BASICS OF MACHINE OPERATION

Block 4 · Lecture 7 · 27 Jan 2027

Life Data, Maintenance Logistics and Industry 4.0; Course Review



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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: L7. Life Data, Maintenance Logistics and Industry 4.0; Course Review

Last week in six points

Series: **Rs = ∏Ri** – weaker than the weakest element.

Parallel: **Rs = 1 − ∏(1 − Ri)** – beware common-cause failures.

FTA: AND = parallel, OR = series; find **single points of failure**.

FMEA: **S, O, D** – severity first.

RCA: physical → human → **latent** causes; Ishikawa, Pareto, 5 Whys.

Improve early; derating; maintainability; **FRACAS** loop.

TODAY

Plan for today – our last lecture

PART A

Data, logistics and economics

1. Operational testing and life data
2. Maintenance logistics and spare parts
3. LCC and replacement decisions
4. Industry 4.0 and predictive maintenance

PART B

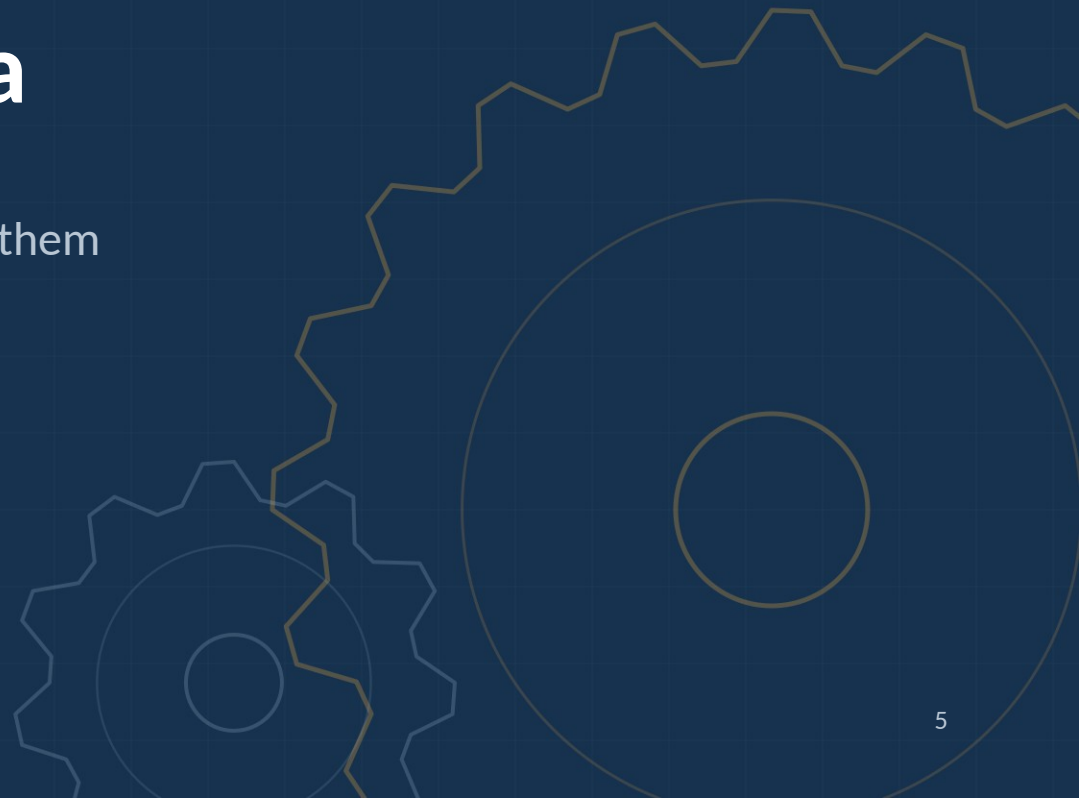
Course review

5. The course in one picture
6. Key concepts and formulas
7. Final case study (group work)
8. Final quiz and exam tips

01

Operational testing and life data

Where reliability numbers come from – and how much we can trust them

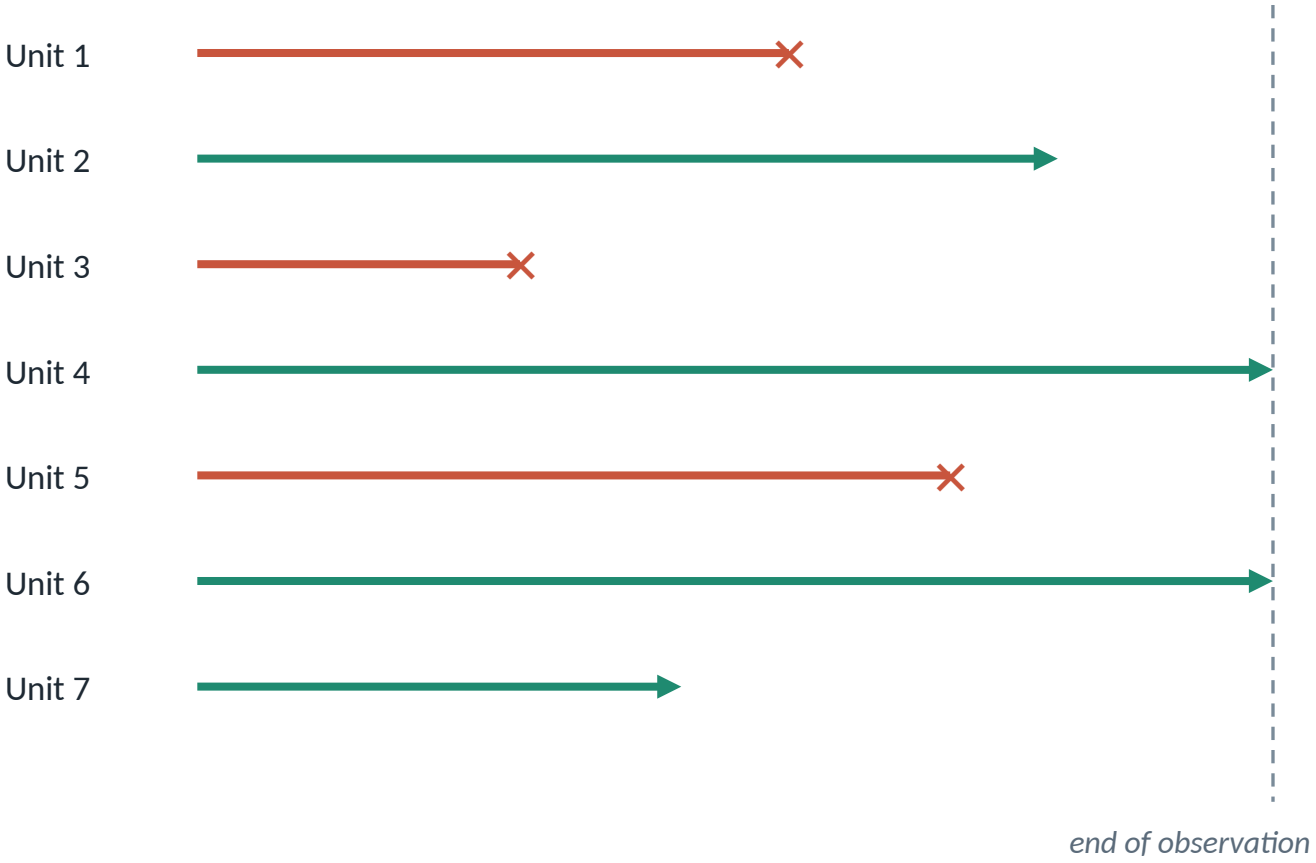


Types of reliability tests

Test	What it is	Purpose
Field (operational) data	observing machines in real use; CMMS records	real reliability in real conditions
Laboratory life test	units run under controlled, normal conditions until failure	estimate life distribution (e.g. Weibull)
Accelerated life test (ALT)	higher stress (load, temperature, speed) → failures come faster	shorter tests; extrapolate to normal use
HALT	highly accelerated – step stress until the design breaks	find weak points in development
Burn-in / run-in	short operation before delivery	remove early failures ($\beta < 1$)
Demonstration test	test with a pass/fail rule	prove a required MTBF to a customer

Polish tradition calls the whole field "operational research" (badania eksploatacyjne) – collecting and analysing data from use.

Complete and censored data



✕ failure → still working (censored / suspended)

Complete data: every unit failed – rare in practice.

Censored (suspended) data: some units are still working at the end, were removed for other reasons or were replaced preventively.

Never ignore the survivors! Using only failed units makes the machine look **much worse** than it is.

Weibull software and the formula on the next slide handle censored data.

EXAMPLE

MTBF from field data – and its uncertainty

DATA: 10 pumps observed for one year · total operating time T = 80 000 h · r = 4 failures

Failure rate λ	$r / T = 4 / 80\,000 = 5 \cdot 10^{-5}\ 1/h$
MTBF (point estimate)	$1 / \lambda = 20\,000\ h$
90% lower bound	$2T / \chi^2(0.90; 2r+2) = 160\,000 / 15.99$
MTBF ≥	≈ 10 000 h (with 90% confidence)

Use the **total** operating time of **all** units – failed and still working.

With only 4 failures the uncertainty is **large**: the true MTBF could be about half of the estimate.

More data → narrower bounds. Small samples need **careful** decisions.

Accelerated life testing

Machines are designed to last years – we cannot wait years for test results. **Accelerated tests** increase the stress so that failures come faster, then a **model** converts the result back to normal conditions.

Mechanical load – inverse power law

life ∝ (1 / load)^p – e.g. ball bearings p = 3: a test at **2× load** runs about **8× faster**.

Temperature – Arrhenius model

chemical ageing (oil, insulation, electronics) speeds up with temperature; a common rule of thumb: about **2× faster per +10 °C**.

Cycles and speed

more cycles per hour (e.g. a valve opened 10× more often) – if the failure depends on the number of cycles, not on time.

Danger: too high stress can create failure modes that never happen in real use. The mechanism must stay the same.

EXAMPLE

Weibull analysis of field failures

Six gearbox seals failed at these operating hours (all units failed):

i	Time t [h]	Median rank F = (i − 0.3)/(n + 0.4)
1	1 200	0.109
2	1 900	0.266
3	2 400	0.422
4	2 900	0.578
5	3 500	0.734
6	4 300	0.891

Plot on Weibull scales and fit a line (or use a spreadsheet):

β ≈ 2.3, η ≈ 3 100 h

β > 1 → **wear-out**.

B10 ≈ 1 170 h – 10% fail before ~1 200 h.

Decision: replace seals preventively at about **1 000 h**, or monitor leakage.

EXERCISE

ACTIVITY

Your turn: MTBF of electric motors from field data

DATA

- 20 identical motors observed
- total operating time of all motors: **T = 150 000 h**
- number of failures: **r = 3**
- hint: $\chi^2(0.90; 8) \approx 13.36$



Calculate (5 minutes):

1. failure rate λ
2. MTBF (point estimate)
3. MTBF 90% lower bound
4. Is the manufacturer's claim "MTBF = 60 000 h" credible?

EXERCISE

ANSWERS

Motor MTBF – solution

λ	$3 / 150\,000 = 2 \cdot 10^{-5}\ 1/\mathrm{h}$
MTBF	$50\,000\ \mathrm{h}$
90% lower bound	$300\,000 / 13.36 \approx 22\,500\ \mathrm{h}$

Our estimate (50 000 h) is close to the claim (60 000 h).

With only 3 failures, **60 000 h is possible** – the data do not contradict it.

But we can only be 90% sure that MTBF is above **~22 500 h** – collect more data before big decisions.

02

Maintenance logistics and spare parts

The right part, the right person, the right tool – at the right time



Elements of maintenance logistics

Remember the pump from Lecture 3: waiting for parts and people was longer than the repair itself. **Maintenance logistics** – the "maintenance support" in IEC 60050-192 – decides about MTTR and operational availability.

People
number, skills, shifts, contractors, on-call service

Spare parts
what to stock, how many, where – and who supplies the rest

Tools and equipment
special tools, lifting gear, diagnostic instruments

Documentation
manuals, drawings, procedures, parts lists – digital and up to date

Information
CMMS, failure history, stock levels, supplier lead times

Facilities and transport
workshops, storage conditions, transport of heavy parts

Classifying spare parts

ABC – by value

A: few parts, high value (spindles, gearboxes); **B**: medium; **C**: many cheap parts (bolts, filters). Control A parts very carefully.

XYZ – by demand

X: regular demand (filters, belts); **Y**: variable; **Z**: rare, unpredictable (a main shaft, a transformer).

VED – by criticality

Vital: without it, a critical machine stops; **Essential**; **Desirable**. Vital parts are stocked even if rarely used – “insurance spares”.

Combining the classes gives the policy: e.g. **A–Z–Vital** (expensive, rare, critical) → hold one insurance spare or a pool agreement with other plants or the manufacturer.

EXAMPLE

How many spare motors? – the Poisson model

DATA: 50 motors, λ = 1 · 10^{-5} 1/h, delivery time of a new motor T = 2 000 h (≈ 12 weeks)

$$\mu = n \cdot \lambda \cdot T = 50 \cdot 10^{-5} \cdot 2\,000 = 1.0$$

Spares in stock s	P(demand ≤ s)
0	0.368
1	0.736
2	0.920
3	0.981

μ – expected number of failures **during the delivery time**.

The number of failures follows a **Poisson distribution**.

Target **95%** service level → **3 spare motors** (98%).

With **2 spares** – an 8% risk that a motor fails and none is in stock.

Shorter delivery time (e.g. a framework contract) → fewer spares needed.

EXERCISE

ACTIVITY

Your turn: bearings for a conveyor fleet

DATA

- 200 identical bearings in conveyors
- failure rate $\lambda = 5 \cdot 10^{-5}$ 1/h
- delivery time T = 500 h
- Poisson cumulative for $\mu = 5$: $P(\leq 5) = 0.616$, $P(\leq 6) = 0.762$, $P(\leq 7) = 0.867$, $P(\leq 8) = 0.932$, $P(\leq 9) = 0.968$



Calculate (5 minutes):

1. expected demand μ during delivery time
2. stock for a 90% service level
3. stock for a 95% service level
4. Would you choose 90% or 95% for these bearings? Why?

EXERCISE

ANSWERS

Bearings – solution

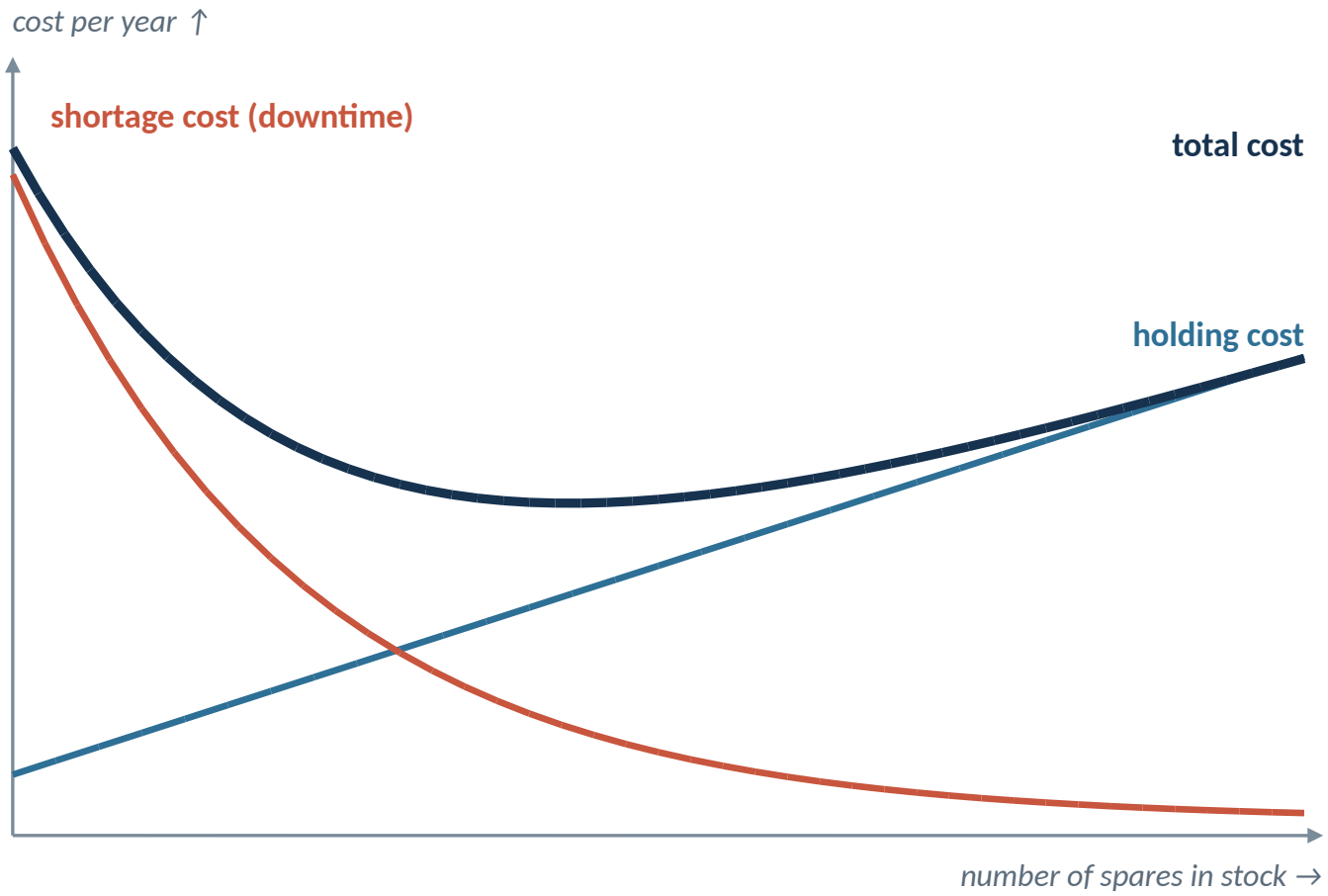
μ	$200 \cdot 5 \cdot 10^{-5} \cdot 500 = 5$
90% service level	$P(\leq 8) = 0.932 \rightarrow 8$ bearings
95% service level	$P(\leq 9) = 0.968 \rightarrow 9$ bearings

One extra bearing (cheap, C-class) raises the service level from 93% to 97%.

For **cheap parts with expensive downtime**, choose the higher service level.

For **expensive parts**, consider pooling, faster delivery contracts, or repairable spares.

The stock level trade-off



Holding cost grows with stock: capital, storage, ageing of parts (rubber, grease, electronics).

Shortage cost falls with stock: downtime, express delivery, emergency purchases.

The optimum is the **minimum of the total** – different for every part.

Do not forget: spare parts also need **maintenance** (rotating motors in storage, preservation).

In-house, contractor or manufacturer service?

In-house team

+ knows the machines, available immediately, builds know-how. **–** fixed costs, hard to keep rare skills.

Contractors

+ flexible, specialists (vibration, NDT, shutdowns). **–** less plant knowledge, availability, need for supervision.

Manufacturer (OEM) service

+ best product knowledge, original parts, updates. **–** expensive, dependence, response time.

Typical mix: in-house for daily work and critical know-how; contractors for peaks and special methods; OEM for complex machines and warranty. Measure the results with the same KPIs.

03

Life cycle cost and replacement decisions

Money over time – choosing and replacing machines rationally



LCC with the time value of money

In Lecture 1 we added costs over 10 years without discounting. In real decisions, **future money is worth less** than money today – we use the **present value**:

$$PV = \frac{C_t}{(1+i)^t}$$

Ct – cost in year t, **i** – discount (interest) rate.

For equal yearly costs over n years we multiply by the **annuity factor**: [1 − (1 + i)^−n] / i.

LCC = acquisition + PV(operation + maintenance + downtime) + PV(disposal − resale)

A higher price can be justified by **lower energy**, **higher reliability** (less downtime) and **easier maintenance**.

Methodology: **IEC 60300-3-3**; in public procurement, LCC can be an award criterion.

EXAMPLE

Discounted LCC: two machine tools

	Machine A	Machine B
Purchase price	50 000 €	70 000 €
Yearly operating + maintenance + downtime	20 000 €	14 000 €
Period / discount rate	5 years, i = 8%	5 years, i = 8%

Annuity factor $[1 - 1.08^{-5}] / 0.08 \approx 3.993$

LCC A $50\,000 + 20\,000 \cdot 3.993 \approx 129\,900$ €

LCC B $70\,000 + 14\,000 \cdot 3.993 \approx 125\,900$ €

Machine B is **≈ 4 000 € cheaper** over 5 years, although it is 20 000 € more expensive to buy.

Without discounting, the difference would look bigger (10 000 €) – discounting gives a fairer picture.

Sensitivity: check the result for other discount rates and operating hours.

EXERCISE

ACTIVITY

When should we replace the machine?

End of year N	1	2	3	4	5	6
Operating + maintenance cost in year N [k€]	10	12	15	19	24	30
Resale value at the end of year N [k€]	70	55	45	37	30	25



A new machine costs **100 k€**. Work in pairs – **7 minutes**. For each N calculate the **average annual cost**:

AAC(N) = [price − resale(N) + sum of operating costs for years 1…N] / N

Which N gives the **minimum**? (no discounting)

ANSWERS

Replacement – solution

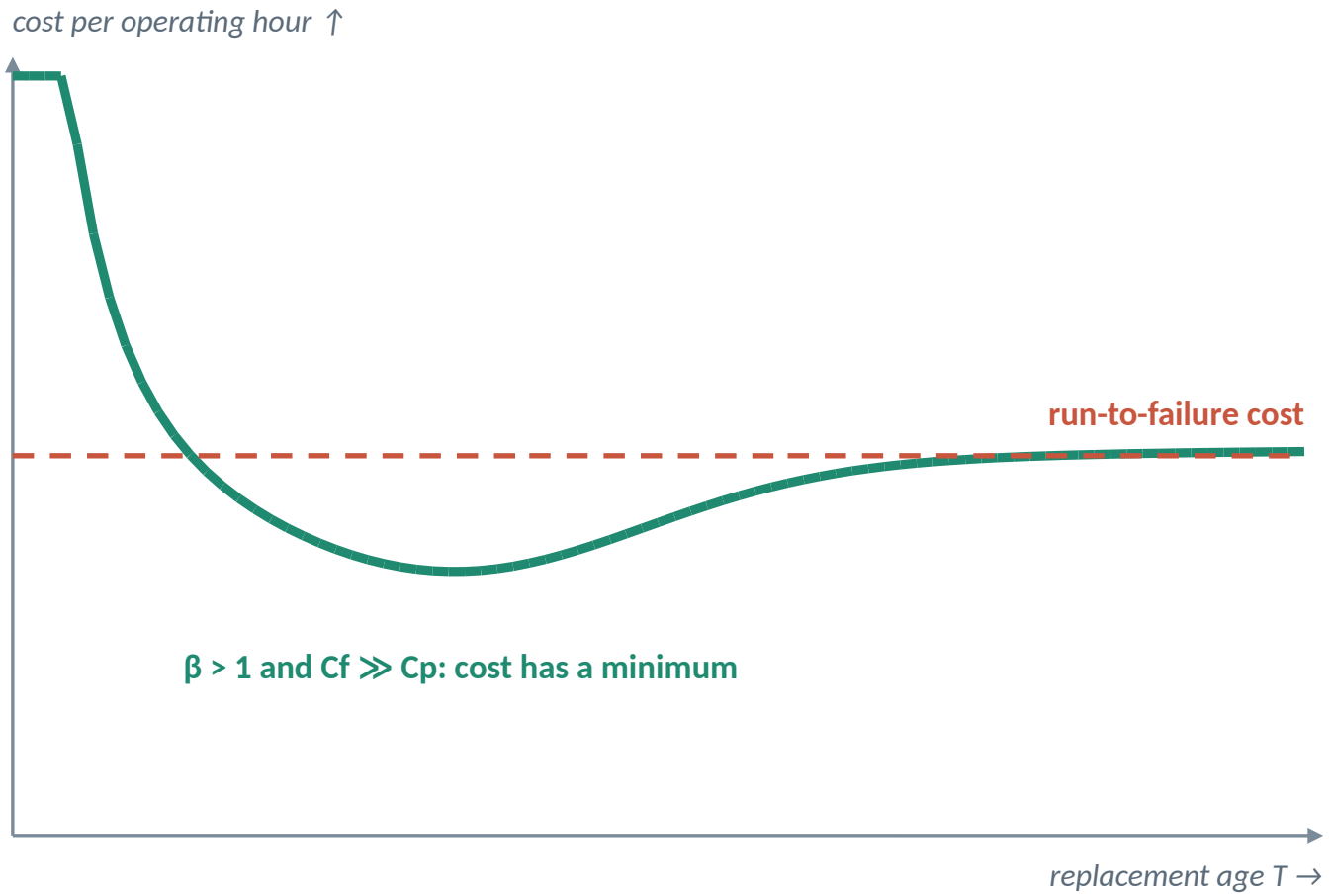
N	Capital loss 100 – resale	Σ operating costs	Total	AAC = Total / N
1	30	10	40	40.0
2	45	22	67	33.5
3	55	37	92	30.7
4	63	56	119	29.8 ← minimum
5	70	80	150	30.0
6	75	110	185	30.8

The average annual cost is lowest after **4 years** – the **economic life** of the machine.

Before: capital cost per year is high. After: rising operating costs dominate.

The curve is **flat** near the minimum – years 3–5 are almost equal, so other factors (technology, capacity) can decide.

Optimal age replacement – when it pays off



Replace a part at age **T** (planned, cost **Cp**) or at failure (unplanned, cost **Cf**).

Planned replacement pays off only if: **β > 1** (wear-out) **and Cf is much larger than Cp** (downtime, damage).

With β ≤ 1 the best T is "never" – run-to-failure or condition monitoring.

This connects Weibull (L5), RCM (L3) and LCC.

04

Industry 4.0 and predictive maintenance

Data, models and people – the future of machine operation



Industry 4.0 technologies in maintenance

IIoT and sensors

cheap wireless sensors – continuous monitoring of many machines

Cloud and edge computing

storage and processing of large data sets; fast local alarms

Artificial intelligence

anomaly detection, fault classification, RUL prediction, assistants

Digital twin

virtual model updated with real data – simulate before deciding

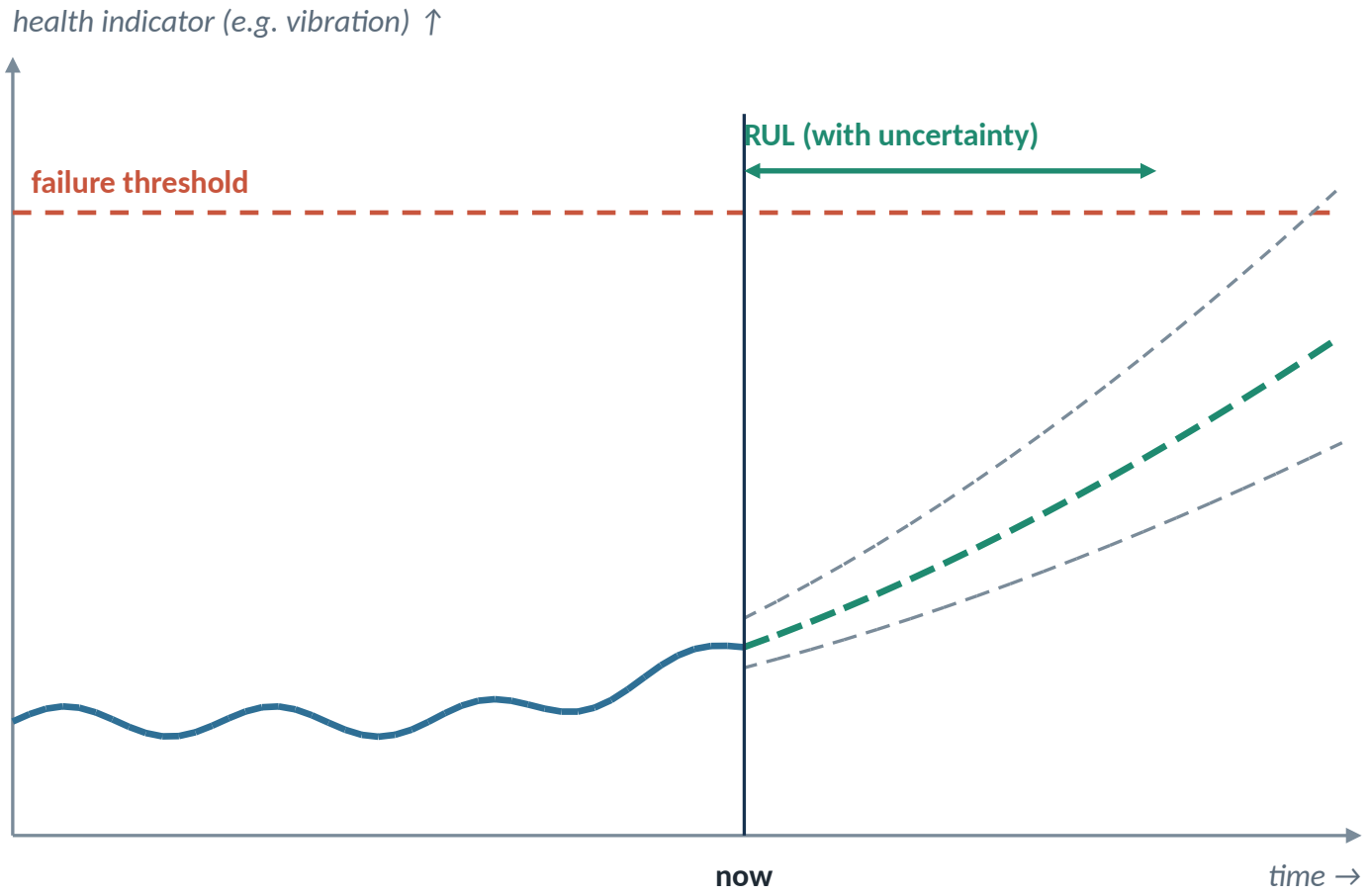
Augmented reality

instructions on smart glasses or tablets; remote expert support

Mobile CMMS

work orders, photos, checklists and history in the pocket

From data to remaining useful life (RUL)



1. Collect data (sensors, operating conditions).
2. Extract **features** (RMS, envelope, temperature).
3. Build a **health indicator** and detect the start of degradation.
4. Extrapolate to the threshold → **RUL** – always with an **uncertainty band**.
5. Decide: plan the action before the predicted failure.

EXAMPLE

A simple RUL estimate from a trend

DATA: fan bearing – vibration velocity grows linearly by about 0.15 mm/s per week; today 3.4 mm/s; alarm limit 4.5 mm/s

Margin to the limit	$4.5 - 3.4 = 1.1\ \text{mm/s}$
RUL (linear)	$1.1 / 0.15 \approx 7$ weeks
Planning	repair in the shutdown in week 5

Linear extrapolation is the **simplest** model – real degradation often **accelerates** (remember phase III of wear).

So plan the action **before** the predicted date and **measure more often**.

Better models: exponential trends, Weibull-based or machine-learning models – but the logic stays the same.

AI in maintenance – possibilities and limits

Anomaly detection

learns the normal behaviour of a machine and signals deviations – no failure examples needed.

Fault classification and RUL

recognises fault types and predicts remaining life – needs labelled failure data.

Text and knowledge

language models search manuals and work-order history, suggest causes and procedures.

Limits

few real failures (imbalanced data), poor data quality, changing conditions, need for explainability – and responsibility stays with people.

AI is a **tool**, not a replacement for engineering knowledge – the physics of wear, diagnostics and reliability from this course remain the foundation.

Connected machines: safety and cybersecurity

Machinery Regulation 2023/1230

from 20 Jan 2027: protection against corruption of control systems; machines with self-evolving behaviour (AI).

NIS2 Directive (EU 2022/2555)

cybersecurity obligations for many companies in essential and important sectors, including manufacturing.

Good practice

separate networks (OT/IT), access control, updates, backups, IEC 62443 for industrial systems.

A remote-access connection for monitoring is also a possible entry point for an attack – maintenance and IT must work together.

Sustainability and the human-centred factory

Energy efficiency

well-maintained machines use less energy – leaks, friction, misalignment, fouling.

Circular economy

longer life, regeneration, remanufacturing, recycling – maintenance keeps value in use.

Human-centred

technology supports people: ergonomics, safety, assistance systems, new skills.

Resilience

reliable machines and good spare-parts strategies make supply chains robust to disruptions.

How to start predictive maintenance – a roadmap

The most common mistake: buying sensors before the basics (data, procedures, people) are in place.

1. Basics first

CMMS with good data, preventive plan, lubrication, alignment

2. Criticality

choose 3–5 critical machines with known failure modes

3. Pilot

sensors + simple thresholds and trends; train people

4. Show value

document avoided failures and savings

5. Scale up

more machines, integration with CMMS, analytics/AI

QUIZ

Quiz – data, logistics and economics

1 When estimating MTBF from field data, the survivors (still working units)...

A) are ignored | B) count in total time | C) are counted as failures | D) double the result

2 Expected failures during delivery time: 50 motors, $\lambda = 10^{-5}$ 1/h, T = 2 000 h...

A) 0.1 | B) 1.0 | C) 10 | D) 100

3 A spare part that is expensive, rarely needed and critical is...

A) C–X–Desirable | B) A–Z–Vital | C) B–Y–Essential | D) never stocked

4 The economic life of a machine is the age with minimum...

A) resale value | B) operating cost | C) average annual cost | D) purchase price

5 Age-based preventive replacement pays off when...

A) $\beta < 1$ | B) $\beta = 1$ | C) $\beta > 1$ and $C_f \gg C_p$ | D) always

ANSWERS

Quiz – answers

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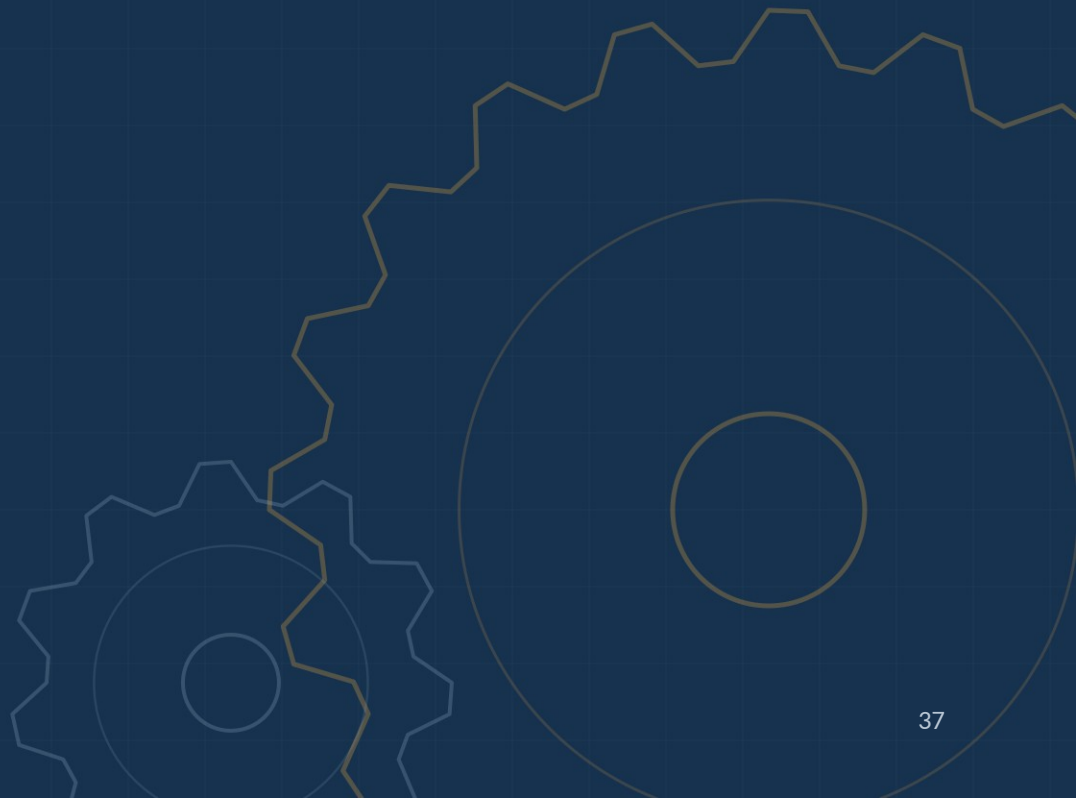
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05

Course review

Seven lectures in one picture – and a final case study



The course in one picture

L1

Machine operation, life cycle, LCC, safety, wear

L2

Systems approach; maintenance organisation and strategies

L3

RCM, TPM, OEE, CMMS; availability, durability, wear

L4

Tribology and lubrication; fundamentals of diagnostics

L5

Condition monitoring; reliability R(t), exponential, Weibull

L6

System reliability, FTA, FMEA, RCA, improvement

L7

Life data, spare parts, LCC, replacement, Industry 4.0

One thread through all lectures: keep machines able to perform their function – safely, reliably and economically.

Key formulas – one page

Topic	Formula	Lecture
Availability	A = MTBF / (MTBF + MTTR)	L1, L3
OEE	OEE = Availability × Performance × Quality	L3
Exponential distribution	R(t) = exp(−λt), MTTF = 1/λ	L5
Weibull distribution	R(t) = exp[−(t/η)^β]	L5
Bearing life	L10 = (C/P)^p [10^6 rev]	L5
Series / parallel	Rs = ∏Ri / Rs = 1 − ∏(1 − Ri)	L6
FMEA	RPN = S × O × D	L6
Wear (Archard)	V = K·F·s / H	L4
Present value / LCC	PV = Ct / (1 + i)^t	L7

Key concepts to remember

Maintenance (EN 13306) – technical, administrative and managerial actions over the life cycle.

Strategies: corrective, predetermined, condition-based, predictive; choose by consequences.

P-F curve – inspection interval shorter than the P-F interval.

RCM – maintain functions; only ~11% failures age-related.

Tribological system; Stribeck curve; four wear mechanisms.

Diagnostics: symptoms, m ≥ n, thresholds and trends.

Weibull β: early / random / wear-out → strategy.

Root causes: fix the system, not only the part.

ACTIVITY

Final case: a bottling line

Groups of 3–4, **15 minutes**. A bottling line: **filler → capper → labeller** in series.

1	**Availability**	Line MTBF = 120 h, MTTR = 3 h. Calculate A.
2	**OEE**	With A from Q1, performance = 0.90, quality = 0.98. Calculate OEE.
3	**System reliability**	For 100 h: filler R = 0.90, capper 0.95, labeller 0.97. Calculate Rs. Better: a 2nd capper in parallel, or improving the filler to 0.95?
4	**FMEA**	“Glass breakage in filler”: S 8, O 4, D 3. “Label misaligned”: S 3, O 6, D 2. Which first?
5	**Strategy**	Filler valve seals: Weibull β = 3.2, failure stops the line. Which strategy?

ANSWERS

Final case – solution

#	Calculation	Result
1	A = 120 / (120 + 3)	≈ 0.976
2	OEE = 0.976 × 0.90 × 0.98	≈ 0.86 (86%)
3	Rs = 0.90 × 0.95 × 0.97; 2nd capper: 0.90 × 0.9975 × 0.97; better filler: 0.95 × 0.95 × 0.97	0.829; 0.871; 0.875 → improve the filler (slightly better)
4	RPN glass = 96 (S = 8, safety); label = 36	glass breakage first
5	β = 3.2 → wear-out; failure stops the line (Cf ≫ Cp)	age-based replacement or condition monitoring

Q3: both options are close – the decision would also depend on cost. That is a typical engineering trade-off.

How to prepare for the exam

Review questions

every lecture ends with six review questions – practise answering them in your own words.

Calculations

availability, OEE, R(t), MTTF, Weibull, series/parallel, RPN, spare parts, replacement – repeat the worked examples and exercises.

Definitions and standards

maintenance (EN 13306), dependability (IEC 60050-192), asset management (ISO 55000), ISO 12100.

Explain with examples

for each method be ready to give one practical example – a pump, a bearing, a conveyor.

QUIZ

Final quiz – the whole course

1 MTBF = 200 h, MTTR = 5 h. Availability is about...

A) 0.95 | B) 0.976 | C) 0.99 | D) 0.025

2 Which wear mechanism causes pitting of rolling bearings?

A) adhesion | B) abrasion | C) surface fatigue | D) erosion

3 Point P on the P-F curve is...

A) the functional failure | B) the first detectable sign of failure | C) the purchase | D) the overhaul

4 Two elements in parallel with R = 0.8 each give...

A) 0.64 | B) 0.80 | C) 0.96 | D) 1.60

5 Weibull β < 1 suggests...

A) wear-out | B) random failures | C) early failures | D) no failures

ANSWERS

Final quiz – answers

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- B) random failures
- **C) early failures**
- D) no failures

SUMMARY

Key takeaways from the course

Operation is the **longest and most expensive** phase – decide with LCC.

Choose maintenance by **function and consequences**, not by habit.

Most failures start in **surfaces** – lubrication and cleanliness matter.

Measure the condition – trends tell more than single values.

Reliability is a probability – use data and the right model.

Fix root causes, learn from every failure, and keep people at the centre.

REVIEW

Review questions



1. How do you estimate MTBF from field data with surviving units? Why are confidence bounds important?
2. Explain ABC, XYZ and VED classification of spare parts. How does the Poisson model help to set the stock?
3. Calculate a discounted LCC for two machines and explain the result.
4. What is the economic life of a machine? When does age-based replacement pay off?
5. Describe the steps from sensor data to remaining useful life. What are the limits of AI in maintenance?
6. Summarise in your own words how the topics of all seven lectures are connected.

Thank you – and good luck in the exam!

Basics of Machine Operation · 2026/2027

dr inż. Radosław Gościniak

