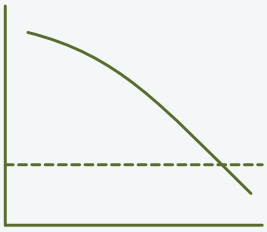
LESSON BOOK — VOLUME I



Asset Health and Condition Monitoring Volume I

Foundations, degradation, measurements, health assessment and diagnostics

Draft · twenty lessons · 296 pages

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Asset Health and Condition Monitoring

Volume I

Foundations, degradation, measurements, health assessment and diagnostics

A lesson sequence, drafted as a book (skeleton draft)

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How to read this book

This book is about one question: what the current condition of an engineering asset is, how that condition is changing, how deterioration can be detected, and how that information should influence maintenance and operational decisions. Each chapter expands one lesson of a sequence that builds the answer in the order the discipline itself uses,

$$\text{measure} \rightarrow \text{assess} \rightarrow \text{diagnose} \rightarrow \text{predict} \rightarrow \text{decide}.$$

The sequence has nine parts and thirty-six lessons, published in two volumes. This first volume holds Parts I to V, Chapters 1 to 20: the foundations of condition monitoring, the physical mechanisms of degradation, industrial measurements and signal analysis, condition indicators and health assessment, and fault detection and diagnostics. The second volume holds Parts VI to IX, Chapters 21 to 36: prognostics, remaining useful life and risk, maintenance decisions, and industrial applications. Chapter numbers run continuously across the two volumes.

The book is independent of any software framework. It teaches the established terminology, principles and mathematical methods of condition monitoring, diagnostics and prognostics, and it keeps four activities apart: condition monitoring (observing measurable characteristics), condition assessment (interpreting them as a condition), diagnostics (identifying the nature and cause of an abnormal condition) and prognostics (predicting how the condition will evolve). A centrifugal pump and motor assembly recurs throughout as the teaching example; other equipment appears where a method needs it. The numbers in the examples are illustrative.

State of this draft. This is a skeleton: each chapter is a direct transcription of its lesson, so paragraphs are short and some headings are many. Figures marked *to be drawn* and photographs marked *to be sourced* are placeholders; charts appear as tables of their data. The chapters will be rewritten as book prose later.

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Part I

Foundations of Asset Health and Condition Monitoring

Chapter 1

Introduction to Asset Health and Condition Monitoring

1.1 The engineering problem

Consider an industrial facility operating a centrifugal pump.

The pump has been operating continuously for three years. It still delivers water, its motor is running, and no protective alarms have been triggered.

However, recent measurements reveal several changes:

- Bearing vibration has gradually increased.
- Motor temperature is slightly higher than usual.
- Electrical power consumption has increased.
- The pump delivers somewhat less flow at the same operating speed.

The pump has not failed. It continues to perform its required function.

Nevertheless, an engineer responsible for the equipment must answer several questions:

1. **Condition:** Is the pump healthy?
2. **Detection:** Has its condition deteriorated?
3. **Diagnosis:** What is causing the deterioration?
4. **Prognosis:** How is the deterioration likely to progress?
5. **Decision:** Should the pump continue operating, be inspected, or be repaired?

These questions introduce the discipline of asset health and condition monitoring.

The central idea is straightforward:

> An asset can continue operating while its physical condition deteriorates. Condition monitoring attempts to detect, understand, and predict that deterioration before it results in unacceptable performance or failure.

This is fundamentally different from waiting until equipment stops functioning.

1.2 What is an engineering asset?

An *engineering asset* is a physical item that provides value to an organization through one or more functions.

Examples include:

Industry	Asset	Required function
Manufacturing	Electric motor	Deliver mechanical power
Water systems	Centrifugal pump	Deliver required flow and pressure
Power systems	Transformer	Transfer electrical power within operating limits
Data centers	Chiller	Remove heat from a cooling system
Energy storage	Battery	Store and deliver electrical energy
Transportation	Gearbox	Transmit torque at a specified speed ratio

Every asset has a physical condition that influences its ability to perform its required function.
Importantly, an asset's condition and its performance are related but are not identical.
For example, a pump with a deteriorating bearing may continue delivering its required flow.
The pump's performance remains acceptable even though its condition has worsened.
This distinction is central to condition monitoring.

1.3 Asset performance versus asset condition

Let

$$y(t)$$

represent a measurable performance quantity at time t.
For a centrifugal pump, this might be its delivered flow rate:

$$y(t) = Q(t).$$

Suppose the pump must deliver at least

$$Q_{\min} = 80 \text{ m}^3/\text{h}.$$

Its performance requirement is

$$Q(t) \geq Q_{\min}.$$

Now suppose the pump currently delivers

$$Q(t) = 95 \text{ m}^3/\text{h}.$$

The performance requirement is satisfied.
However, this does not establish that the pump is healthy.
Its bearing may be deteriorating, its impeller may be eroding, or internal leakage may be increasing.
We therefore introduce a second quantity:

$$x(t) = \text{physical condition of the asset.}$$

The condition may be described by several physical variables:

$$x(t) = \begin{bmatrix} c_b(t) \\ c_i(t) \\ c_s(t) \end{bmatrix},$$

where:

- $c_b(t)$: bearing condition,
- $c_i(t)$: impeller condition,
- $c_s(t)$: shaft condition.

These quantities need not be directly measurable.

Instead, engineers infer condition from measurements such as vibration, temperature, pressure, flow, and electrical power.

Thus, **acceptable performance does not necessarily imply acceptable physical condition**.

1.4 What is condition monitoring?

Condition monitoring is the process of observing selected characteristics of an asset to detect changes that may indicate deterioration or developing faults.

Measurements may be collected:

- Continuously through permanently installed sensors.
- Periodically during scheduled inspections.
- On demand when abnormal behavior is suspected.

For our centrifugal pump, we might measure:

$$y(t) = \begin{bmatrix} v(t) \\ T_b(t) \\ P_e(t) \\ Q(t) \end{bmatrix},$$

where:

- $v(t)$: measured vibration,
- $T_b(t)$: bearing temperature,
- $P_e(t)$: electrical power consumption,
- $Q(t)$: delivered flow.

These measurements provide evidence about the equipment's condition.

Photograph (to be sourced): see the surrounding text.

Typical centrifugal pump assembly and condition-monitoring activities.

An important complication is that measurements are also influenced by operating conditions.

For example, vibration may increase because:

1. A bearing is deteriorating.
2. The pump is operating at a different speed.
3. The pump is approaching an unfavorable hydraulic operating point.
4. The measurement sensor has become loose.

The measurement alone does not establish which explanation is correct.

This leads to one of the most important principles of condition monitoring:

> **A change in a measured quantity is not necessarily a change in asset health.**

The engineer must distinguish deterioration from normal operating variability, environmental influences, and measurement errors.

1.5 Condition indicators

A *condition indicator* is a measurable or calculated quantity used to assess some aspect of equipment condition.

Examples include:

Asset	Condition indicator	Possible interpretation
Pump	Vibration RMS	Mechanical deterioration
Motor	Winding temperature	Thermal stress or abnormal loading
Transformer	Dissolved gas concentration	Possible insulation or thermal fault
Battery	Available capacity	Capacity degradation
Heat exchanger	Overall heat-transfer coefficient	Fouling or thermal deterioration
Bearing	Vibration envelope features	Possible localized bearing damage

A condition indicator does not necessarily represent physical degradation directly.

For example, high bearing temperature may result from excessive loading rather than bearing damage.

Therefore, a useful condition indicator should ideally be:

- Sensitive to the deterioration of interest.
- Relatively insensitive to unrelated operating changes.
- Repeatable under comparable conditions.
- Measurable with known uncertainty.
- Interpretable in relation to equipment performance or failure.

Later lessons will examine how indicators are constructed, normalized, and validated.

1.6 From measurements to a health assessment

A common approach is to summarize asset condition using a *health index*.
Suppose a health index $H(t)$ is defined on a scale from 0 to 100, where:

$$H(t) = 100$$

represents a reference healthy condition, and lower values indicate increasing deterioration.
An illustrative classification might be:

Health index	Condition
80–100	Good
60–79	Moderate deterioration
40–59	Significant deterioration
0–39	Severe deterioration

These thresholds are illustrative, not universal engineering standards.
Chart data — Illustrative asset health history. The asset's reported condition deteriorates over three years, even if it continues meeting its operating requirements. Synthetic example. The index and thresholds are defined for illustration.

month	Health index
0	100
6	97
12	94
18	86
24	77
30	64
36	48

Although convenient, health indices introduce important questions:

- How is the index calculated?
- Which measurements contribute to it?
- How are different indicators weighted?
- Does a value of 60 mean the asset has lost 40% of its useful life?
- Can two assets with the same health index have different failure risks?

The answer to the fourth question is generally no.
A health index is a constructed measure of condition. Unless explicitly calibrated to a life or risk model, it is neither a remaining-life percentage nor a failure probability.
This distinction will become important when we study prognostics.

1.7 Detection, diagnostics, and prognostics

Three closely related activities form the technical core of condition monitoring.
Detection (Has something changed?)
Determine whether observed behavior departs meaningfully from expected behavior.

Example: The pump's vibration is unusually high for its current operating speed.

Diagnostics (What is wrong?)

Identify the likely fault, its location, and its underlying cause.

Example: Evidence suggests a developing outer-race bearing defect.

Prognostics (What happens next?)

Estimate future deterioration and the time until a defined limit may be reached.

Example: Under the expected operating conditions, the bearing may reach an unacceptable vibration level within the next three months.

These activities answer different questions and require different forms of evidence.

A monitoring system may detect abnormal vibration without being able to identify its cause.

Likewise, a diagnostic system may correctly identify a bearing defect without having enough information to estimate how quickly the defect will progress.

Successful detection does not guarantee successful diagnosis, and successful diagnosis does not guarantee accurate prognosis.

1.8 The relationship to reliability engineering

Condition monitoring and reliability engineering are closely connected, but they have different immediate objectives.

Reliability engineering asks:

> What is the probability that the asset will perform its required function over a specified period under stated conditions?

For a lifetime random variable T, conventional reliability is expressed as

$$R(t) = P(T > t).$$

Condition monitoring asks:

> What can current and historical observations tell us about the asset's physical condition?

The two disciplines meet when current condition is used to update predictions about future performance.

Let E_t denote the evidence collected up to time t.

A condition-informed reliability question can be written as

$$\boxed{R(\tau \mid E_t) = P(T > t + \tau \mid T > t, E_t)}$$

This expresses the probability that an asset currently surviving at time t will continue operating without the defined failure for another interval τ, given the available condition evidence.

For example:

- A conventional reliability model might estimate a pump's probability of surviving the next six months using fleet failure statistics.
- A condition-informed model might update that estimate using the pump's actual vibration history, temperature, operating load, and other relevant observations.

Condition monitoring supplies evidence. Reliability modeling translates that evidence into probabilities of future functional success or failure.

The distinction is important: **condition is not reliability, but condition can help predict reliability**.

1.9 Condition monitoring and maintenance strategies

Maintenance strategies differ in how they use information about equipment condition.

Strategy	Basis for maintenance	Example
Reactive	Equipment has failed	Replace the bearing after seizure
Time-based preventive	Fixed calendar or operating interval	Replace the bearing every two years
Condition-based	Observed condition meets an intervention criterion	Inspect when vibration exceeds a justified threshold
Predictive	Forecast condition or failure risk supports intervention	Schedule replacement before predicted unacceptable deterioration
Risk-based	Condition, probability, consequence, and cost	Prioritize the pump whose deterioration poses the greatest production risk

These categories can overlap. Predictive maintenance commonly operates as a form of condition-based maintenance, and risk-based decision-making can be applied to several maintenance strategies.

The most sophisticated approach is not necessarily the best.

For inexpensive, noncritical equipment, reactive maintenance may be economically justified.

For expensive equipment with serious failure consequences, condition monitoring and prognostics may provide substantial value.

We will study how to evaluate these tradeoffs in Volume II.

1.10 Worked example — An industrial pump

Consider a pump equipped with a vibration sensor.

At commissioning, the measured overall vibration velocity was:

$$v_0 = 1.2 \text{ mm/s}.$$

Three years later, the measured vibration is:

$$v_1 = 3.6 \text{ mm/s}.$$

Assume both measurements were taken under comparable operating conditions with the same validated measurement procedure.

The relative increase is

$$\frac{v_1 - v_0}{v_0} = \frac{3.6 - 1.2}{1.2} = 2.$$

Thus, vibration has increased by 200%, or to three times its initial value.

What can we conclude?

Conclusion 1: The measured vibration has increased.

This follows directly from the observations.

Conclusion 2: The asset may have deteriorated.

This is plausible, but it is not established solely by the vibration increase.

Conclusion 3: The bearing is failing.

This conclusion is not justified by the available evidence. Other mechanical and hydraulic causes remain possible.

Conclusion 4: The pump must be replaced.

This conclusion is also unjustified. We have not established the applicable vibration limits, fault severity, expected progression, failure consequences, or maintenance alternatives.

The example illustrates the distinction between observation, interpretation, diagnosis, and decision.

An engineer must avoid drawing a stronger conclusion than the evidence supports.

1.11 What to retain

1. Asset condition and asset performance are distinct concepts.
2. Equipment can deteriorate while continuing to satisfy its functional requirements.
3. Condition monitoring observes characteristics that may reveal developing faults or deterioration.
4. Measurements are influenced by both equipment condition and operating circumstances.
5. Condition indicators and health indices require careful definition and interpretation.
6. Detection, diagnosis, and prognosis answer different engineering questions.
7. Current condition can inform reliability predictions, but condition is not itself a reliability probability.
8. Maintenance decisions require additional consideration of costs, consequences, and uncertainty.

1.12 Exercises

Exercise 1.1 — Performance versus condition

A heat exchanger continues delivering the required heat-transfer duty, but its measured overall heat-transfer coefficient has decreased by 15% under comparable operating conditions.

1. Has the heat exchanger failed?
2. Does the evidence suggest deterioration?
3. What additional information would help determine the cause?

Exercise 1.2 — Detection and diagnosis

An electric motor begins drawing 12% more current than normal.

1. Is this sufficient evidence of a fault?
2. Identify three possible explanations.
3. Suggest two additional measurements that could distinguish among them.

Exercise 1.3 — Health indicators

A battery's measured available capacity has decreased from 100 Ah to 84 Ah.

1. Calculate its capacity retention relative to the initial measurement.
2. Explain why capacity retention does not directly determine remaining useful life.
3. Identify two factors that could influence its future rate of degradation.

Exercise 1.4 — Condition and reliability

Two identical pumps have operated for the same number of hours.

Pump A exhibits stable vibration and temperature measurements. Pump B exhibits a sustained increase in vibration and bearing temperature.

1. Do the pumps necessarily have identical reliability over the next year?
2. Can their future failure probabilities be calculated from these observations alone?
3. Explain what additional models or information would be required.

1.12.1 Where Lesson 2 takes us

Lesson 2 — Asset Functions, Performance, and Condition will formalize the distinction introduced here.

We will examine how to define an asset's required functions, operating limits, condition variables, degradation states, and failure criteria.

That will establish the vocabulary and engineering foundation needed before introducing sensors, condition indicators, and diagnostic methods in later lessons.

Chapter 2

Asset Functions, Performance, and Condition

2.1 The engineering question

In Lesson 1, we established that an asset can deteriorate while continuing to perform its required function.

We now examine a more fundamental question:

> **How do we distinguish what an asset is required to do, how well it is performing, and the physical condition responsible for that performance?**

This distinction matters because an abnormal measurement does not necessarily indicate deterioration, and deterioration does not necessarily imply functional failure.

Consider a centrifugal pump delivering water to an industrial cooling system.

The pump is designed to deliver a specified flow against a required pressure difference. Over time, its impeller may erode, internal clearances may increase, and its bearings may deteriorate.

Nevertheless, the pump might continue delivering sufficient flow.

To assess its health, an engineer must distinguish three quantities:

1. **Required function:** What must the pump accomplish?
2. **Observed performance:** What is the pump actually accomplishing?
3. **Physical condition:** What is the state of the components that enable that performance?

These quantities are related, but they are not interchangeable.

2.2 Required functions and performance criteria

Every engineering asset exists to perform one or more functions.

A function describes what the asset must accomplish. A performance criterion specifies the conditions under which that function is considered acceptable.

For a centrifugal pump, a function might be:

> Deliver cooling water to a process at sufficient flow and pressure.

We can make this statement quantitative.

Let

- $Q(t)$: delivered volumetric flow rate, in m^3/s;
- $\Delta p(t)$: pressure rise across the pump, in Pa;
- $Q_{\min}$: minimum required flow;
- $\Delta p_{\min}$: minimum required pressure rise.

The pump satisfies these two requirements at time t when

$$Q(t) \geq Q_{\min}$$

and

$$\Delta p(t) \geq \Delta p_{\min}.$$

The combined performance criterion is

$$\boxed{Q(t) \geq Q_{\min} \quad \wedge \quad \Delta p(t) \geq \Delta p_{\min}}$$

where $\wedge$ means that both conditions must hold.

This is a simplified criterion. In a real installation, the required pressure may depend on flow, and acceptable operation may also require limits on vibration, temperature, cavitation, or power consumption.

The important point is that **functional adequacy must be defined against an explicit requirement**.

A pump delivering 100 m^3/h may be performing adequately in one installation and inadequately in another.

The numerical performance alone does not establish success or failure.

2.2.1 Performance margin

For a single lower-bound requirement, we can define a performance margin:

$$M_Q(t) = Q(t) - Q_{\min}.$$

If

$$M_Q(t) > 0,$$

the flow requirement is satisfied.

If

$$M_Q(t) < 0,$$

the requirement is violated.

A zero margin represents operation exactly at the limit.

Suppose

$$Q_{\min} = 80 \ \mathrm{m}^3/\mathrm{h}$$

and the pump delivers

$$Q = 95 \ \mathrm{m}^3/\mathrm{h}.$$

Then

$$M_Q = 95 - 80 = 15 \text{ m}^3/\text{h}.$$

The pump has 15 m^3/h of flow margin relative to the specified minimum.

This says something about current functional adequacy, but nothing directly about the condition of its bearings, seals, or impeller.

2.3 Physical condition

The physical condition of an asset describes the state of its materials, components, and characteristics that influence its ability to perform.

Condition may include quantities such as:

- Bearing clearance.
- Remaining wall thickness.
- Impeller geometry.
- Surface roughness.
- Insulation resistance.
- Battery capacity.
- Internal electrical resistance.
- Heat-transfer surface fouling.

These quantities may deteriorate gradually, change abruptly, or sometimes improve following maintenance.

Let

$$x(t)$$

represent the asset's physical condition.

For a pump, one possible condition vector is

$$x(t) = \begin{bmatrix} c_b(t) \\ w_i(t) \\ c_s(t) \end{bmatrix},$$

where

- $c_b(t)$: bearing clearance, in mm;
- $w_i(t)$: impeller wear depth, in mm;
- $c_s(t)$: seal clearance, in mm.

The condition vector is not necessarily observable directly.

For example, bearing clearance may require disassembly to measure accurately.

A vibration sensor provides indirect evidence about bearing condition, but vibration is not itself a measurement of clearance.

This distinction becomes important when diagnosing faults.

2.4 The relationship between condition and performance

Asset performance depends on physical condition, operating circumstances, and the environment.
A general mathematical representation is

$$\boxed{y(t) = f(x(t), u(t), e(t))}$$

where

- $y(t)$: asset performance;
- $x(t)$: physical condition;
- $u(t)$: operating inputs;
- $e(t)$: environmental conditions;
- f: relationship connecting these quantities.

For a centrifugal pump:

Quantity	Examples
Physical condition x	Impeller wear, bearing clearance, internal leakage
Operating inputs u	Rotational speed, valve position
Environment e	Water temperature, fluid properties
Performance y	Flow, pressure rise, efficiency, power

The same physical condition can produce different performance under different operating circumstances.
Conversely, two pumps in different physical conditions may produce similar performance at a particular operating point.
This creates an important challenge for condition assessment.
A change in performance cannot automatically be attributed to degradation.

2.4.1 Example: Pump flow

Suppose a pump delivers

$$Q_1 = 100 \text{ m}^3/\text{h}$$

on Monday and

$$Q_2 = 90 \text{ m}^3/\text{h}$$

on Tuesday.
The flow decreased by 10%.
Does this mean the pump deteriorated?
Not necessarily.
The flow could have changed because:

- The pump speed decreased.
- A downstream valve partially closed.

- The system pressure requirement increased.
- The fluid properties changed.
- The impeller deteriorated.

The first four possibilities involve changes in operating or environmental conditions. The final possibility involves physical deterioration.
Without additional information, the cause is ambiguous.

> **Figure (to be drawn):**Condition, operation, and observed performance Observed performance reflects physical condition together with operating inputs and environmental influences.

The purpose of condition monitoring is partly to separate these influences.

2.5 Degradation

Degradation is a process that reduces an asset's condition or its ability to satisfy a required function.
Examples include:

- Metal loss due to corrosion.
- Crack growth due to fatigue.
- Bearing surface wear.
- Battery capacity loss.
- Insulation deterioration.
- Fouling of a heat-transfer surface.

A degradation variable is a quantity chosen to describe the progression of a particular mechanism.
Let

$$d(t)$$

represent accumulated degradation.
For example, $d(t)$ might be the depth of material lost from a component, measured in mm.
A simple linear degradation model is

$$d(t) = d_0 + rt,$$

where

- d_0: initial degradation;
- r: constant degradation rate;
- t: elapsed time.

If a component begins with no measurable wear,

$$d_0 = 0,$$

and accumulates wear at

$$r = 0.05 \text{ mm/year},$$

then after four years,

$$d(4) = 0.05(4) = 0.20 \text{ mm}.$$

This model assumes a constant degradation rate.

Real degradation often depends on operating stress, temperature, loading, and environmental exposure.

A more general representation is

$$\boxed{\frac{dd}{dt} = g(d(t), u(t), e(t))}$$

where the rate of degradation depends on current condition and operating circumstances.

This equation does not prescribe a particular degradation mechanism. It provides a general mathematical structure that can be specialized to wear, corrosion, fatigue, or other physical processes.

We will examine established degradation models in later lessons.

2.6 Degradation does not always imply immediate failure

Suppose a pump impeller gradually wears.

As its geometry changes, the pump may become less efficient.

Initially, the pump continues meeting its required flow.

Eventually, the deterioration may become severe enough that the pump can no longer satisfy the requirement.

Let $d(t)$ represent impeller wear, and let d_{crit} be a wear level associated with an unacceptable condition.

A simplified condition limit is

$$d(t) \leq d_{\text{crit}}.$$

The important distinction is between:

- **Degradation onset:** A physical deterioration process begins.
- **Detectable degradation:** Monitoring provides sufficient evidence to recognize deterioration.
- **Functional failure:** The asset no longer satisfies a specified requirement.

These events need not occur at the same time.

Chart data — Illustrative degradation progression. Degradation progresses over time and eventually crosses a specified condition limit at year 8. A functional failure criterion may be different. Synthetic linear degradation example. The critical limit is assumed, not an equipment standard.

year	Wear depth	Critical limit
0	0	0.4

year	Wear depth	Critical limit
1	0.05	0.4
2	0.1	0.4
3	0.15	0.4
4	0.2	0.4
5	0.25	0.4
6	0.3	0.4
7	0.35	0.4
8	0.4	0.4
9	0.45	0.4
10	0.5	0.4

This distinction allows engineers to intervene before an asset loses its required function.

2.7 Condition limits versus performance limits

A *condition limit* specifies an unacceptable physical state or condition indicator.
A *performance limit* specifies an unacceptable level of functional performance.
They are not necessarily the same.
Consider a pump with:

- Maximum acceptable bearing vibration: $v_{\max}$.
- Minimum required flow: $Q_{\min}$.

The condition-monitoring criterion may be

$$v(t) \leq v_{\max}.$$

The flow-performance requirement is

$$Q(t) \geq Q_{\min}.$$

It is possible for

$$v(t) > v_{\max}$$

while

$$Q(t) \geq Q_{\min}.$$

In this case, the vibration criterion has been exceeded, but the pump continues satisfying its flow requirement.
Whether the vibration exceedance itself constitutes a defined failure depends on the asset's stated requirements. It may instead be an alarm or maintenance-action threshold.
This distinction is essential for correct engineering interpretation.

END OF THE PREVIEW

Asset Health and Condition Monitoring Volume I

These are the opening pages. The complete book runs 296 pages.

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