BASICS OF MACHINE OPERATION

Block 2 · Lecture 3 · 9 Dec 2026

Modern Maintenance Concepts; Availability, Durability and Wear



dr inż. Radosław Gościniak

Akademia Techniczno-Artystyczna Nauk Stosowanych w Warszawie

Course plan

L1 Block 1 · 2 Dec 2026

Introduction to machine operation · Machines as technical means

L2 Block 1 · 2 Dec 2026

Systems approach · Maintenance organisation and strategies

L3 Block 2 · 9 Dec 2026

Modern maintenance · Availability, durability and wear

L4 Block 2 · 9 Dec 2026

Tribology and lubrication · Fundamentals of diagnostics

L5 Block 3 · 20 Jan 2027

Condition monitoring · Reliability fundamentals

L6 Block 3 · 20 Jan 2027

System reliability · Failure analysis and improvement

L7 Block 4 · 27 Jan 2027

Life data and maintenance logistics · Industry 4.0 · Review

Today: **L3. Modern Maintenance Concepts; Availability, Durability and Wear**

RECAP

Last week in six points

A system = elements + relations + environment; **structure determines behaviour**.

Operation system = **use** + **maintenance** subsystems (+ supply).

Iceberg: look at **patterns, structures and mental models**, not only events.

Human factors – the **“Dirty Dozen”**.

EN 13306: **corrective, predetermined, condition-based, predictive**; P-F curve.

Choose a strategy by **consequences × frequency** (criticality matrix).

TODAY

Plan for today

PART A

Modern maintenance concepts

1. Development of maintenance
2. Reliability-Centred Maintenance (RCM)
3. Total Productive Maintenance (TPM) and OEE
4. Computer-aided maintenance (CMMS)

PART B

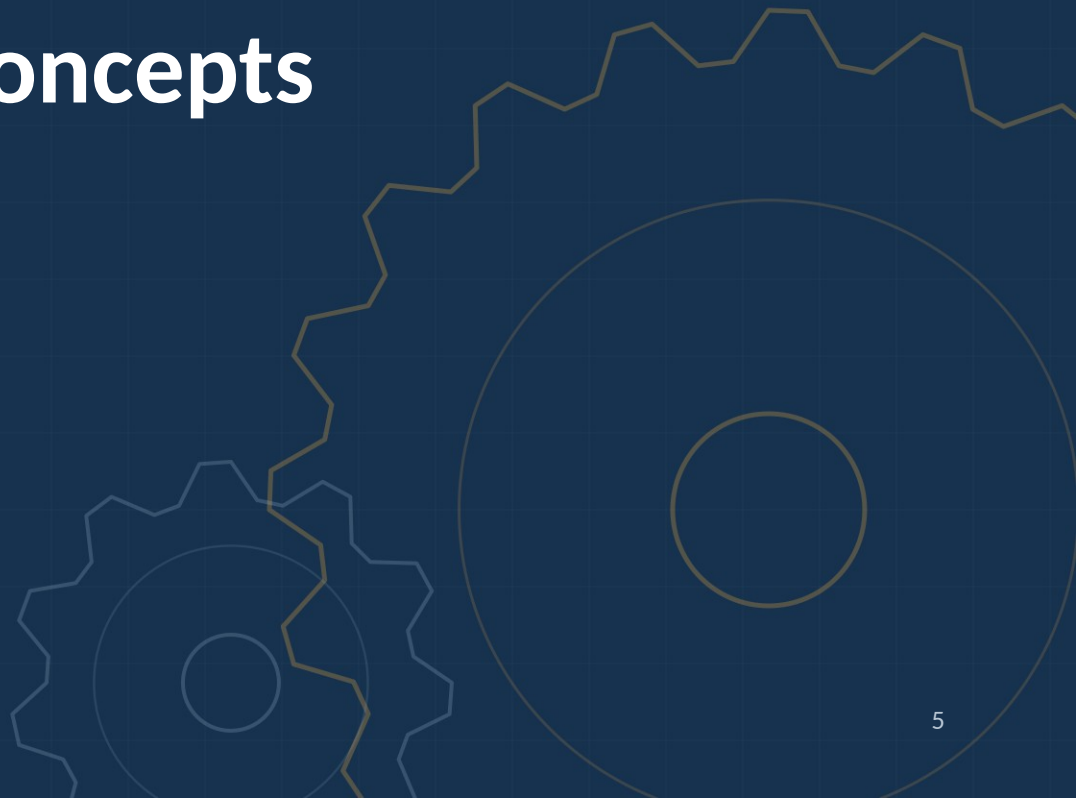
Availability, durability and wear

5. Availability
6. Technical condition and durability
7. Technical wear processes
8. Economic wear and replacement

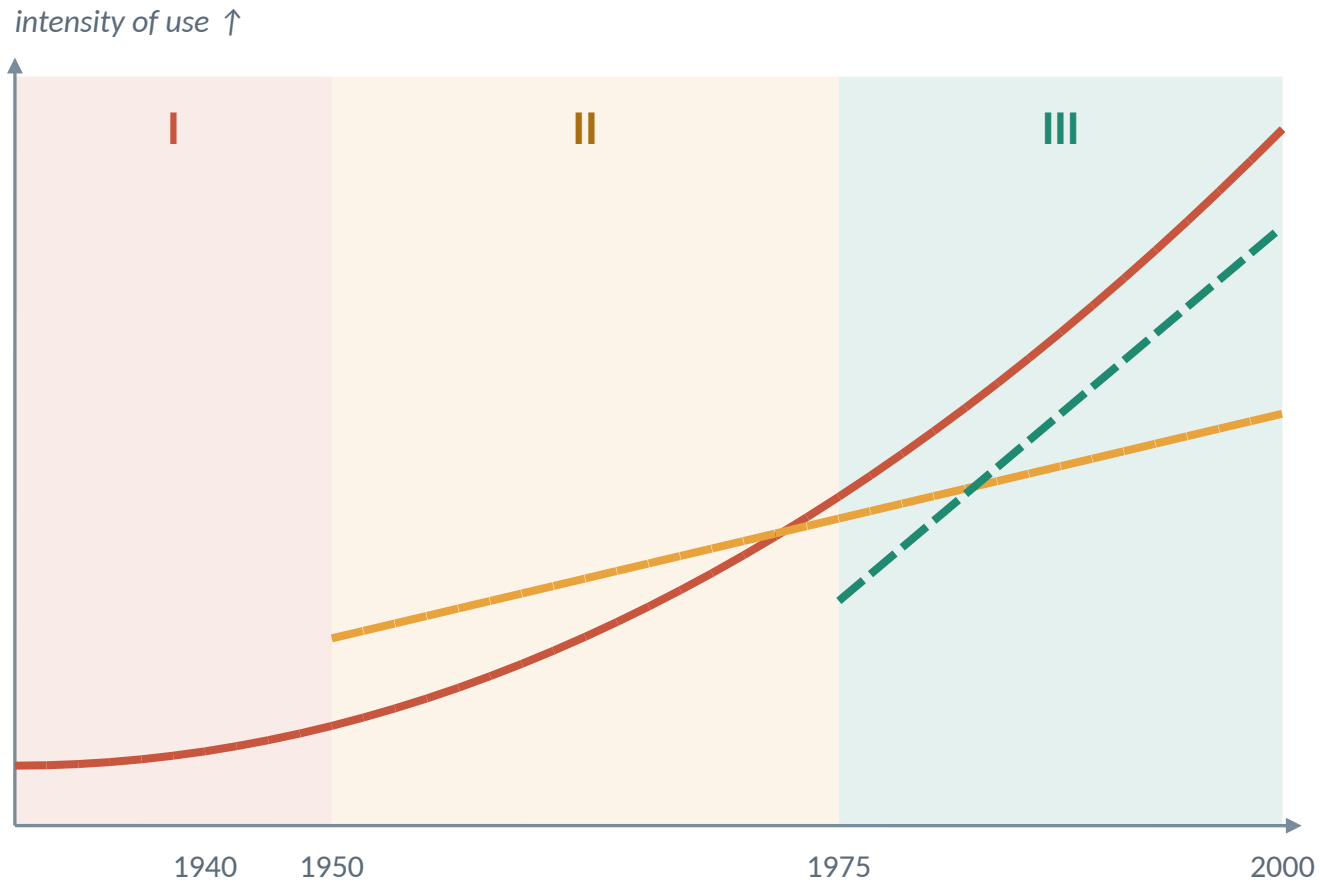
01

Development of maintenance concepts

Three periods – from repairing to preventing to predicting



Three periods of maintenance development



1 **Reactive maintenance**

"curing the symptoms"

2 **Preventive maintenance**

planned, preventive actions

3 **Predictive maintenance**

condition monitoring

Three periods and three concepts (trends 1, 2, 3) – after S. Legutko.

Period I – reacting to failures

Period I – from the first machines until about the Second World War – was characterised by **reacting to failures**. The reactive approach dominated.

Mechanisation was low, so a failure did not have a big influence on production. Machines were simple and easy to maintain, so no preventive actions were needed – except cleaning and lubrication.

Overhauls, repairs and regeneration of parts were done as a reaction to failures. Companies focused on the product and production; maintenance was seen as a **supporting activity**.



KEY TAKEAWAY

Until about 1940: **reactive** – maintenance as a supporting activity.

Period II – the planned-preventive system

Period II – from the 1950s many machines were numerically controlled and their design became more complex. The influence of a failed machine on production grew strongly.

The key questions were: can we prevent failures, and how? The **system of planned-preventive overhauls** appeared: maintenance at fixed intervals or after a fixed amount of work (**by resource**).

Characteristic features: the concept of **preventive maintenance**, a new view of failure rates, and the growing importance of **planning and control systems** for maintenance.



KEY TAKEAWAY

From the 1950s: **preventive** maintenance at fixed intervals.

Period III – RCM and TPM

Period III – from the mid-1970s. The key goal became **failure-free operation during the whole life** of the machine. Preventive maintenance did not work when many failures happened early in the machine's life. New concepts appeared:



RCM – Reliability-Centred Maintenance

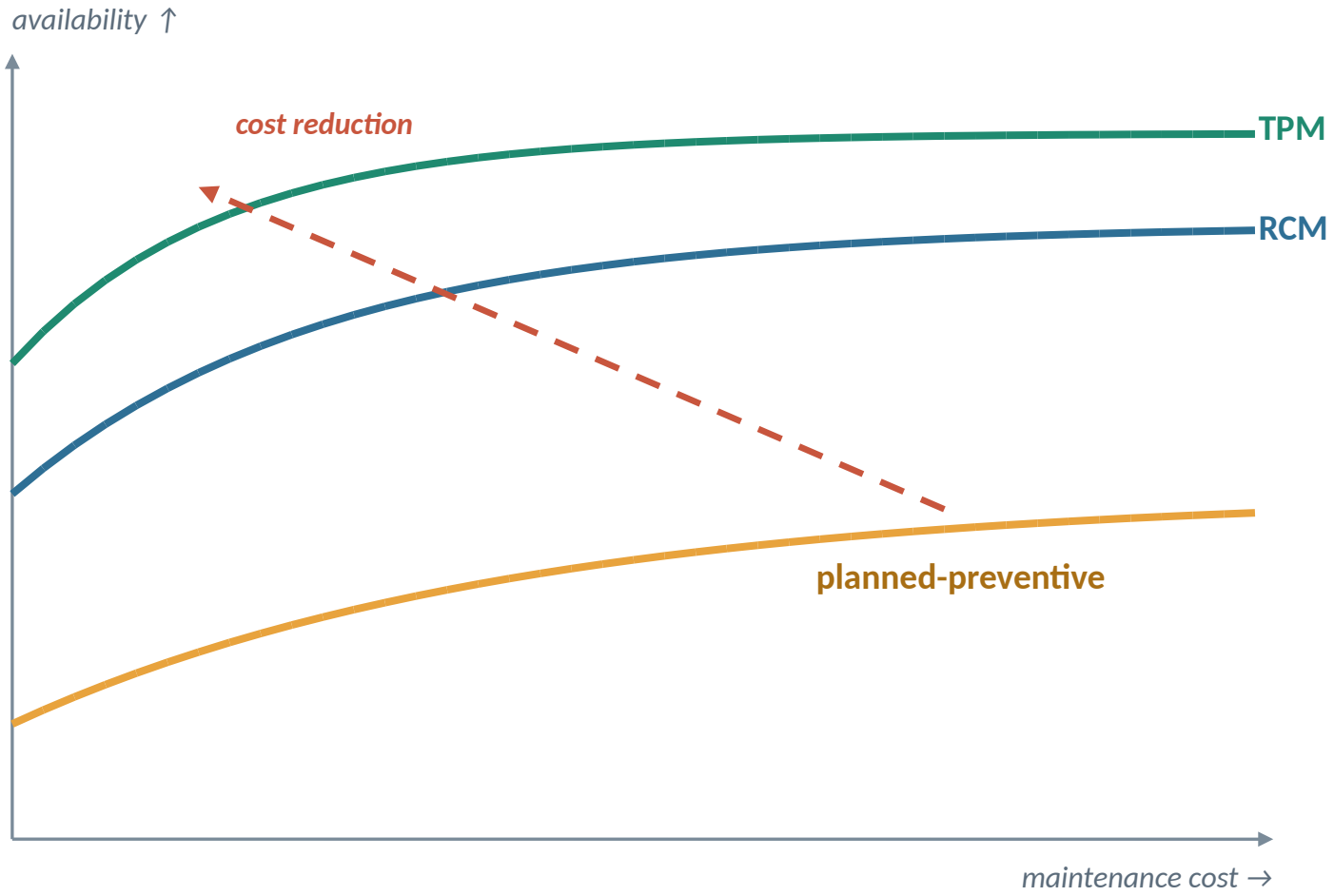
maintenance focused on reliability – a strategy based on the analysis of functions, failures and their consequences.



TPM – Total Productive Maintenance

maintenance integrated with production and focused on productivity – operators take part in caring for their machines.

Competitiveness of maintenance strategies



The goal of company management: **maximum availability at minimum maintenance cost**.

More advanced strategies reach the same availability at a **lower cost**.

TPM and RCM need more involvement of **operators** – and giving them responsibility and authority for preventive actions.

When is planned-preventive maintenance right?

If the requirements of TPM or RCM cannot be met, aim for **condition-based** maintenance. If this is not possible for technical or financial reasons, use **planned-preventive** maintenance. It is right mainly for:

- routine inspections,
- basic care of machines (cleaning, lubrication, adjustment),
- calibration of measuring instruments,
- analysis, planning and scheduling of maintenance work, and meeting legal requirements,
- cases when statistics show that a device fails in a repeatable way, linked to the degree of wear.



KEY TAKEAWAY

Order of choice: **TPM / RCM** → **condition-based** → **planned-preventive** → reactive.

Limits of planned-preventive maintenance

In other situations, planned-preventive maintenance is not appropriate, because:

- the wear rate of machine parts is not constant during use,
- reliability data from manufacturers do not include the specific conditions of a given user,
- the time of correct operation between failures becomes shorter as the machine gets older,
- the scope of services and repairs grows with the operating time.

When prevention is impossible, only **reactive** maintenance remains – “from failure to failure”. It is used for failures with **small economic effects** and no safety risk. Thanks to better and computerised machines, it is having a small **renaissance**.



KEY TAKEAWAY

Fixed intervals assume **constant** wear – real machines rarely behave like that.

02

Reliability-Centred Maintenance (RCM)

From aviation to industry – maintenance based on functions and consequences



What is RCM?

RCM is a structured process to decide **what must be done** to make sure that a physical asset continues to do **what its users want it to do** in its present operating context.

Origin – aviation

Boeing 747 in the late 1960s: classic overhauls were too expensive. Report by **F. S. Nowlan and H. F. Heap** for United Airlines (1978).

Standards

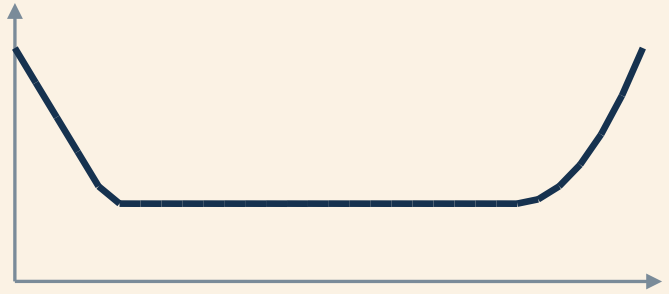
SAE JA1011 – criteria of an RCM process (7 questions); **SAE JA1012** – guide; **IEC 60300-3-11**; in aviation: **MSG-3**.

Key idea

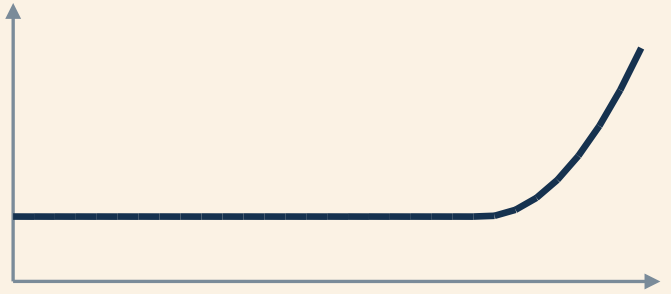
maintain **functions**, not machines; choose tasks by the **consequences** of failures – safety, environment, operation, cost.

Six failure patterns – what Nowlan and Heap discovered

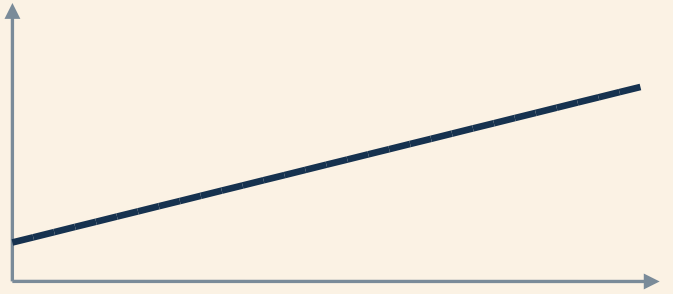
A · bathtub curve — **4%**



B · constant, then wear-out — **2%**



C · slowly increasing — **5%**



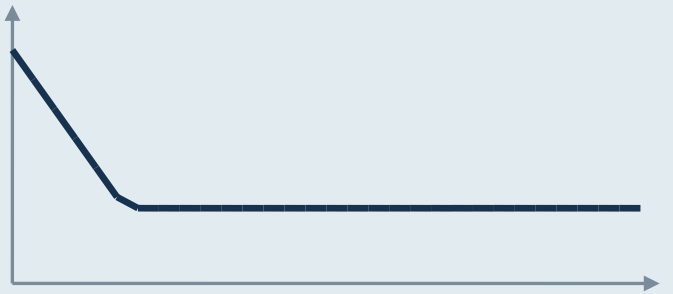
D · low at start, then constant — **7%**



E · random (constant) — **14%**



F · infant mortality — **68%**



vertical: failure rate · horizontal: age · orange – age-related (≈11%) · blue – not age-related (≈89%)

The RCM process step by step

1

Select the system

and define its operating context

2

Functions

and performance standards

3

Functional failures

how can it fail?

4

Failure modes

what causes each failure?

5

Failure effects

what happens?

6

Consequences

how much does it matter?

7

Task selection

prevent, detect, or default action

8

Implement & review

living programme

Steps 2–6 = FMEA/FMECA · Step 7 = maintenance programme · RCM is done by a team: operators, maintenance, engineering

RCM decision logic (simplified)

Is the failure hidden?	YES → failure-finding task (test protective devices)
Does it affect safety or the environment?	YES → task must reduce risk to an acceptable level – otherwise redesign is compulsory
Does it affect operations (output, quality)?	YES → task must cost less than the operational loss + repair
Only repair cost (non-operational)?	task must cost less than the repair – otherwise run-to-failure

ORDER OF PREFERENCE FOR TASKS

1. **Condition-based (on-condition)**
2. **Scheduled restoration**
3. **Scheduled discard (replacement)**
4. **Failure-finding / redesign / run-to-failure**

EXAMPLE

Example: part of an RCM worksheet for a cooling-water pump

Function / failure	Failure mode	Effect	Consequence	Task
Pump 50 m³/h at ≥ 3 bar → delivers no water	Bearing worn (fatigue)	noise, then seizure; line stops after ~10 min	operational	vibration analysis monthly (CBM)
→ delivers no water	Coupling element broken	pump stops immediately	operational	visual check monthly; replace on condition
→ delivers < 50 m³/h	Impeller worn (erosion)	flow and pressure drop slowly	operational	trend flow & pressure (CBM)
Contain water → leaks	Mechanical seal worn	leak onto floor; slip hazard	safety	daily operator inspection; drip tray
Protect motor → overload trip fails	Thermal relay stuck (hidden)	motor burns out at overload	hidden	test relay every 6 months (failure-finding)

Illustrative example. Each row answers RCM questions 1–7 for one failure mode.

GROUP EXERCISE

ACTIVITY

RCM mini-analysis: a bicycle chain drive

Work in groups of 3–4 for **10 minutes**. A city bike-sharing company maintains 500 bicycles. Analyse the **chain drive** (chain, sprockets, derailleur):

1. Define the function and a performance standard
2. Find two functional failures
3. For each, name at least one failure mode (cause)
4. Describe the effect and classify the consequence
5. Choose a task: condition-based, scheduled, failure-finding or run-to-failure

Hint: think about chain elongation, rust, lack of lubrication, a chain coming off, and riders' safety.

GROUP EXERCISE

ANSWERS

Bicycle chain drive – example solution

Function: transmit the rider's pedalling force to the rear wheel smoothly, in all gears, without the chain coming off.

Functional failure	Failure mode	Effect / consequence	Task
Does not transmit force at all	chain breaks (worn link)	rider may fall – safety	measure chain elongation at each service; replace at 0.5%
Chain comes off	worn sprocket teeth; misadjusted derailleur	rider may fall – safety	check shifting and sprockets every 3 months
Transmits force with high resistance	rust, no lubrication	harder pedalling, faster wear – operational	clean and lubricate monthly; more often in winter
Noisy, skipping gears	stretched cable, dirt	unpleasant ride, complaints – non-operational	adjust on condition after user reports (app)

03

Total Productive Maintenance (TPM) and OEE

Operators and maintenance together – zero breakdowns, zero defects, zero accidents



What is TPM?

Total Productive Maintenance was developed in Japan in the 1970s and promoted by **Seiichi Nakajima** and the Japan Institute of Plant Maintenance (JIPM). It ends the stereotype “I produce – you repair”.

Total

everyone takes part – from top management to operators; all equipment, all departments.

Productive

maintenance is done while production continues as much as possible; focus on eliminating losses.

Maintenance

keeping equipment in perfect condition – operators care for “their” machine every day.

Goals: **zero unplanned breakdowns, zero defects, zero accidents**.

The eight pillars of TPM

TPM – Total Productive Maintenance

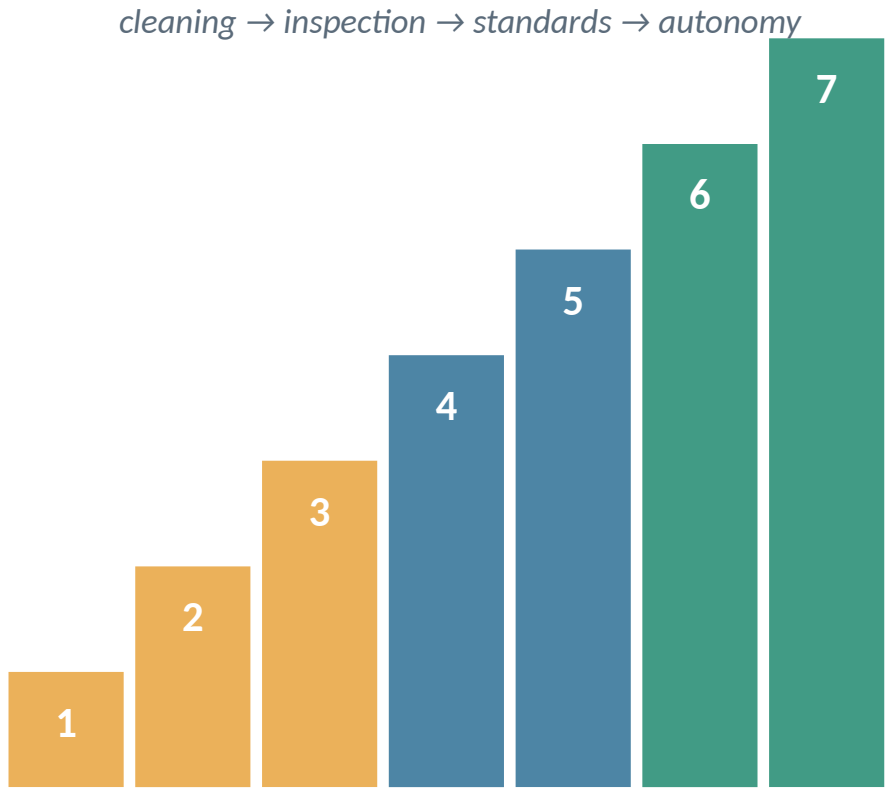
1	2	3	4	5	6	7	8
Autonomous maintenance	**Planned maintenance**	**Quality maintenance**	**Focused improvement**	**Early equipment management**	**Training and education**	**Safety, health, environment**	**TPM in administration**
operators (jishu hozen)	*schedules, CMMS*	*zero defects*	*kaizen, loss elimination*	*easy-to-maintain design*	*skills of operators and staff*	*zero accidents*	*office, logistics*

Foundation: 5S · involvement of all employees

Autonomous maintenance in seven steps

Operators take over simple daily care: **cleaning, lubrication, inspection, tightening**. Maintenance specialists can focus on complex work.

1. Initial cleaning – cleaning is inspection
2. Eliminate sources of contamination and hard-to-reach places
3. Cleaning and lubrication standards
4. General inspection – training of operators
5. Autonomous inspection with checklists
6. Standardisation and visual management
7. Autonomous management – continuous improvement



5S – the foundation of TPM

Sort
(seiri) remove what is not needed

Set in order
(seiton) a place for everything, everything in its place

Shine
(seiso) clean – and inspect while cleaning

Standardise
(seiketsu) rules, colours, labels, checklists

Sustain
(shitsuke) discipline – make it a habit

A clean machine shows leaks, cracks and loose bolts – **cleaning is inspection**.

The six big losses

AVAILABILITY losses	PERFORMANCE losses	QUALITY losses
1. Breakdowns (equipment failures)	3. Idling and minor stops	5. Process defects (scrap, rework)
2. Setup and adjustments (changeovers)	4. Reduced speed	6. Start-up losses (reduced yield)

Nakajima grouped all equipment losses into **six big losses**. Each group reduces one factor of **OEE – Overall Equipment Effectiveness**. Maintenance mainly influences breakdowns, minor stops and reduced speed.

OEE = Availability × Performance × Quality

Availability

90%

run time / planned production time

losses: breakdowns, setups

×

Performance

95%

(ideal cycle time × total count) / run time

losses: minor stops, reduced speed

×

Quality

99.9%

good count / total count

losses: defects, start-up losses

=

OEE

≈ 85%

often called “world class”

OEE combines **reliability** (availability), **process efficiency** (performance) and **quality** in one number. Typical values in industry are much lower than 85% – often 40–60%. OEE shows **where the biggest losses are**.

EXAMPLE

Calculating OEE step by step

DATA – one shift

- shift length: **480 min**
- planned breaks: **30 min**
- breakdowns and setups: **45 min**
- ideal cycle time: **0.5 min per part**
- total parts produced: **760**
- good parts: **740**

Planned production time	$480 - 30 = 450$ min
Run time	$450 - 45 = 405$ min
Availability	$405 / 450 = 90.0\%$
Performance	$0.5 \times 760 / 405 = 93.8\%$
Quality	$740 / 760 = 97.4\%$

OEE = 0.900 × 0.938 × 0.974 ≈ 82%

EXERCISE

ACTIVITY

Your turn: calculate OEE

DATA – an injection moulding machine, one shift

- shift length: **480 min**
- planned breaks: **40 min**
- one breakdown: **30 min**
- one mould change (setup): **20 min**
- ideal cycle time: **1.2 min per part**
- parts produced: **300**, of which **12** defective



Work alone or in pairs – 6 minutes.

1. Planned production time and run time
2. Availability
3. Performance
4. Quality
5. OEE – and the biggest loss

EXERCISE

ANSWERS

Calculate OEE – solution

Planned production time	$480 - 40 = 440$ min
Run time	$440 - 30 - 20 = 390$ min
Availability	$390 / 440 = 88.6\%$
Performance	$1.2 \times 300 / 390 = 92.3\%$
Quality	$(300 - 12) / 300 = 96.0\%$

OEE = 0.886 × 0.923 × 0.960 ≈ 78.5%

Biggest loss: availability (50 min of 440 = 11.4%).

Ideas: SMED to shorten the mould change; root cause analysis of the breakdown; autonomous maintenance.

Second: performance – minor stops or slower cycles (7.7%).

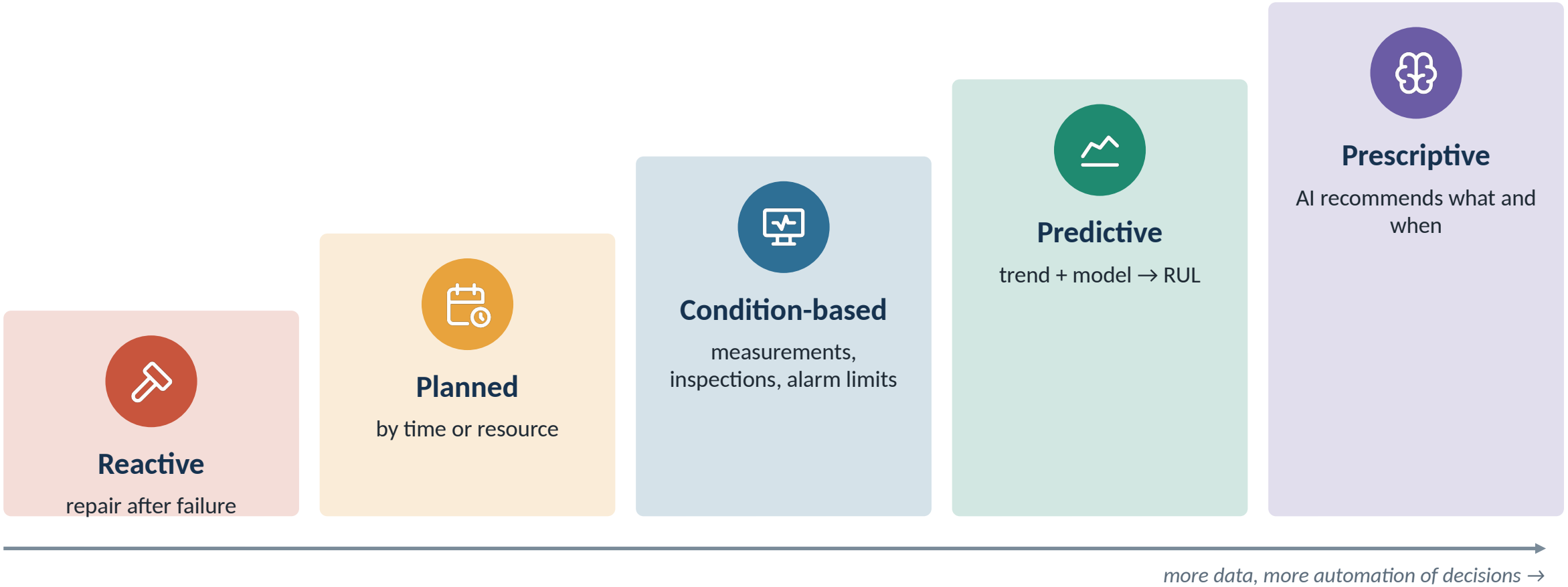
RCM and TPM – a comparison

	RCM	TPM
Origin	aviation, USA (1960s–1978)	manufacturing, Japan (1970s)
Focus	functions and failure consequences	people, losses and equipment effectiveness
Main question	what must be done to keep the function?	how to eliminate all losses?
Key tools	FMEA, decision logic, task selection	8 pillars, 5S, autonomous maintenance, OEE
Who leads	small expert team (engineers + operators)	everyone – top management to operators
Best for	complex, critical, safety-related assets	production lines with many similar losses

In practice, they complement each other: RCM decides WHAT to do; TPM organises WHO does it every day.

Maintenance maturity – from reaction to prediction

RUL = remaining useful life



04

Computer-aided maintenance (CMMS / EAM)

Data, work orders and the digital memory of the machine park



Maintenance tasks supported by computers

- Collecting and analysing the history of machine conditions
- Analysing maintenance and repair costs
- Optimising resource allocation (Pareto analysis)
- Coordinating maintenance with the production plan
- Central registration of failure reports
- Routine planning and scheduling (90% of all maintenance work)
- Standardising maintenance methods
- Link with the spare parts store – orders, condition monitoring and forecasts

What is a CMMS?

IT systems for these tasks are called **CMMS – Computerised Maintenance Management Systems**. They work on transactional databases that store information about operated objects and their environment.

A CMMS can be a stand-alone programme, or a module of an **ERP** system (Enterprise Resource Planning). A broader class is **EAM** – Enterprise Asset Management – covering the whole asset life cycle.

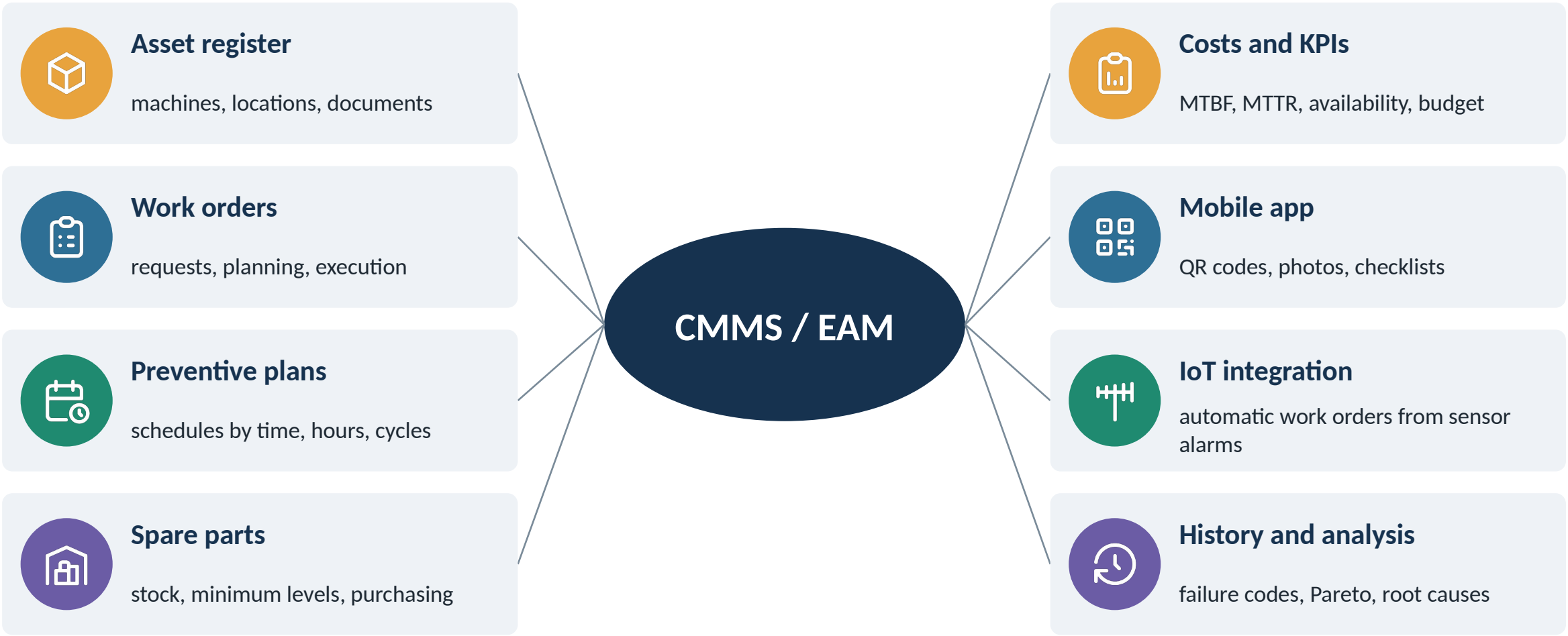
CMMS systems are among the most complex systems in a company: they work at the meeting point of many business processes – **material and financial flows**. They often cooperate with sensors, RFID tags and measurement systems, and contain analytical tools for planning and forecasting.



KEY TAKEAWAY

CMMS = the **digital memory** of the machine park.

Main functions of a CMMS



CMMS / EAM today – market and trends

Large EAM systems

SAP S/4HANA Asset Management (formerly SAP PM); **IBM Maximo Application Suite** – with monitoring and prediction modules.

Cloud CMMS (SaaS)

subscription systems in the browser and on the phone (e.g. Fiix, UpKeep, MaintainX, Limble) – fast to implement, also for SMEs.

Local vendors

national CMMS providers (in Poland e.g. Queris, DIMO Maint, Aretics) – local support and language.

Mobility and tags

failure reports from the phone, QR / NFC codes on machines, photos and signatures in the work order.

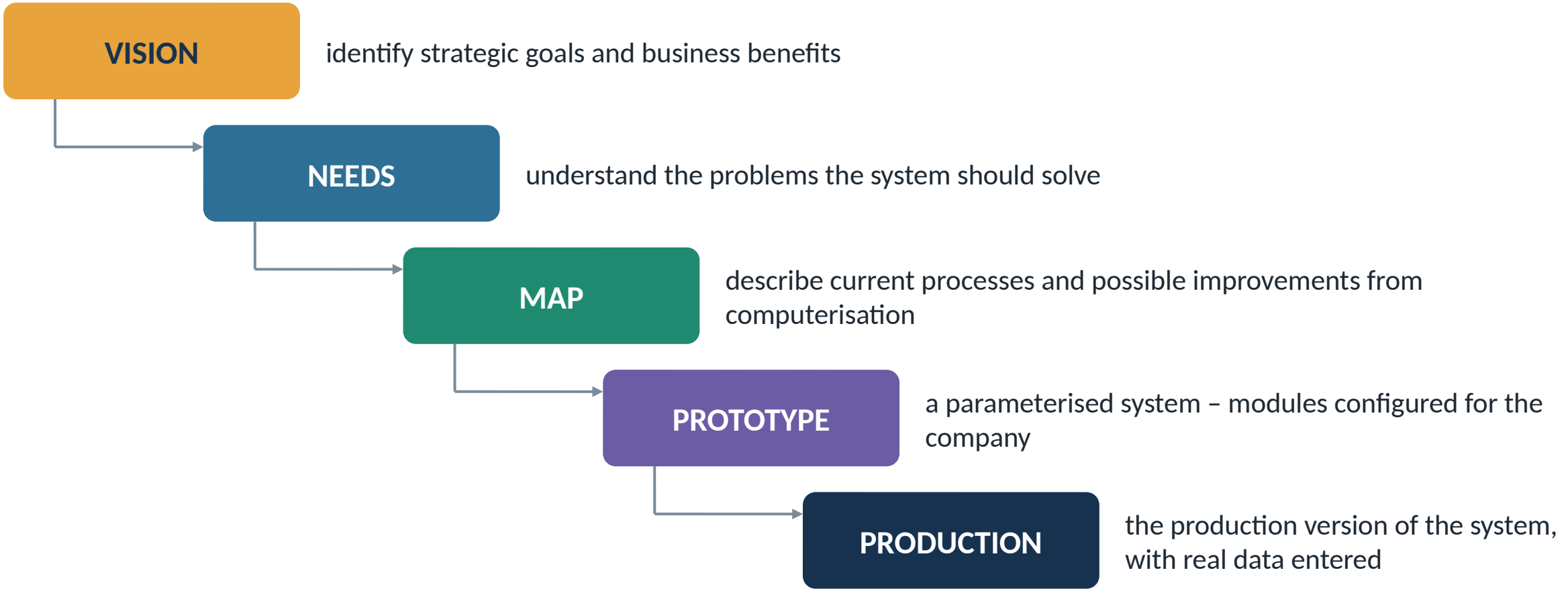
IIoT integration

automatic work orders from sensor data and alarm limits – condition-based maintenance.

Analytics and AI

real-time KPIs; predictive models and AI assistants that search failure history.

Phases of implementing a CMMS



The value of a CMMS is created by its users – by accepting its formulas and matching company procedures with the system.

Garbage in, garbage out – data quality

A CMMS is only as good as its data. To analyse failures, every work order needs **structured failure codes**. The standard **ISO 14224** (reliability and maintenance data collection) suggests a taxonomy:



Equipment

which asset / component?

e.g. pump P-101 / mechanical seal



Failure mode

how did it fail? (what we observe)

e.g. external leakage



Failure mechanism

physical process

e.g. wear of seal faces



Failure cause

why did it happen?

e.g. dry running – no water at start-up



Action

what did we do?

e.g. seal replaced; start-up procedure changed

“Repaired” is not information. “Seal replaced – cause: dry running” is.

QUIZ

Quiz 1 – modern maintenance

1 The report that started RCM was written by...

A) Nakajima | B) Nowlan and Heap | C) Taylor | D) Deming

2 According to Nowlan and Heap, most aircraft components showed...

A) wear-out failures | B) no age-related failure pattern | C) only bathtub curves | D) no failures

3 Which is NOT one of the six big losses?

A) breakdowns | B) reduced speed | C) start-up losses | D) high energy price

4 A = 90%, P = 90%, Q = 100%. OEE equals...

A) 90% | B) 81% | C) 100% | D) 72%

5 The first step of autonomous maintenance is...

A) initial cleaning | B) buying a CMMS | C) vibration analysis | D) replacing the machine

ANSWERS

Quiz 1 – answers

1 The report that started RCM was written by...

A) Nakajima | **B) Nowlan and Heap** | C) Taylor | D) Deming

2 According to Nowlan and Heap, most aircraft components showed...

A) wear-out failures | **B) no age-related failure pattern** | C) only bathtub curves | D) no failures

3 Which is NOT one of the six big losses?

A) breakdowns | B) reduced speed | C) start-up losses | **D) high energy price**

4 A = 90%, P = 90%, Q = 100%. OEE equals...

A) 90% | **B) 81%** | C) 100% | D) 72%

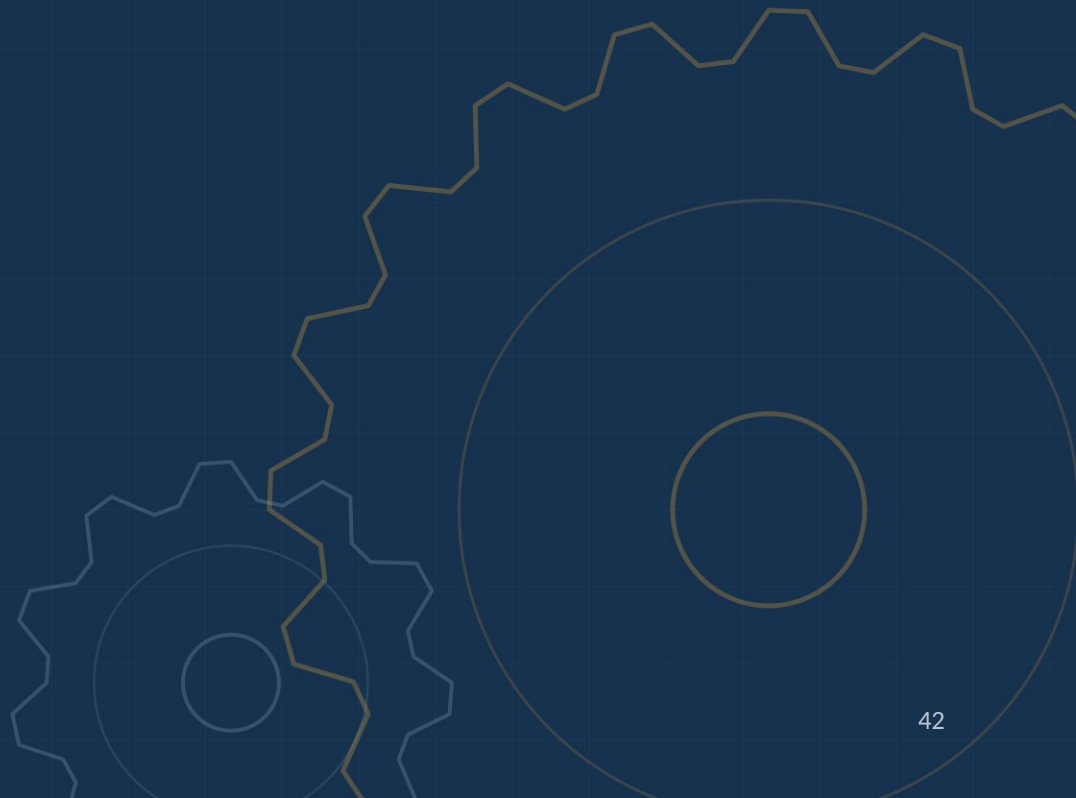
5 The first step of autonomous maintenance is...

A) initial cleaning | B) buying a CMMS | C) vibration analysis | D) replacing the machine

05

Availability of machines

Ready to work when needed – concepts, measures and calculations



Availability – the concept

Availability is the ability to be in a state to perform a required function – often stressed: **when it is needed**. To be available, a technical device must be:

- properly supplied (energy, materials),
- technically fit (in working order).

The first aspect is obvious. The second can be improved by operational strategies and reliability measures. Low operating costs and high availability are basic factors of company profitability.

Availability is most often expressed as the **percentage of time** in which the machine can provide the expected service.



KEY TAKEAWAY

Availability = the **% of time** the machine is ready to work when needed.

Attributes of the operational evaluation of a machine

Positive features	Negative features
AVAILABILITY	FAULTS
RELIABILITY	IMPRACTICABILITY (unfitness)
SAFETY	ERRORS
MODERNITY	FAILURES

Positive features describe what we want; negative features describe what reduces them.

Availability and dependability (IEC 60050-192)



Availability is a **higher-level** concept than reliability: reliability analyses each failure; availability analyses the ratio of **usable time** to **total time**.

Three conditions of availability

Higher reliability of elements means longer operation and decides about the availability of the whole machine. To be available, a machine must be:

Reliable

no failures when needed

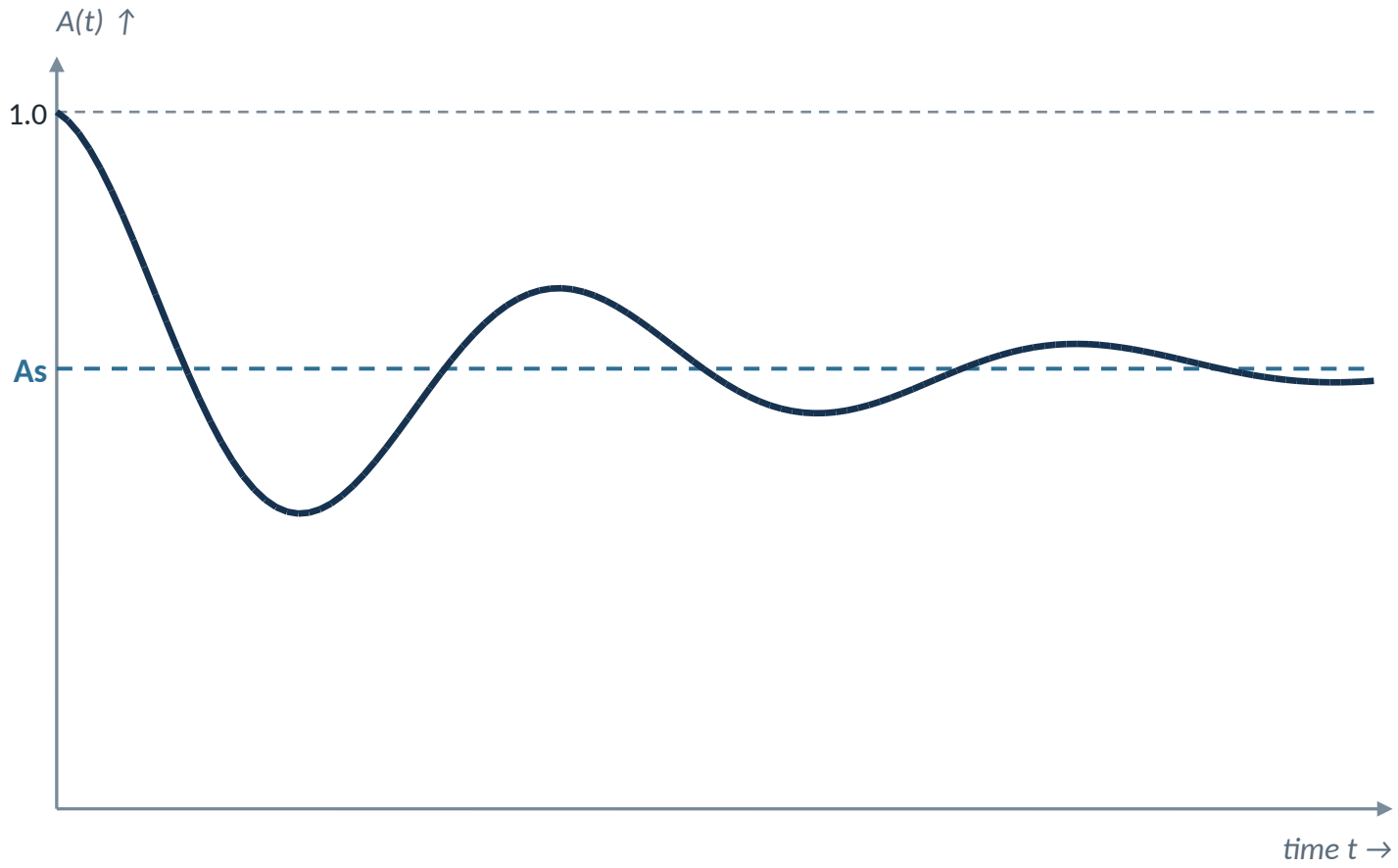
Prepared for work

supplied with consumables and the right equipment

Approved for use

in line with regulations – e.g. road traffic law, technical inspections

Availability coefficient in time



The **availability coefficient A(t)** is the probability that a repairable object is in the up state at time t.

With time it tends to a limit – the **steady-state availability As** (in Polish notation kgs).

In practice we use the steady-state value.

Steady-state availability

$$A = \frac{MTBF}{MTBF + MTTR}$$

$$0 \le A \le 1$$

MTBF — **mean time between failures (u)**

MTTR — **mean time to restore (v)**

For non-repairable objects MTTR = 0 – availability depends only on reliability.

To increase A: **increase MTBF** (fewer failures – reliability, prevention) or **decrease MTTR** (faster repairs – maintainability, spare parts, diagnostics).

Inherent, achieved and operational availability

Inherent availability Ai

$MTBF / (MTBF + MTTR)$

only corrective repair time – the “design” view

Achieved availability Aa

$MTBM / (MTBM + M)$

includes preventive maintenance time as well

Operational availability Ao

$MTBM / (MTBM + MDT)$

includes all downtime: waiting for parts, people, logistics, administration

MTBM – mean time between maintenance actions; M – mean active maintenance time; MDT – mean downtime. Ai ≥ Aa ≥ Ao

EXERCISE

ACTIVITY

Availability of a pump – inherent vs operational

DATA – a process pump, one year

- operating time: **8 200 h**
- number of failures: **6**
- total active repair time: **90 h**
- waiting for spare parts and technicians: **120 h** in total



Calculate (5 minutes):

1. MTBF and MTTR
2. inherent availability Ai
3. mean downtime MDT and operational availability Ao
4. What would you improve first?

ANSWERS

Availability of a pump – solution

MTBF	$8\,200 / 6 \approx 1\,367$ h
MTTR	$90 / 6 = 15$ h
Inherent availability Ai	$1\,367 / (1\,367 + 15) \approx 0.989$
MDT	$(90 + 120) / 6 = 35$ h
Operational availability Ao	$1\,367 / (1\,367 + 35) \approx 0.975$

Waiting time (**120 h**) is larger than repair time (**90 h**)!

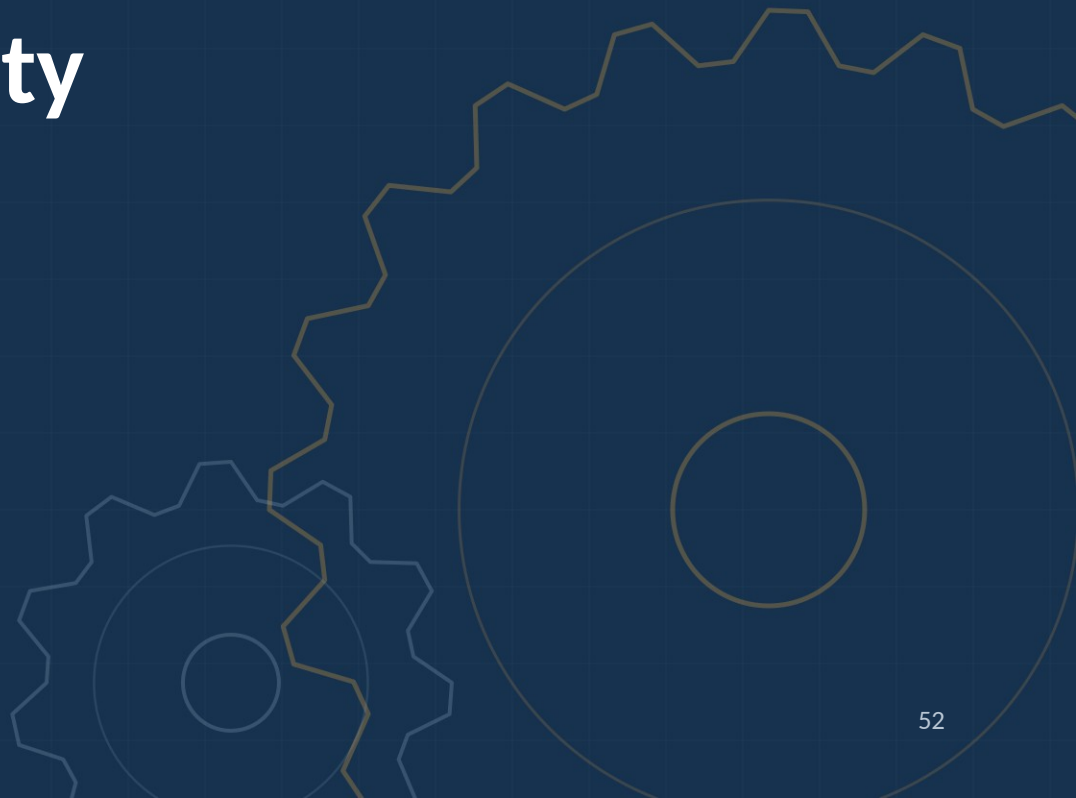
First improvement: **logistics** – critical spare parts in stock, faster access to technicians.

This is invisible in Ai – that is why companies should measure **Ao**.

06

Technical condition and durability

States, parameters, limits – and how long machines live



Physical ageing of machines

Negative attributes of a technical object result mainly from its **physical ageing** – natural changes in the materials of machine parts caused by internal and external forces, which irreversibly change their functional properties. Some changes can be eliminated or prevented – but with time they become more intensive.

Time leaves its mark on every technical object in two dimensions:

- **historical** – as the process of modernisation of objects,
- **current** – as the degradation of condition through wear and failures.



KEY TAKEAWAY

Time works in two ways: **modernisation** (history) and **degradation** (current).

State of an object and the history of states

The “life history” of a technical object is a sequence of its technical states. The moments when we observe the object are called **steps**. The state of object a at time t is a set of numbers x:

$$a(t) = (x_1, x_2, \dots, x_n)$$

The ordered set of states of object a, in the order in which they occur in time, is the **history of states S**:

$$S = a(k), a(k+1), a(k+2), \dots, a(k+n)$$

For an object, time is a sequence of its technical states – or, in the information sphere, a sequence of our knowledge about its important features F (power, output, speed…).

Diagnosis, retrospection and prognosis

Assume a phenomenon k in a technical object, shown by its characteristics F_1 … F_n, which depend only on time t:

$$k\{a, F_1, F_2, F_3, \ldots, F_n\}$$

The technical state at a given moment t is established by a **diagnosis** (from Greek: recognition).

But a moment is very short. In reality we deal either with the **past** – recognised by **retrospection** (genesis) – or with the **future** – predicted by a **prognosis**.

RETROSPECTION

the past – why did it happen?

DIAGNOSIS

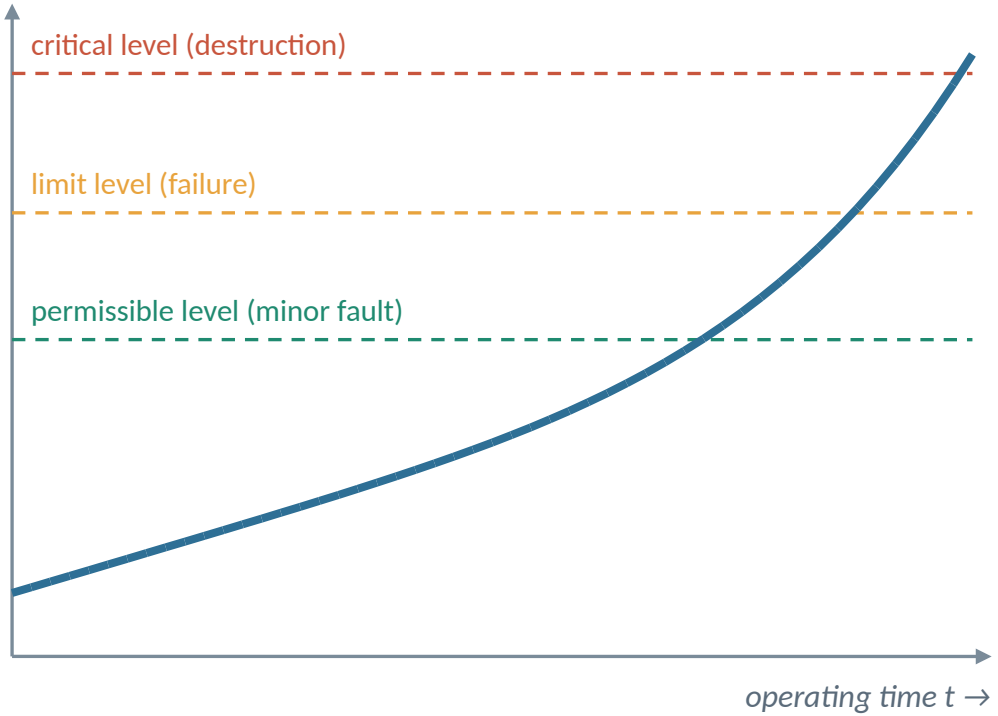
moment t – what is the state now?

PROGNOSIS

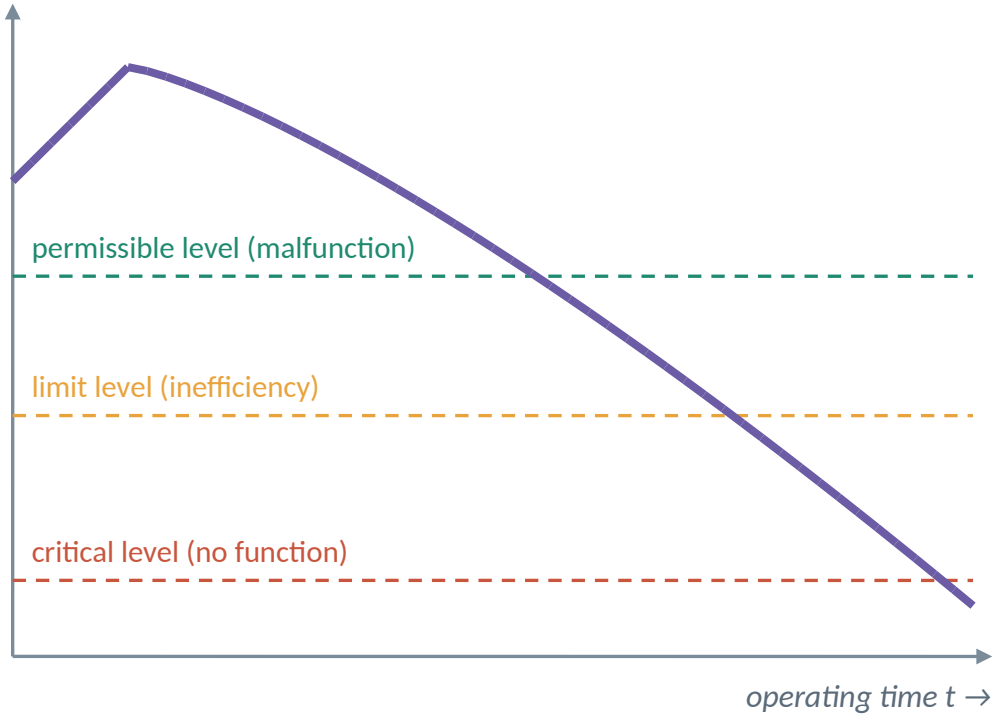
the future – what will happen?

Structural and functional parameters in time

a) Structural parameter X(t) – e.g. clearance, wear



b) Functional parameter F(t) – e.g. power, output



Structural parameters grow with wear; functional parameters fall. Both are compared with permissible, limit and critical levels.

Permissible, limit and critical states

Structural parameter X	Functional parameter F
Permissible – e.g. because of mating dimensions (fits)	**Permissible** – within tolerance, e.g. of power
Limit – when a repair is still possible	**Limit** – unacceptable drop of a functional parameter
Critical – sudden, uncontrolled increase of wear; danger for the whole machine	**Critical** – the machine cannot be started or does not work
Events: minor faults, failures, destruction	*Events: malfunctions, inefficiencies, non-operation*

Durability – how long should a machine last?

Durability has been one of the basic criteria of machine evaluation for decades – for scientists, designers, manufacturers and users. Real durability is determined in real operating conditions.

For consumer products, the buyer would feel cheated if a product, e.g. a TV set, did not work for at least some time. This is regulated by **warranty and legal guarantee**.

Durability – the ability of an object to perform a required function under given conditions of use and maintenance **until a limiting state is reached**.



KEY TAKEAWAY

Durability = the ability to work **until a limiting state** is reached.

Durability versus reliability

Manufacturers know that customers expect a long life – often much longer than the warranty. Durability and reliability are related, but they are **not the same**:

Durability T

a property of **one specific object**, described as a function of time.

Reliability R

a property of a **population of objects** of a given type, described by the **probability** of an event.

Types of durability

By the measure of durability we distinguish:

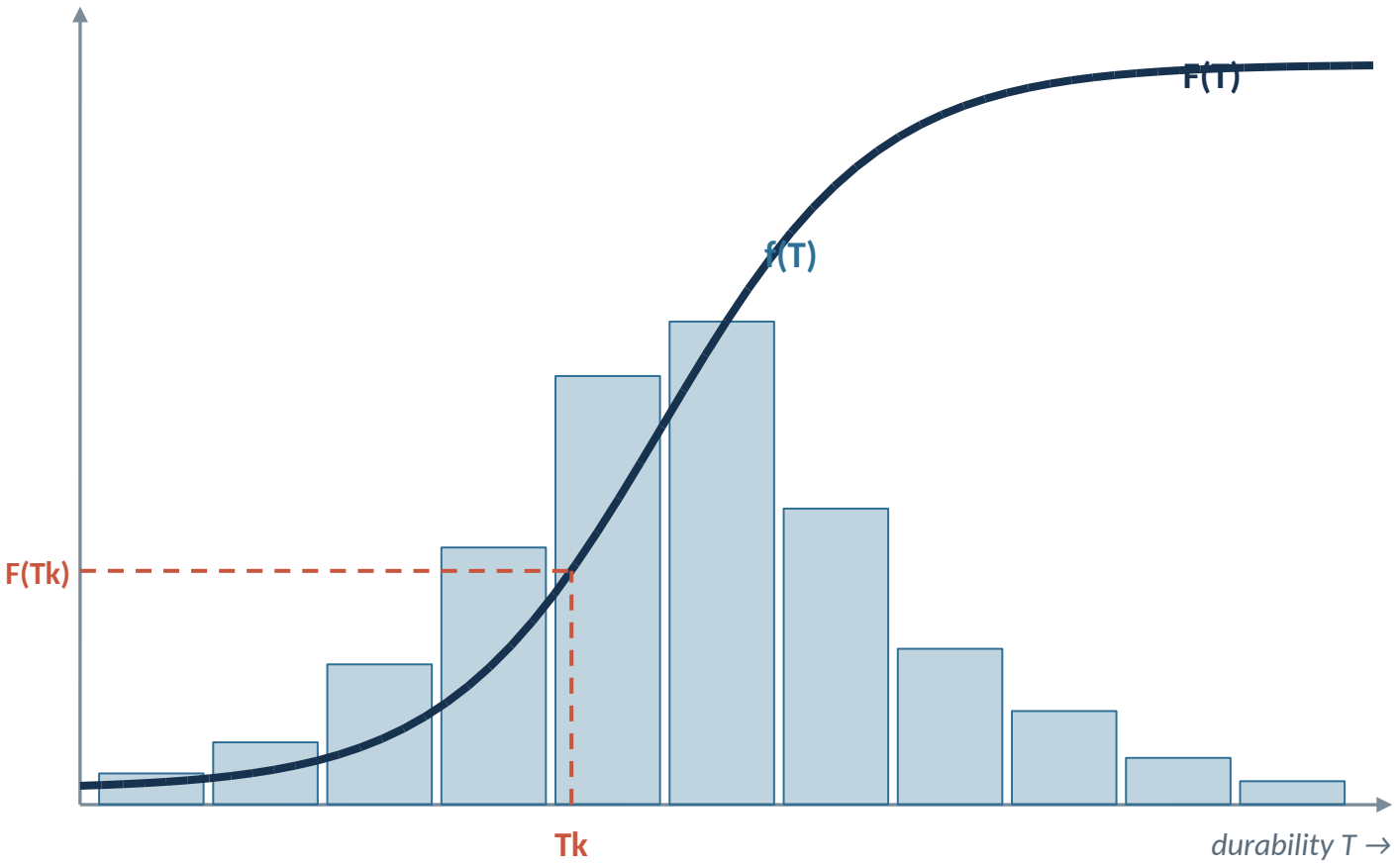
Use durability
measured by the time of use

Maintenance durability
measured by the time of maintenance

Operation durability
measured by calendar (operation) time

Properties affected by **physical** wear define the **technical** durability (use value); properties affected by **economic** wear define the **economic** durability (exchange value).

Distribution of durability f(T) and F(T)



From the durability T of many objects we get the **distribution f(T)** – the probability density (bars).

Adding up the probabilities gives the **cumulative distribution F(T)** – the S-curve.

F(Tk) – the share of objects that fail before time Tk. At some moment, **all** objects fail.

Tribology – the science of durability

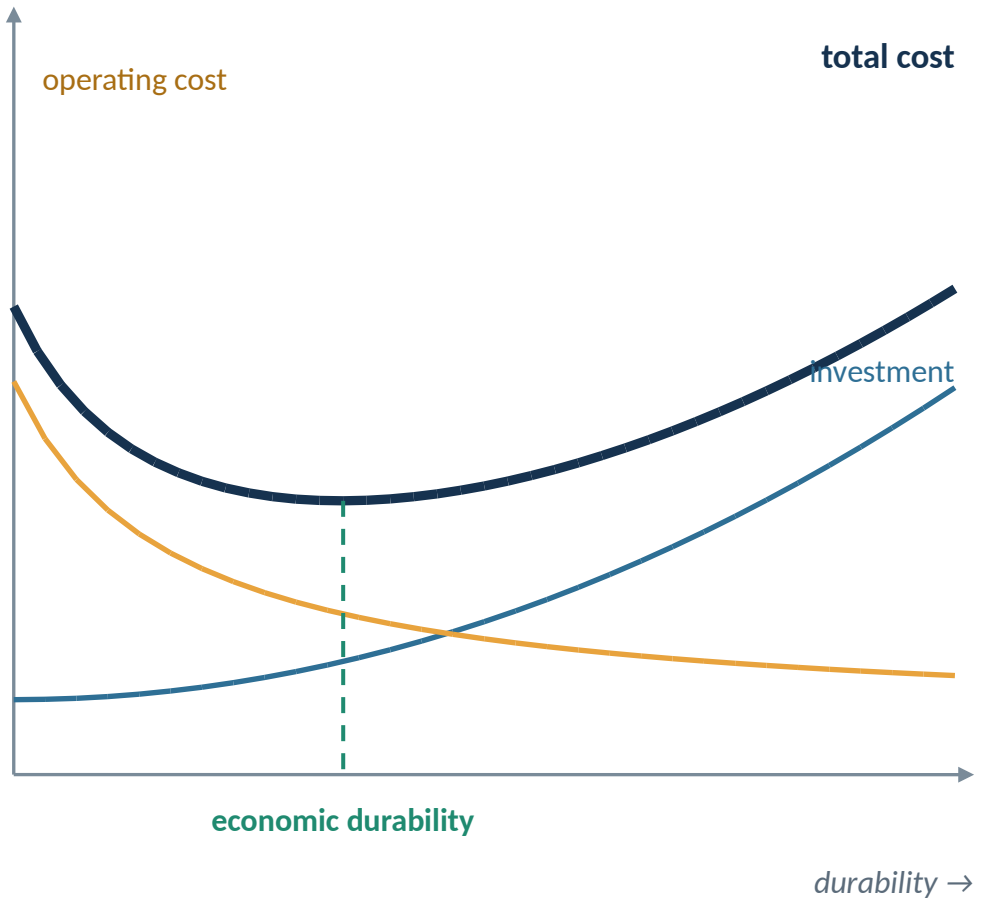
Tribology is the science of processes in the moving contact of solid bodies. It is important for design and operation, because it deals with:

- Setting rational (technical) limits of durability
- Methods of testing machine operation
- Studying operating conditions
- The relation between durability and the period of use
- Methods of durability testing of machines

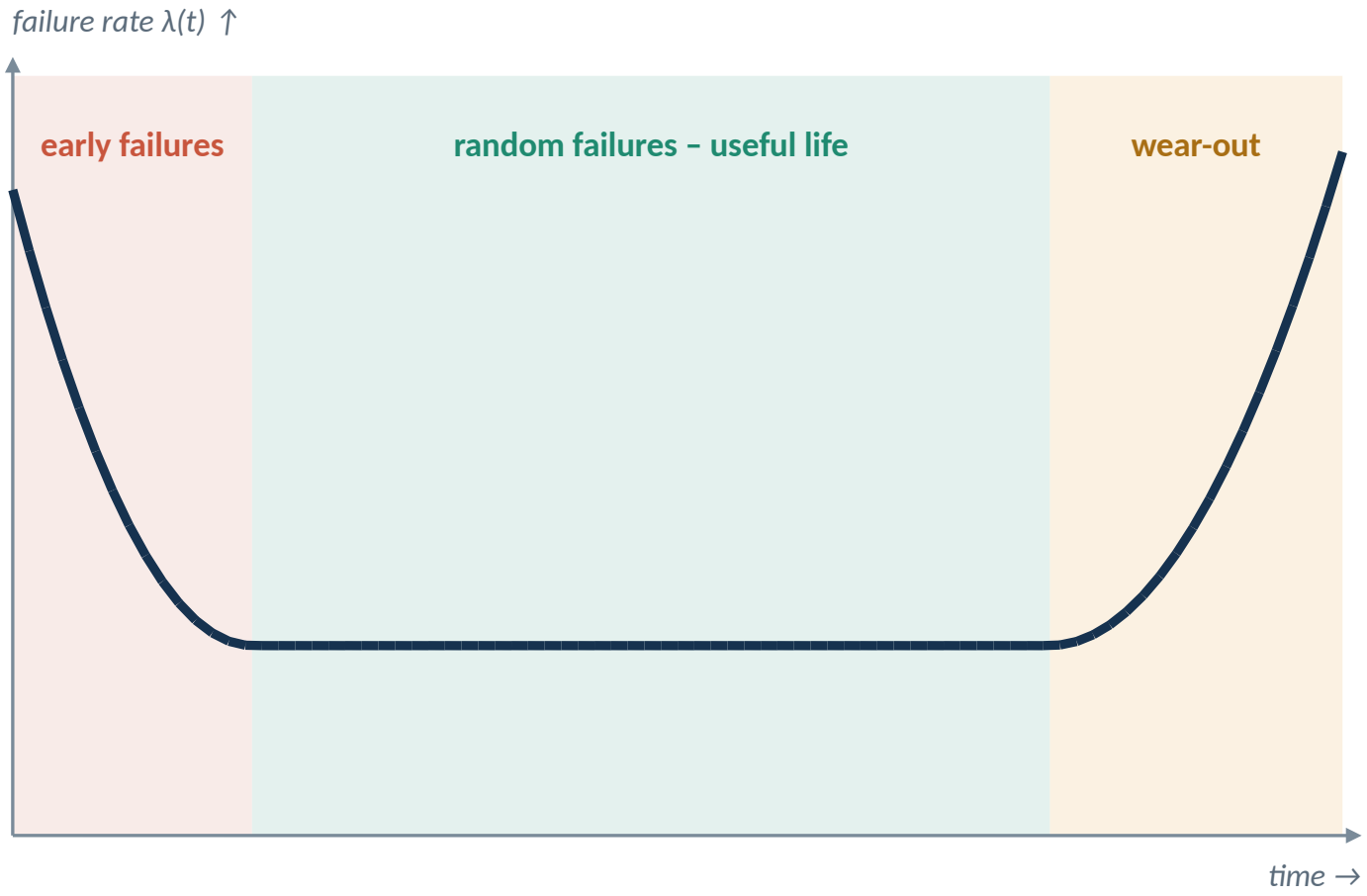
Economic durability – the cost minimum

Higher durability costs money. For some products durability is more important than price – satellites, undersea cable amplifiers, military equipment.

The total price of an object as a function of durability is the sum of a **rising investment cost** and a **falling operating cost** (maintenance and downtime). It often has a **minimum** – the **economic durability** – if the failure frequency still allows acceptable operation.



The bathtub curve of failure rate



Early failures – manufacturing and assembly defects; reduced by running-in, quality control, burn-in tests.

Useful life – random failures, roughly constant rate.

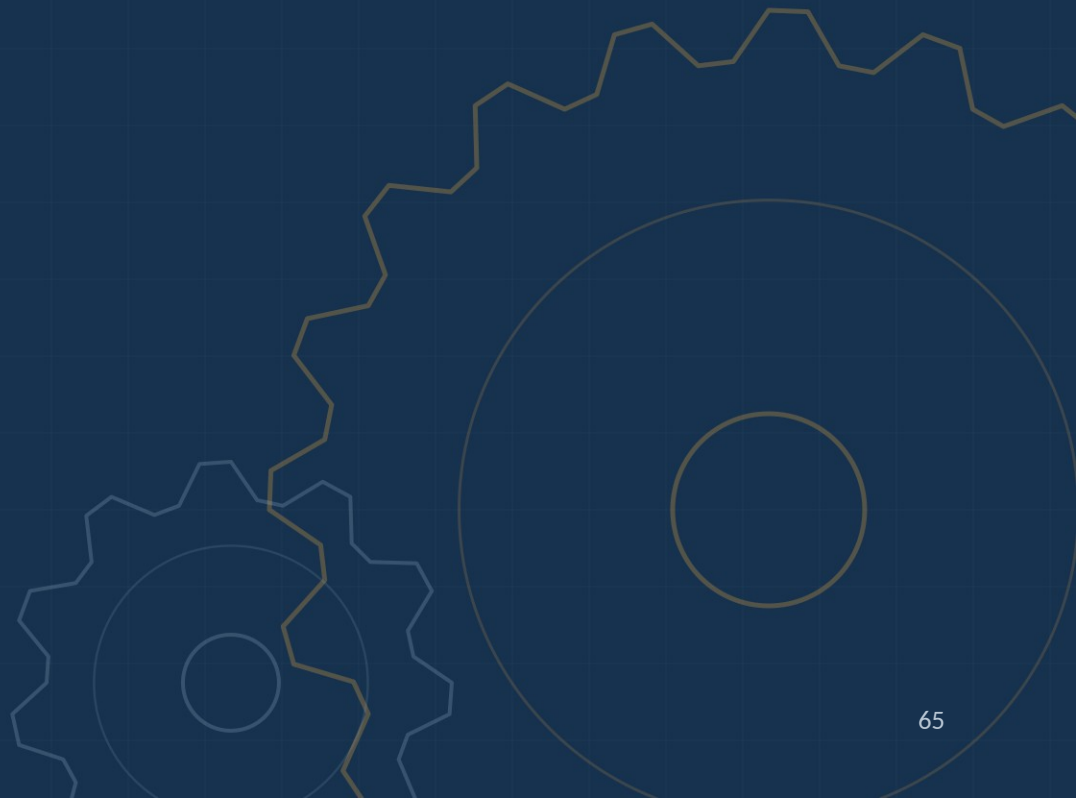
Wear-out – failure rate grows; preventive replacement makes sense here.

Remember Nowlan & Heap: only a few components follow this curve!

07

Technical wear processes

The surface layer, the Lorenz curve and how to reduce wear



Wear starts in the surface layer

Wear of parts and mechanisms always accompanies the work of machines. It results from normal work – mainly long-term interaction of mating parts, high temperature and corrosion. Wear worsens the technical condition and, in the end, makes correct operation impossible.

Destruction processes **start in the surface layer** of the material. So we define **wear** as the processes of change in the surface layer of a solid body, caused by cooperation with other parts or by the environment.

Wear factors are related either to the machine itself (its work) or to the environment – **corrosion**.



KEY TAKEAWAY

Wear factors: **the machine itself** (its work) or **the environment** (corrosion).

Normal and accelerated wear

Normal wear

mainly the result of **friction** – mechanical, physical and chemical in nature; always present in dry and mixed friction. Mechanical wear is the main factor of durability, usually combined with adhesive, diffusive or fatigue wear.

Accelerated wear

caused by **wrong operating conditions, incorrect maintenance, poor repairs, design or manufacturing errors**. Much worse – and avoidable.

How material is removed – two groups of processes

Material is removed either directly, by mechanical interaction of contacting micro-areas, or after **preparing** phenomena that weaken the surface. The effect can be measured by volume, length or mass.

Immediate processes

micro-cutting, tearing off or shearing of asperities.
Counter-measure: increase mechanical properties of the material (hardness, strength).

Prepared processes

friction fatigue, formation of friction joints (adhesion).
Counter-measure: slow down the preparing phenomena – e.g. proper lubrication of the friction pair.

Classification of wear in a friction pair

A friction pair is described by material, design and geometric properties; external influences are motion, friction, environment, load and maintenance quality. Types of wear:

Mechanical wear

caused by mechanical interactions

Physical-mechanical wear

mechanical wear combined with physical processes (e.g. heat)

Chemical-mechanical wear

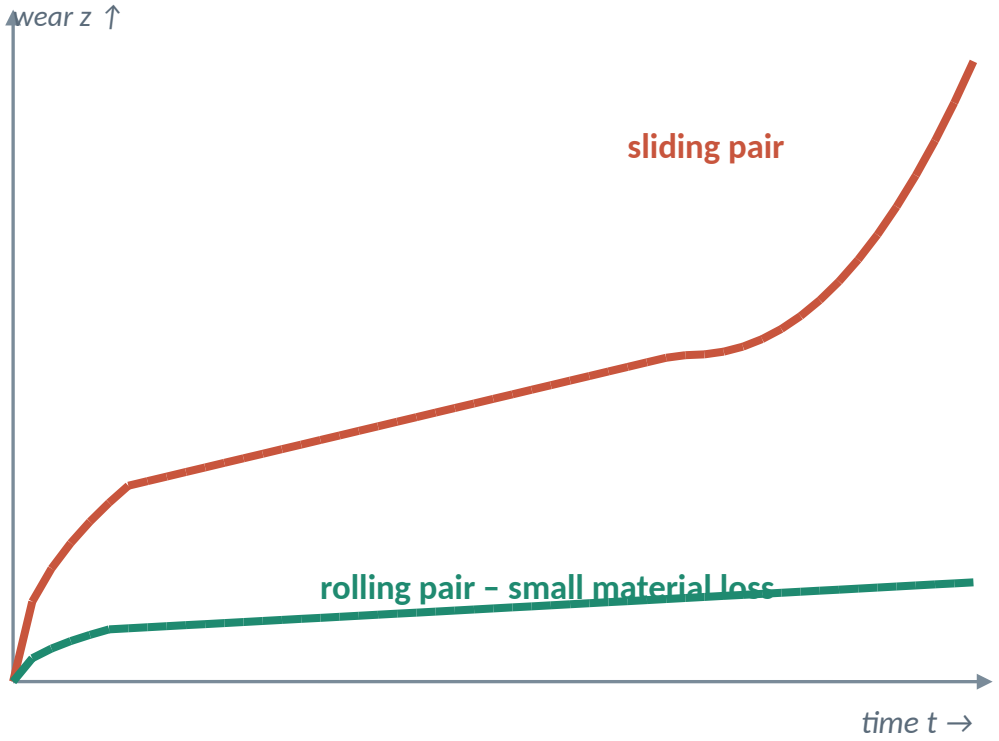
mechanical wear combined with chemical processes (e.g. oxidation)

Complex wear

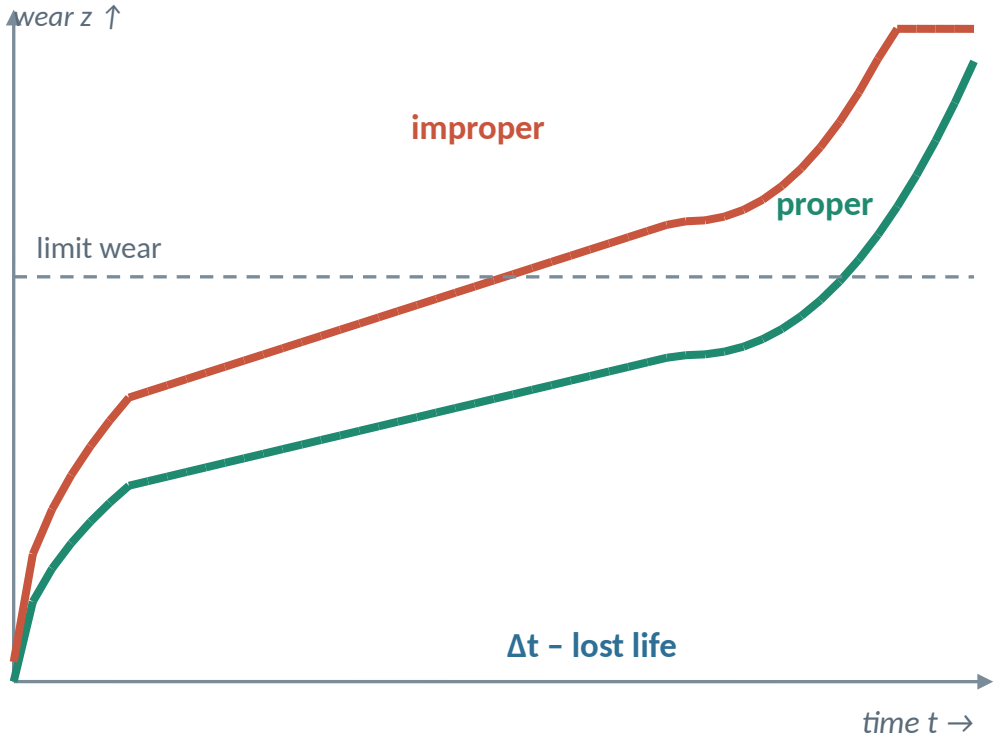
a combination of all types

The Lorenz curve in different conditions

a) Different types of friction



b) Proper and improper operation



Higher load accelerates wear by Δz – and the machine reaches the limit wear Δt earlier.

Actions reducing the wear of machine parts

Actions reducing wear of machine parts

Design

- correct composition
- right materials
- right sealing
- correct choice of friction pairs
- optimal lubrication system
- moderate stresses

Production and repair

- quality of the surface layer
- correct choice of mating pairs
- optimal lubrication system
- control of material fatigue
- clean assembly

Operation – use

- avoid overloads
- correct operating temperature
- avoid sudden speed changes
- keep the right engine speed
- drive slowly on bad surfaces

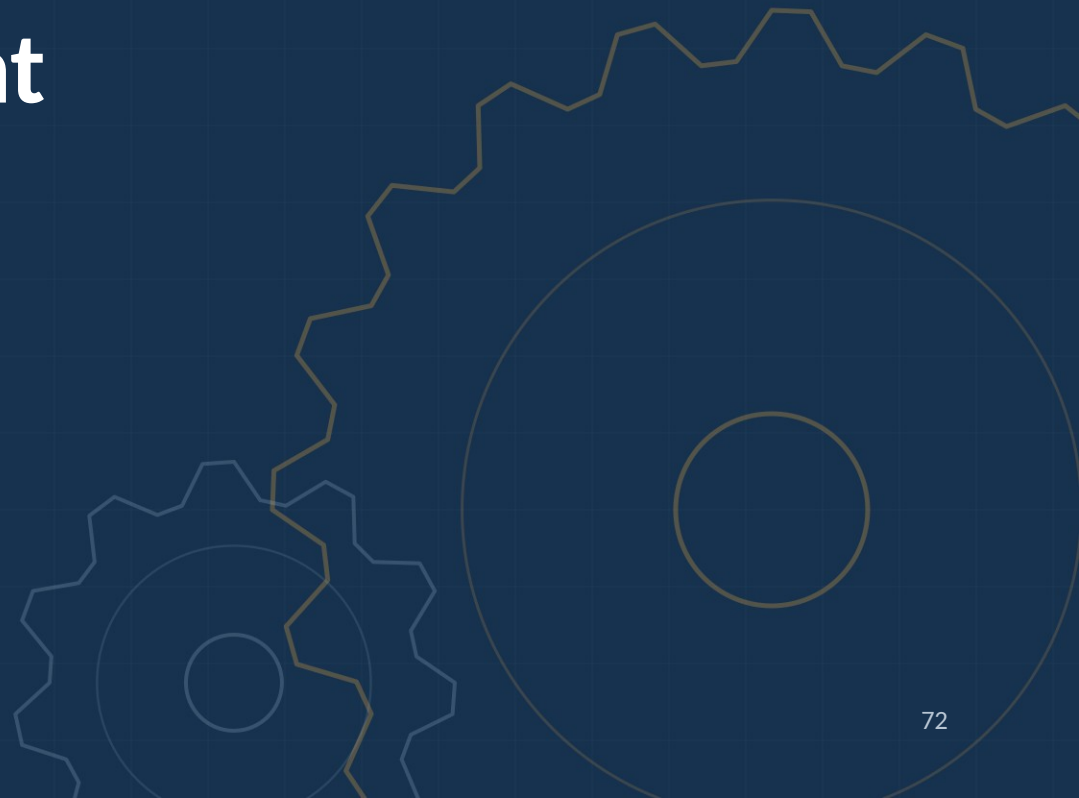
Operation – service

- lubrication
- filtration of oil and air
- adjustment
- corrosion protection

08

Economic wear and replacement

Obsolescence, depreciation, replacement timing and valuation



Three types of wear by cause

Technical causes

caused only by internal physical factors (friction)

Functional causes

internal factors that reduce efficiency (energy consumption)

Economic causes (obsolescence)

external factors – the machine is no longer modern

Economy of operation depends on **energy efficiency** (power used / power taken) and on **profitability** (value of production minus operating costs and depreciation).

Obsolescence – technical progress

The economy of manufacturing is shown mainly by the **own cost** of a machine that performs all required functions. A machine may be withdrawn not only because of technical wear, but also for **economic reasons** – mainly technical and technological progress (and also ecological and ergonomic requirements).

Old machines usually have low productivity, which increases production costs. New, more efficient machines make further use of the old ones **unprofitable**.



KEY TAKEAWAY

Steam locomotives were withdrawn after electric traction came – although they were **not physically worn out**.

Other causes of economic wear

Economic wear of a fixed asset also happens when:

- there is no demand for products made with the device,
- deposits are exhausted – e.g. mine shafts, drilling towers,
- technology changes – e.g. plasterboard replaced wet plastering machines.

The value of machines decreases – but the action is different from technical wear: **not repair, but replacement**. Machines are scrapped or sold and new ones are bought. Justified replacement (**substitution**) gives the user better operating parameters.



KEY TAKEAWAY

Economic wear → **replace**, not repair.

Accumulated depreciation and depreciation charges

Economic wear forces companies to replace machines to keep production capacity and market position – this means **investment in renewal**. In accounting, the process is reflected by:

Accumulated depreciation

yearly reduction of the asset value by a calculated amount – giving its current (net book) value.

Depreciation charge

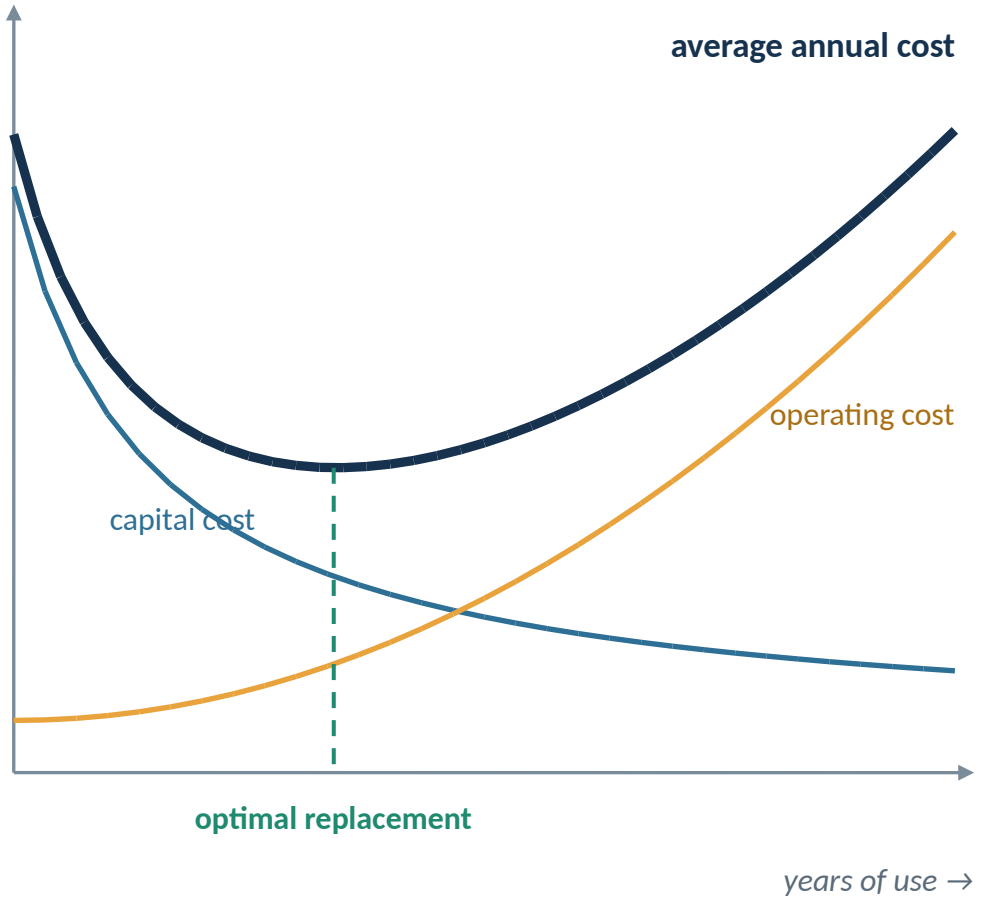
a regular, usually monthly, amount of wear included in the costs of business activity.

The optimal time to replace a machine

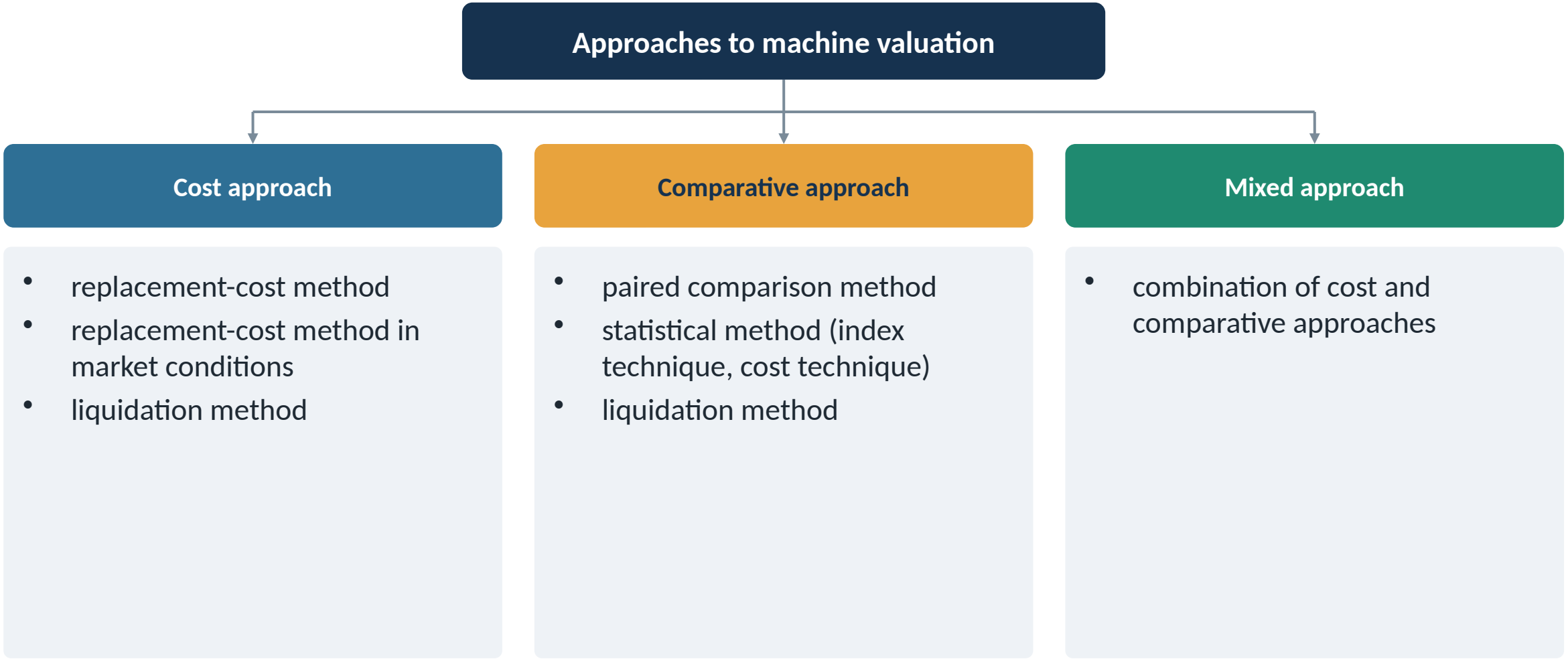
With time, **operating costs rise** (inspections, maintenance, repairs, overhauls), while the **value of the asset falls**. We look for the optimal period of use – the minimum of the average annual cost.

We need:

- the value of a new device (or how its price changes in time),
- the function of net value loss in time, or a depreciation model.



Approaches to machine valuation



The replacement-cost method

replacement-cost method

$$V_r = V_i \cdot (1 - W_p) \cdot K$$

in market conditions (market factor E)

$$V_r = V_i \cdot (1 - W_p) \cdot K \cdot E$$

modernity factor (economic wear)

$$K = 1 - \alpha \cdot (t_e - 1)$$

where:

Vr – replacement (current) value,

Vi – initial value of the machine,

Wp – wear of the operational potential (0–1),

K – modernity factor (obsolescence and usefulness),

E – market factor,

α – expert factor, 0.01–0.03 (except electronics),

te – years of operation.

EXAMPLE

Example: valuing a used machine tool

DATA

- initial (replacement) value **Vi = 500 000 €**
- wear of potential **Wp = 0.40**
- age **te = 8 years**
- expert factor **α = 0.02**
- market factor **E = 0.95**

1. Modernity factor

$$K = 1 - 0.02 \cdot (8 - 1) = 0.86$$

2. Replacement-cost method

$$V_r = 500\,000 \cdot 0.60 \cdot 0.86 = 258\,000\ €$$

3. In market conditions

$$V_r = 258\,000 \cdot 0.95 \approx 245\,100\ €$$

QUIZ

Quiz 2 – availability, durability and wear

1 MTBF = 190 h, MTTR = 10 h. Steady-state availability equals...

A) 0.90 | B) 0.95 | C) 0.99 | D) 19

2 Operational availability Ao also includes...

A) only repair time | B) waiting for parts and people | C) only design time | D) nothing more than Ai

3 Reliability, as opposed to durability, describes...

A) one specific object | B) a population of objects | C) only the price | D) the colour of a machine

4 In the bathtub curve, the middle period has...

A) a falling failure rate | B) a roughly constant failure rate | C) a rising failure rate | D) no failures

5 Economic wear is best answered by...

A) regeneration | B) lubrication | C) replacement | D) running-in

ANSWERS

Quiz 2 – answers

1 MTBF = 190 h, MTTR = 10 h. Steady-state availability equals...

A) 0.90 | **B) 0.95** | C) 0.99 | D) 19

2 Operational availability Ao also includes...

A) only repair time | **B) waiting for parts and people** | C) only design time | D) nothing more than Ai

3 Reliability, as opposed to durability, describes...

A) one specific object | **B) a population of objects** | C) only the price | D) the colour of a machine

4 In the bathtub curve, the middle period has...

A) a falling failure rate | **B) a roughly constant failure rate** | C) a rising failure rate | D) no failures

5 Economic wear is best answered by...

A) regeneration | B) lubrication | **C) replacement** | D) running-in

SUMMARY

Key takeaways from today

RCM maintains functions; only ~11% of failures are age-related (Nowlan & Heap).

TPM involves everyone; **OEE = A × P × Q** shows where losses are.

A **CMMS** is only as good as its data – use structured failure codes.

A = MTBF / (MTBF + MTTR); operational availability includes waiting time.

Durability = one object; reliability = population. Economic durability = cost minimum.

Physical wear → repair; economic wear → **replace** at the optimal time.

REVIEW

Review questions



1. Describe the three periods of maintenance development. What are RCM and TPM?
2. What did Nowlan and Heap discover about failure patterns? What does it mean for fixed-interval replacement?
3. Name the eight pillars of TPM and the six big losses. Calculate OEE for given data.
4. Define availability. Explain the difference between inherent and operational availability.
5. Compare durability and reliability. What is economic durability?
6. Explain the replacement-cost method of machine valuation and the modernity factor K.

Thank you for your attention

Next: after the break – Lecture 4 · Tribology and Lubrication; Fundamentals of Technical Diagnostics

dr inż. Radosław Gościniak

