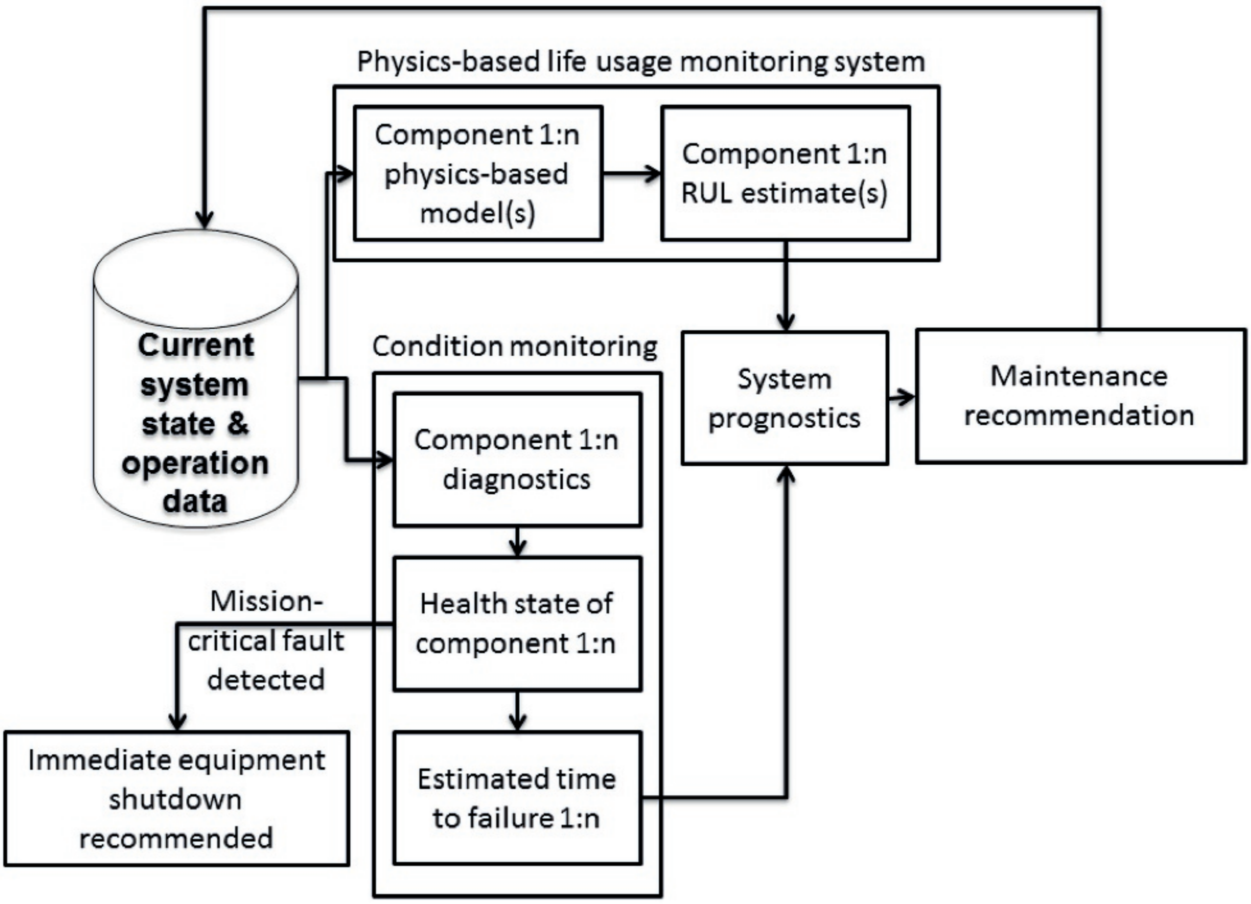
5.2 Influence factors

Influence factors are parameters that affect the deterioration rate of a failure mode; for example, temperature, viscosity, clearance, load, speed, operating conditions, etc. Each influence factor can be considered a contributing driver of an existing failure mode. Influence factors also affect the progression and initiation of other existing or future faults.

One example, as shown in Figure 2, is when the initial parameter of vibration, caused by a fault in a lubricating oil pump bearing (primary failure mode), influences the initiation of a seal failure (secondary failure mode), which has a faster deterioration rate than the bearing. As this seal fails, the leakage of oil creates a loss of oil delivery pressure, which influences the initiation of an impeller failure in the pump (tertiary failure mode), which has a slower deterioration rate.



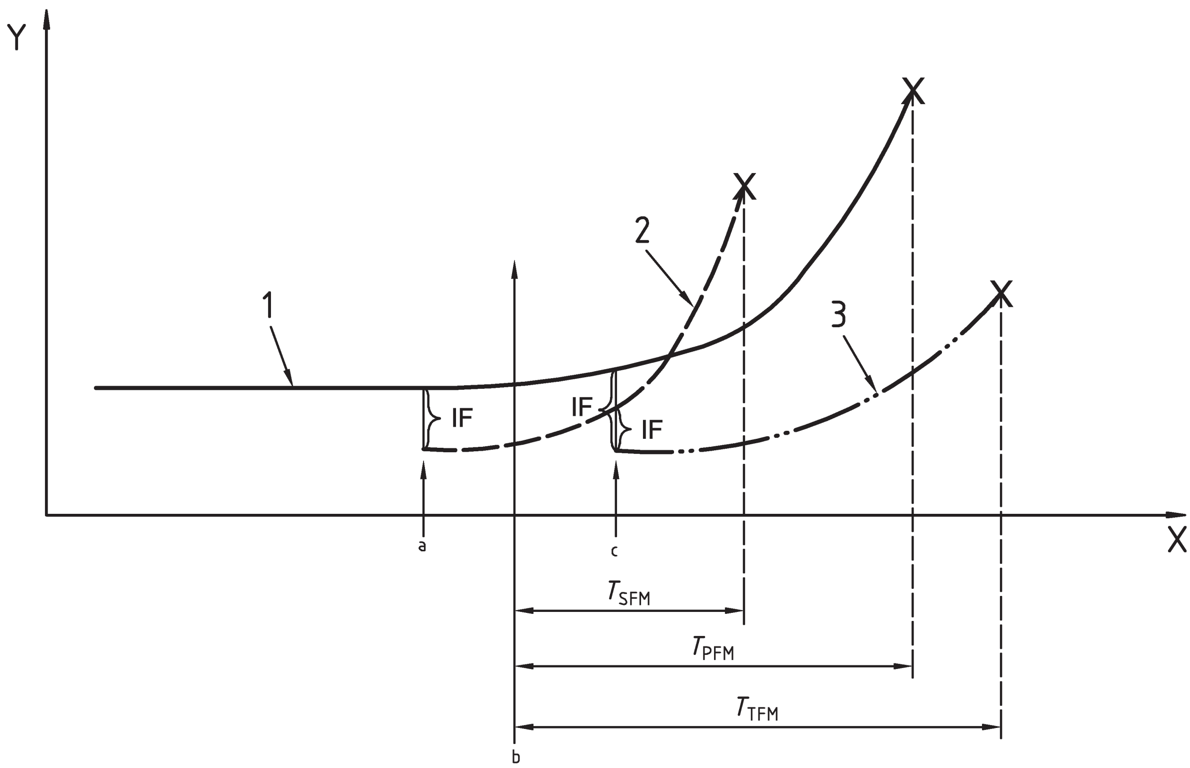
a) Prognostics and diagnostics across the failure progression timeline



b) Diagnostic and prognostic process

NOTE Life usage and condition monitoring need not occur in all systems.

Figure 1 — Two perspectives of the diagnostic and prognostic processes



Key

X	time	T_{PFM}	estimated time to failure of the PFM
Y	severity of parameter	T_{SFM}	estimated time to failure of the SFM
1	PFM: primary failure mode (solid line)	T_{TFM}	estimated time to failure of the TFM
2	SFM: secondary failure mode (dashed line)	a	time of secondary failure mode initiation
3	TFM: tertiary failure mode (dotted and dashed line)	b	present time
IF	influence factor	c	time of tertiary failure mode initiation

Figure 2 — Influence factors

5.3 Trending, setting alert, alarm, and trip (shutdown) limits

The failure definition set point for a parameter or descriptor is the final value it reaches at the point in time when the item fails. This value is normally determined historically from failure history.

The trip set point, however, is the parameter or descriptor value at which the machine is shut down and is normally less than its failure set point. This value is normally determined from standards, manufacturers' guidelines and experience. This is the value normally used to define the failed condition. However, this value is not normally reflective of the fully failed condition due to the lower set point required to prevent consequential damage or catastrophic failure.

Alert and alarm limits are normally set at a value less than the trip set point. Usually this value is determined based on the maintenance lead time required; however, such alert values should take the following into account:

a) confidence level of prognosis;

b) future production requirements;

c) spare parts delivery lead times;

d) maintenance planning lead time required;

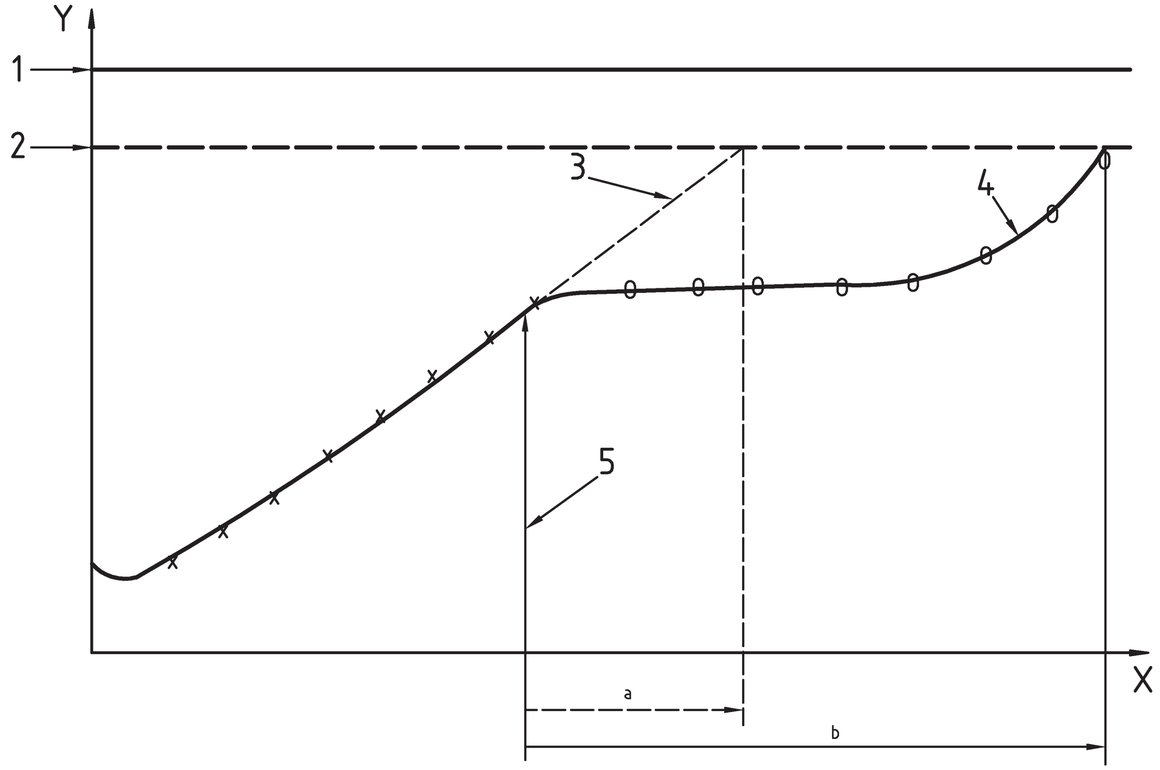
e) scope of work required to rectify faults;

f) trend projection and extrapolation.

The basic difference between trend projection and trend extrapolation is that projection requires the estimation of future data followed by curve fitting whereas the extrapolation curve fits only to existing data (Figure 3). Most current curve fitting is extrapolative in nature in that a curve is extrapolated using existing data points.

This process requires an understanding of the behaviour of a set of parameters for a given failure mode set and given conditions. Trend projection requires mathematical equations expressing the rate of change of a variable that describes the deterioration of a given failure mode under given conditions.

One example of this concept is an equation that describes the rate of change of an overall acceleration value for a bearing housing mounted 6316 deep groove ball bearing, running at 3 000 rpm, lubricated by an 220 cSt viscosity grade mineral oil, running at 80 °C. If such equations are known, then trend projections result in far more accurate prognoses than extrapolations as the future data behaviour is known.



Key

X	time	1	failure value
Y	value of parameter	2	trip set point
x	known points	3	extrapolation
0	behaviour points	4	projection
a	ETTF (extrapolation)	5	present time
b	ETTF (projection)		

Figure 3 — Extrapolation versus projection

5.4 Multiple parameter analysis

Prognosis can be performed using a single parameter or multiple parameters. Multiple parameter analysis is the simultaneous utilization of relevant data within the one system. This concept is paramount to prognostics in that the relationship between parameters can be observed, not just the parameters themselves. This is particularly important for different yet possibly interdependent parameters such as bearing temperature and oil viscosity (see Figure 4).

One principle of multiple-parameter analysis is that the technique trends relevant parameters (unfiltered/unprocessed variables) and descriptors (filtered/processed data) simultaneously. For example, the use of narrow-band filters allows spectra to be divided into discrete elements; the band amplitude can then be used for multiple-parameter analysis trending. The failure definition set point for each narrow band is the assigned maximum allowable amplitude for each band. This allows for each narrow-band amplitude to be plotted against other vibration descriptors, oil analysis results, process parameters and performance values in order to identify and establish relationships between each of them.

The difficulty with multiple-parameter analysis is that each variable can have a different unit of measurement. This is compounded if the variable can attain the same value more than once in the life of the component (see Figure 4). Multiple-parameter analysis trending and alarming is also made difficult when the value of the variable in the failed condition is zero (e.g. flow or pressure).

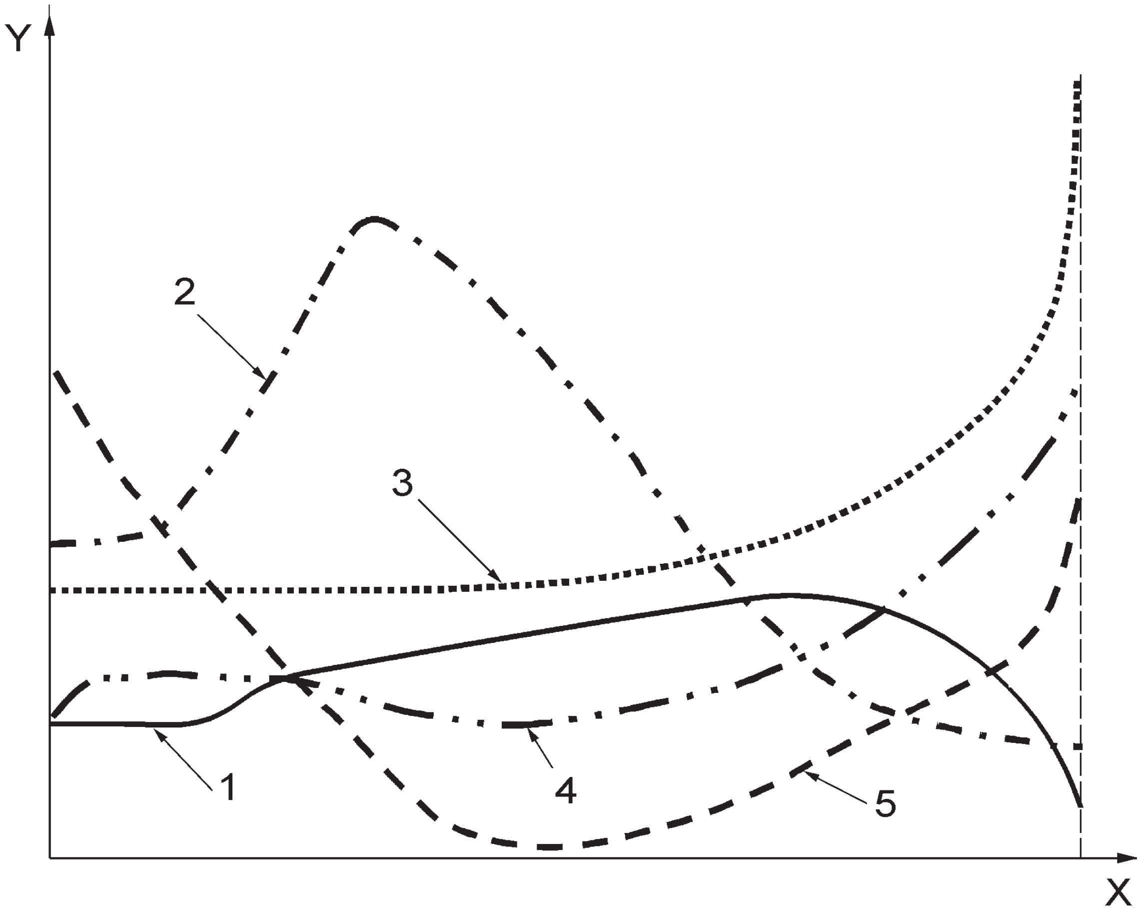
One key difference between standard multiple-parameter analysis for monitoring and multiple-parameter analysis for prognosis is that prognosis often uses a common severity axis (scaling). For simplicity, this can be set to percentage of life usage, where 0 % life used occurs when the machine has not been operated and 100 % life used occurs when the machine is in the failed condition. At this stage, data that may approach zero when the machine is in the failed condition, such as flow or pressure, shall be inverted to reflect the “percent life usage” relationship.

It is important when doing multiple-parameter analysis based prognosis that for each parameter and/or descriptor being used it is understood that

— the start value represents 100 % asset life or new condition,

— the end value represents 0 % asset life or failed condition, and

— the manner in which the parameter and/or descriptor behaviour reflects the failure mode development and associated reduction in asset life.



Key

X independent reference value

Y value of parameter

1 parameter 1

2 parameter 2

3 parameter 3

4 parameter 4

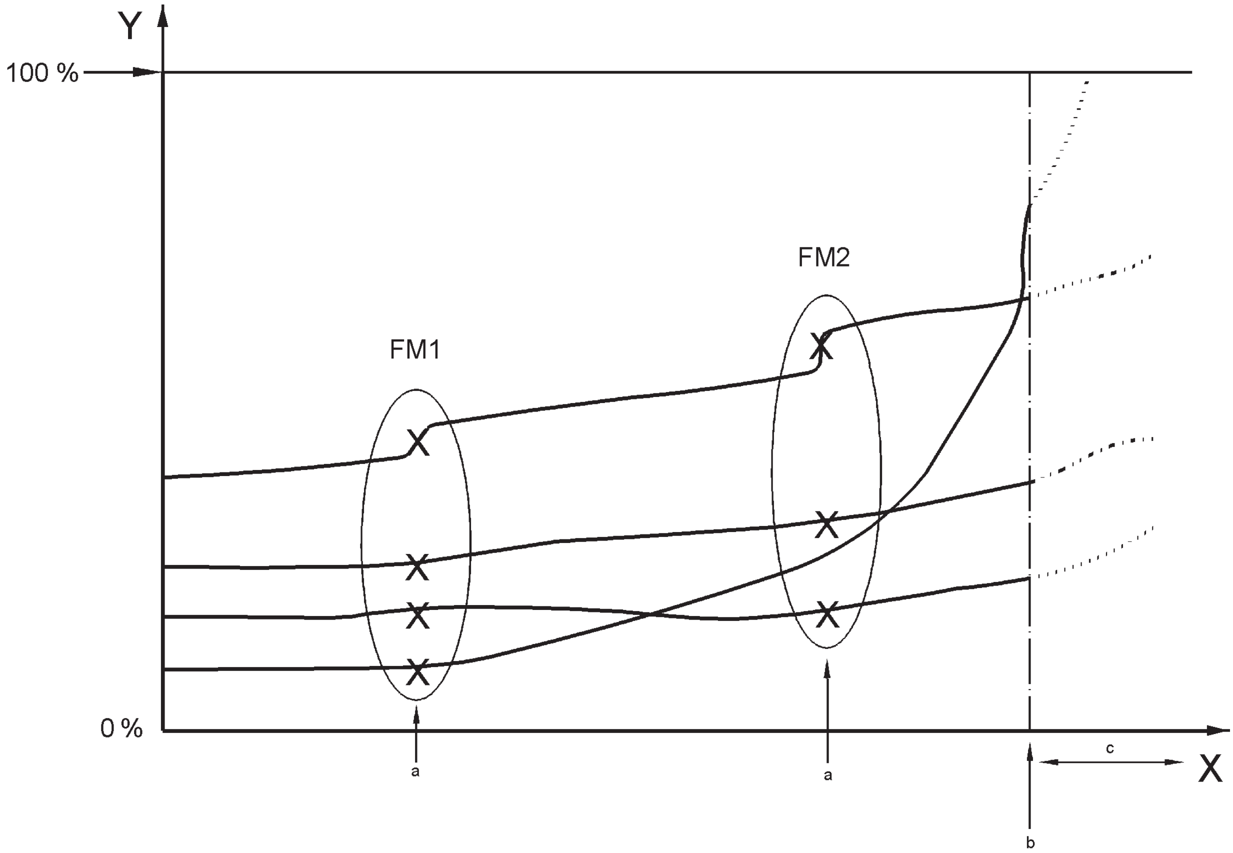
5 parameter 5

Figure 4 — Example of multi-parameter display

5.5 Initiation criteria

For future failure modes, these influence factors shall first be described as initiation criteria in that the same parameter can be both an influence factor for an existing mode and an initiation criterion for a future mode. This introduces the concept of initiation criteria data sets where the root cause of a failure mode can be described in terms of a set of different parameter values that either directly or indirectly measure its occurrence (see Figure 5). Different features may be more useful for diagnostics or prognostics.

Direct measurement can take such forms as valve position whereas indirect measurement can include a symptom of a change such as temperature.



Key

X time

Y percent life usage (100 % = failed; 0 % = full life)

FM1 action

FM2 condition and action

a initiation criteria set

b present time

c estimated extrapolation

Figure 5 — Failure mode initiation criteria

5.6 Prognosis of failure mode initiation

The initiation of a failure mode should always be traced back to its root cause. The cause of a degradation can be described in terms of a set of conditions and actions whereby a condition will generally produce a steady rate of change and an action will usually result in a step change (see Figure 6). "Pseudo-healing" or corrections may occur and health indicators may change with progression.

By using multiple-parameter analysis techniques, the evidence of actions, conditions and their interdependence can be readily observed. Failure mode initiation criteria, expressed as a set of values for all monitored parameters, can therefore be used to trigger alarms indicating that a failure mode has been initiated once this set of values has been achieved or exceeded.

Prognosis of future failure mode *initiation* can, therefore, be achieved given a known initiation criteria set and trend projection techniques. The accuracy of the prognosis will depend greatly on whether or not trend extrapolation or projection is used (see Figure 6).

This method requires a thorough understanding of

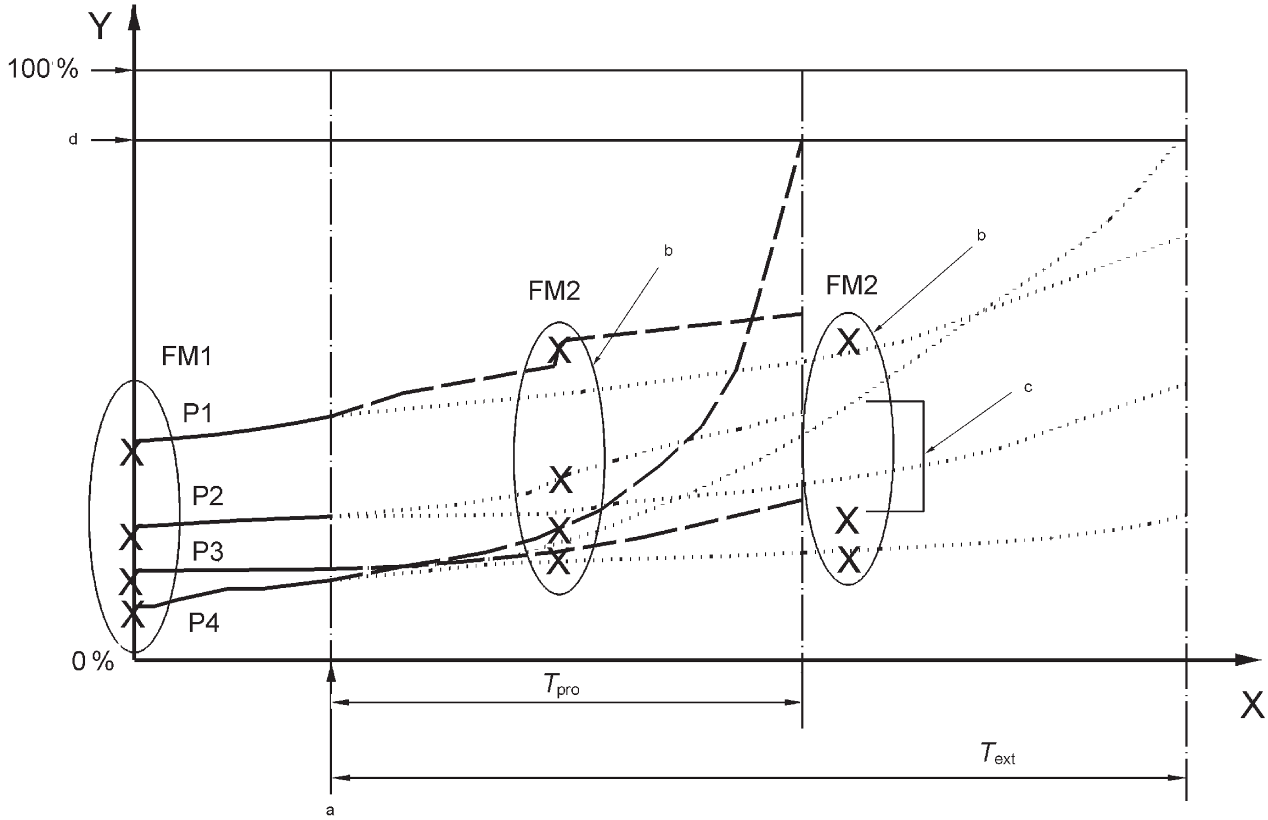
— failure mode initiation criteria, which can be historically or statistically generated over time (or both),

— sufficient multiple-parameter analyses of a wide set of monitored parameters,

— relationships between and interdependence of failure modes,

— known operating conditions at the time of failure mode initiation, and

— behaviour of parameters under varying conditions and influences.



Key

X	time	T_{pro}	ETTF (projection)
Y	percent life usage (100 % = failed; 0 % = full life)	T_{ext}	ETTF (extrapolation)
— —	projection	a	present time
…	extrapolation	b	initiation criteria
P	parameter	c	exceedence
FM	failure mode	d	trip set point

Figure 6 — Initiation prognosis: projection versus extrapolation

6 Failure and deterioration models used for prognostics

6.1 Failure mode behaviour modelling concepts

Prognosis requires a methodology that conceptually includes the use of such existing failure mode behaviour models such as

a) failure modes effects criticality analyses (FMECA),

b) causal/fault tree analyses,

c) risk and hazard assessment methods,

d) physics-based damage initiation and progression models,

e) trend extrapolation and projection methods, and

f) RUL defined as a function of acceptable confidence level and risk.

These methodologies provide the source data on failure modes and relationships, severity and risk, rates of deterioration and prognosis data.

Once an incipient fault has been detected or diagnosed, one of the main issues is to establish the estimated time to failure (ETTF) or to achieve a mission critical date without failure. This is sometimes accomplished using performance based RUL prediction techniques. The most accurate method will rely heavily on the underlying physical phenomena, although building models based on the principles of physics may be useful; in cases where there is no model, or the physics of failure is poorly understood, data-driven approaches or expert opinion can be used.

Several sources of information are generally used to determine the ETTF, such as

— monitoring data,

— test data,

— life duration data,

— reliability/availability data,

— manufacturers' data,

— previous case histories, and

— operational data.

6.2 Modelling types

Different types of models exist and can be used to varying degrees based on expertise in building the models and the availability of data. Generally, the choice is between physics-based models, data-driven models and knowledge-based models. The first model encapsulates the physics of the component under investigation and the physics of the deterioration process using appropriate equations. In contrast, a data-driven model is typically agnostic of the underlying physics. Data-driven models are a representation of a collection of observed run-to-failure instances. Often, machine learning methods are used to build data-driven models. Knowledge-based models rely on input from design engineers, long-time users and practitioners.

7 Generic prognosis process

7.1 Prognosis confidence levels

One inherent property of prognostics is the associated uncertainty of the remaining life estimation. A remaining life estimation is only as good as the confidence with which it is made. If the confidence bounds are very wide, the estimate is not very valuable because a decision based on the estimate has to be made based on accepted risk levels. For an accepted risk level, an operator would typically take action if the risk falls inside a particular remaining life confidence bound.

The generic condition monitoring process, including prognosis, is outlined in Annex A. Within this flow chart there are several concepts requiring sub-processes such as determining confidence levels and the iterative confirmation process.

A confidence level is a figure of merit (percentage) that indicates the degree of certainty that the diagnosis/prognosis is correct.

This figure essentially represents the cumulative effect of error sources on the final certainty or confidence in the accuracy of the outcome. Such a figure can be determined algorithmically or via a weighted assessment system.

Such a system should incorporate a weighted assessment of the negative impact of errors or lack of information associated with, but not limited to, the following:

a) maintenance history;

b) design and failure mode assessment;

c) analysis technique parameters used (sensitivity to detection and change);

d) severity limits used;

e) measurement interval;

f) database set-up;

g) data acquisition;

h) severity assessment processes;

i) trend assessment;

j) diagnosis process;

k) prognosis process;

l) future load conditions;

m) future environmental conditions.

It should be noted that assigned weightings for each confidence factor criteria can vary between diagnoses and prognoses as each criterion can have a different bearing on the outcome for each process. An example of a simple determination is given in Annex B.

7.2 Prognosis process

7.2.1 General

The generic process involves four basic phases: pre-processing, existing failure mode prognosis, future failure mode prognosis and post-action prognosis. The process is generally sequential as detailed in 7.2.2 to 7.2.5.

It should be noted that several elements in the flow chart can be skipped. For example, it is not always necessary to perform formal diagnosis before estimation RUL.

7.2.2 Pre-processing

a) Carry out a diagnosis in order to identify all existing failure modes.

b) Identify influence factors between existing failure modes.

c) Define failure definition and trip set points for all current symptoms, parameters, and descriptors.

d) Determine potential future failure modes, their initiation criteria and failure definition set points.

e) Select a suitable failure mode model (see Annex C).

7.2.3 *Existing* failure mode prognosis process

a) Assess severity of all measured failure modes and their parameters/descriptors against their trip set points.

b) Project all failure mode parameter and descriptor trends to their trip set points.

c) Select the existing failure mode with the shortest ETTF.

d) If possible, execute an iterative confirmation process until the confidence in the ETTF is acceptable.

7.2.4 *Future* failure mode prognosis process

a) Assess future failure mode initiation criteria and determine most probable future failure modes.

b) Determine influence factors between all existing and future failure modes.

c) Estimate initiation point, trends and ETTF for each future failure modes taking into account all influence factors and trip set points.

d) Select the most critical future failure mode with the shortest ETTF and develop an "initial prognosis" with associated confidence level and validity conditions.

There may be a requirement to produce one or more action options. The simplest action that may be taken in certain circumstances, such as low criticality machines, is to carry out no immediate action. The prognosis for this option is identical to the "initial prognosis".

The initial prognosis should state the critical existing failure mode, ETTF and confidence level, and the critical future failure mode, ETTF and confidence level if there is a high risk of occurrence and/or impact risk. A statement detailing the conditions under which the prognosis is valid should accompany the prognosis.

7.2.5 Post-action prognosis

a) Identify any actions that will retard, halt or eliminate the progression of the critical existing failure mode and try to mitigate the initiation of future failure modes.

b) Revise the failure model and repeat the prognosis process [steps 7.2.2 b) to 7.2.4 b), inclusive] taking into account the effects of any maintenance action.

c) Develop a feedback and continuous action plan with associated confidence level and validity conditions.

It may be beneficial to consider interim maintenance actions to alleviate the failure mode progression and prevent the occurrence of future modes. These interim actions are normally non-intrusive, e.g. re-greasing a bearing.

An ultimate solution option should also be considered. These actions are normally intrusive, e.g. overhauling the machine or replacing a part. The post-action prognosis for this option is normally based on historical reliability data.

The post-action prognosis should state the critical *existing* failure mode, ETTF and confidence level (post-interim-maintenance action), and the critical *future* failure mode, ETTF and confidence level if there is a high risk of occurrence and/or impact risk.

A statement detailing the conditions under which the prognosis is valid should accompany the prognosis.

The recommendation of any action (nil, interim or final solution) will essentially be a risk-based decision process that includes any financial, environmental, safety and other forms of risk or impact.

7.3 Prognosis report

A complete prognosis report shall include the diagnostic requirements report described in ISO 13379-1 and, as a minimum, the following:

a) machine identification code or number;

b) machine description;

c) a statement of the operating condition of the machine at the time of measurement;

d) a statement detailing the conditions under which the prognosis is valid;

d) a list, or reference to an available list, of all measurement points, parameters and measurement instrumentation used during the prognosis process;

e) the diagnosis including all identified failure modes;

f) the initial prognosis (existing and future modes), confidence level, validity conditions and associated risk (no action);

g) any additional tests required to increase confidence levels;

h) any recommended action, its associated prognosis (existing and future modes), confidence level, validity conditions and associated risk;

i) any alternative action, its associated prognosis (existing and future modes), confidence level, validity conditions and associated risk.

In general, the report may consist of a tabulated exception part detailing the facts in brief with an attached detail section that provides more information on each individual diagnosis, any additional tests required, any recommended and alternative actions, future failure modes, associated prognoses and other pertinent information.

It may also be beneficial to include a severity indicator and a trend indicator in any tabulated section. This would enable the immediate recognition of severe and/or changing conditions and situations where the condition is approaching alarm and may become critical before the next set of readings.

Annex A
(normative)

Condition monitoring flow chart

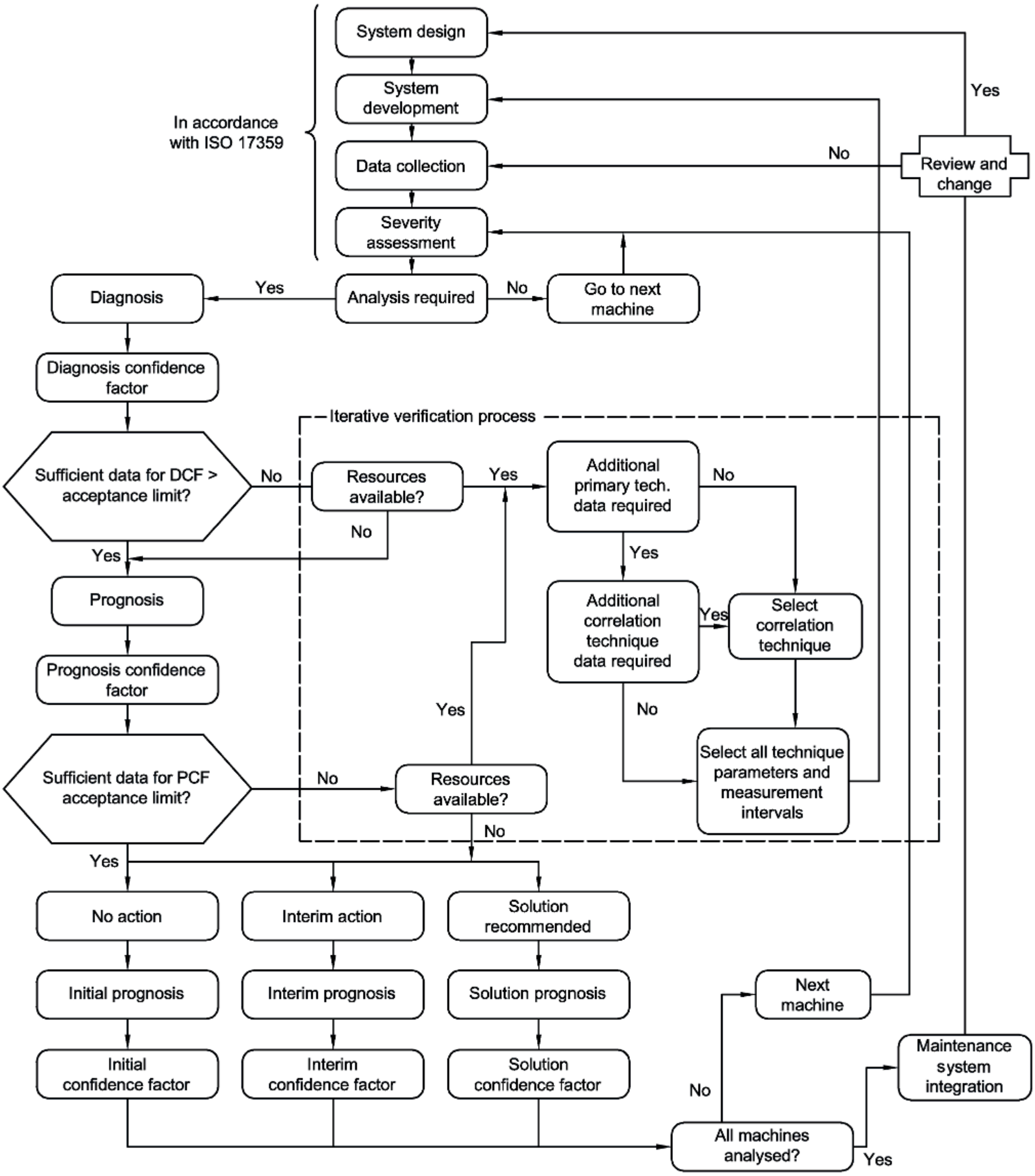


Figure A.1 — Condition monitoring flow chart

Annex B
(informative)

Example prognosis confidence level determination

Table B.1 — Example prognosis confidence level determination

Process activity step	Error sources	Weighting	Assigned confidence value %	Resultant confidence level %
1	Maintenance history	0,15		
2	Design and failure mode analysis	0,1		
3	Analysis technique parameters used	0,15		
4	Severity limits used	0,1		
5	Measurement interval	0,1		
6	Database set-up	0,05		
7	Data acquisition	0,05		
8	Severity assessment process	0,05		
9	Diagnosis process	0,1		
10	Prognosis process	0,15		
OVERALL CONFIDENCE LEVEL				
NOTE Confidence level = sum (weighting * assigned confidence value)				

Annex C
(informative)

Failure modelling techniques

C.1 Five general modelling approaches

C.1.1 Physics-based models

Behaviour models encapsulate the underlying physical phenomena of a component under nominal operation as well as under fault conditions. For the latter, a separate damage propagation model is often employed, which also relies on description of the physics. Such models can use first principles, finite element methods or other suitable techniques.

C.1.2 Statistical models

Statistical models derive information from the behaviour of a population of components. The techniques are very popular in reliability analysis. Because they average over a large population of devices, their estimates are not always as accurate as condition-based approaches such as physics-based models. To counteract their shortcomings, these models are sometimes adjusted with measurements that result in a change of the model parameters.

C.1.3 Heuristic models

Heuristic models capture the expected behaviour of a system that has been abstracted into more general rules. These models are sometimes also referred to as knowledge-based models. They can be instantiated in expert systems, causal trees and similar systems.

C.1.4 Data-driven models

Data-driven models provide a representation of observed behaviour without the need to have a specific understanding of the physics. The models are built using pattern matching techniques (such as those used in machine learning) to match observed measurement and derived features to remaining life based on a population of run-to-failure cases. Such techniques are, for example, case-based reasoning, artificial neural networks and other pattern matching techniques.

C.1.5 Hybrid models

It is not uncommon that any one technique is not able to comprehensively cover all fault modes of a component. For these cases a combination of techniques can be used. For example, the most critical fault modes can be modelled using a physics-based approach and the remaining fault modes can be covered by using data-driven models.

C.2 Three modelling applications

C.2.1 Life expectancy

Life duration of individual components in a machine can be estimated with respect of the risk of deterioration during inspection and the risk of failure during operation and can be

— reliability based, or

— deterioration based (e.g. statistical, deterministic, expert opinion, equations, tests, FEM, damage models).

C.2.2 Reliability models

These models provide reliability-related information as probabilistic values with respect to time. Computation on these functions can provide mean time to failure (MTTF) values.

Weibull analysis can be used to take into account failure rate increase when components get old or in cases of “infant mortality” (i.e. failures that occur in early stages of an asset’s life).

Reliability factors can be adjusted with respect to monitoring data and operating conditions. This enables reliability factors to be individualised for a given machine.

C.2.3 Deterioration models

These estimate the initiation and progression (e.g. wear, cracks, corrosion) of deterioration (damage).

They may be modelled with several states of deterioration based on previous inspection results on similar machines. These models may be coupled with “good behaviour models” to predict future deterioration.

C.3 Model validation

The purpose is to associate a known and/or quantified state of deterioration observed by inspection with the condition predicted by the modelling process. This validation process may also include verifying the magnitude of any measured parameters or descriptors with the physical damage evidence.

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