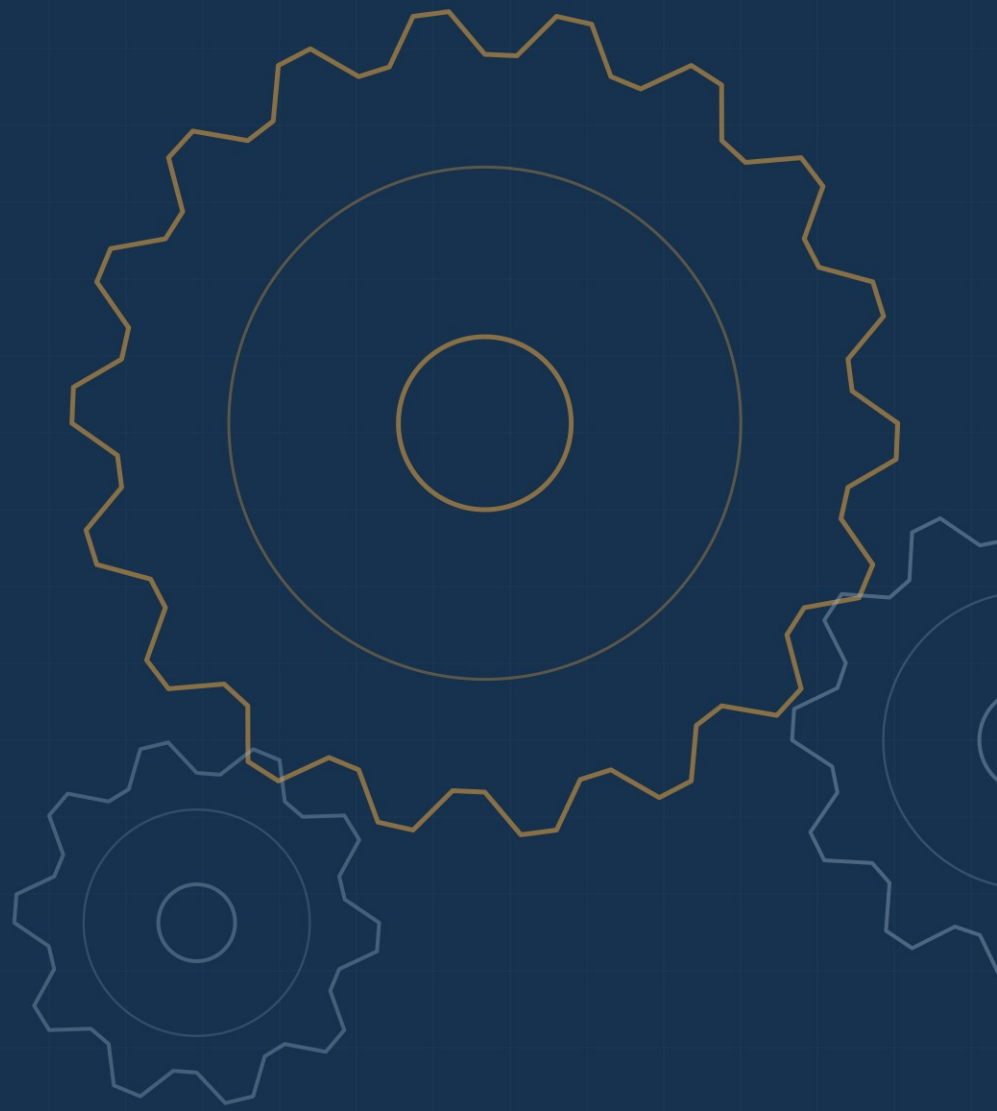
BASICS OF MACHINE OPERATION

Block 3 · Lecture 6 · 20 Jan 2027

System Reliability; Failure Analysis and Reliability Improvement

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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: L6. System Reliability; Failure Analysis and Reliability Improvement

RECAP

Before the break – six points

Vibration: velocity → severity; acceleration / envelope → early bearing damage; **spectrum** → which fault.

Thermography (ΔT), oil analysis (**condition, contamination, wear**), ultrasound (leaks).

R(t) + F(t) = 1; λ(t) – failure rate; MTTF = area under R(t).

Exponential: R = exp(−λt), MTTF = 1/λ – only **37%** survive to MTTF.

Weibull **β**: <1 early, =1 random, >1 wear-out.

Bearing L10: double the load → **8×** shorter life.

TODAY

Plan for today

PART A

System reliability

1. Reliability block diagrams
2. Series, parallel, k-out-of-n, standby
3. Fault tree analysis

PART B

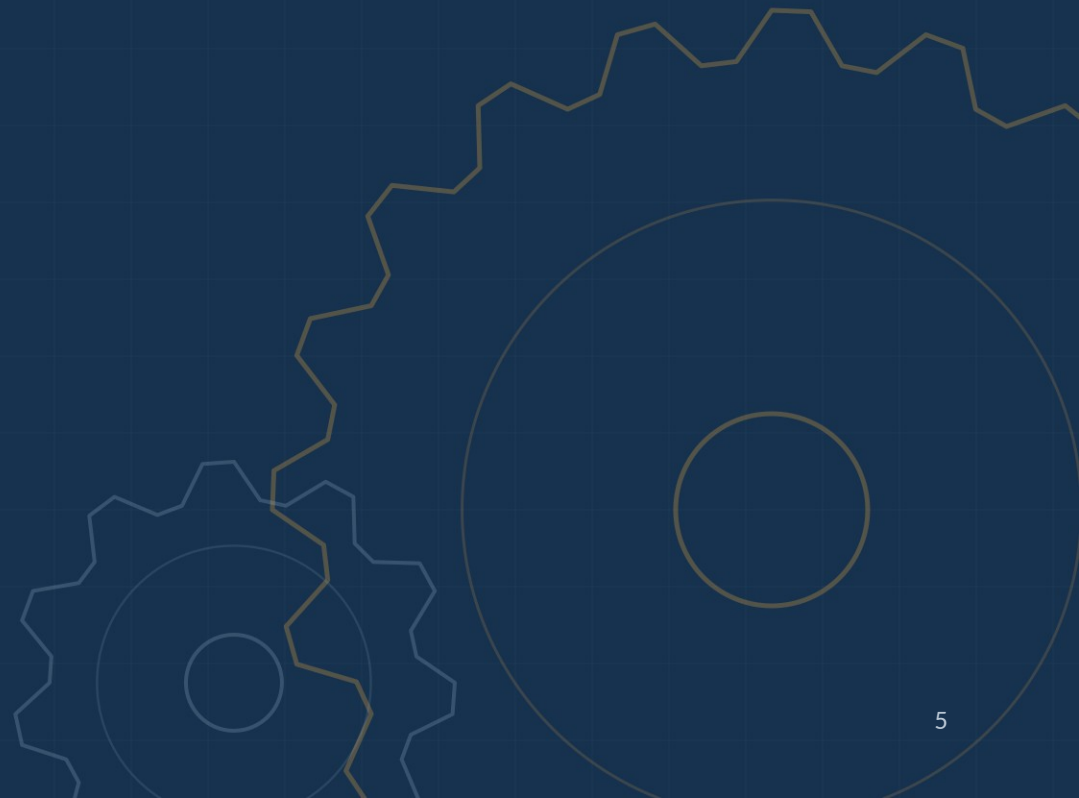
Failure analysis and improvement

4. FMEA and FMECA
5. Root cause analysis: 5 Whys, Ishikawa, Pareto
6. Methods of reliability improvement

01

Reliability block diagrams

How the structure of a system determines its reliability



What is a reliability block diagram (RBD)?

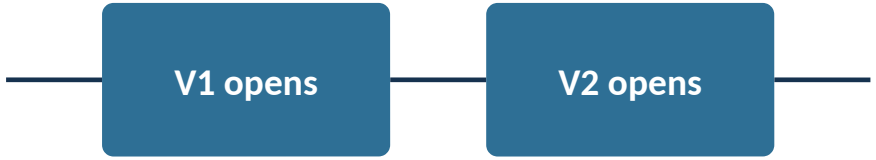
An **RBD** shows how the **functioning** of components contributes to the functioning of the system. The system works if there is at least one **working path** from input to output (IEC 61078).

Physical layout: two shut-off valves in one pipe

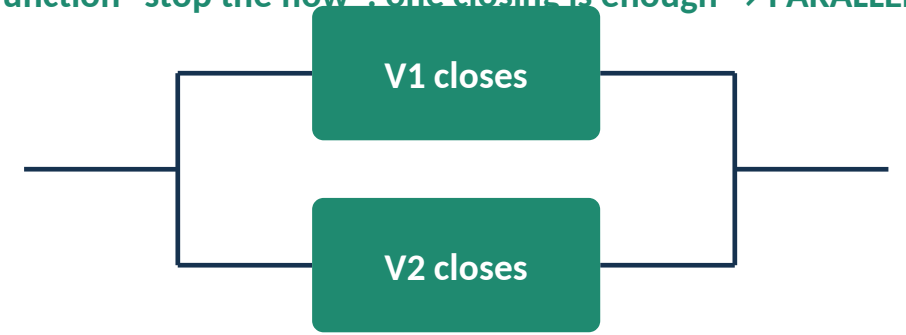


The RBD describes a **function**, not the physical drawing. The same two valves are **in series** for one function and **in parallel** for another!

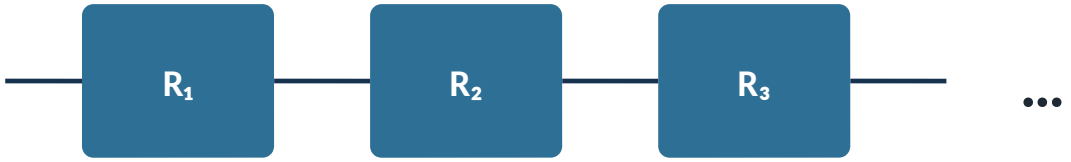
Function "let water flow": both must open → SERIES



Function "stop the flow": one closing is enough → PARALLEL



Series system – every element must work

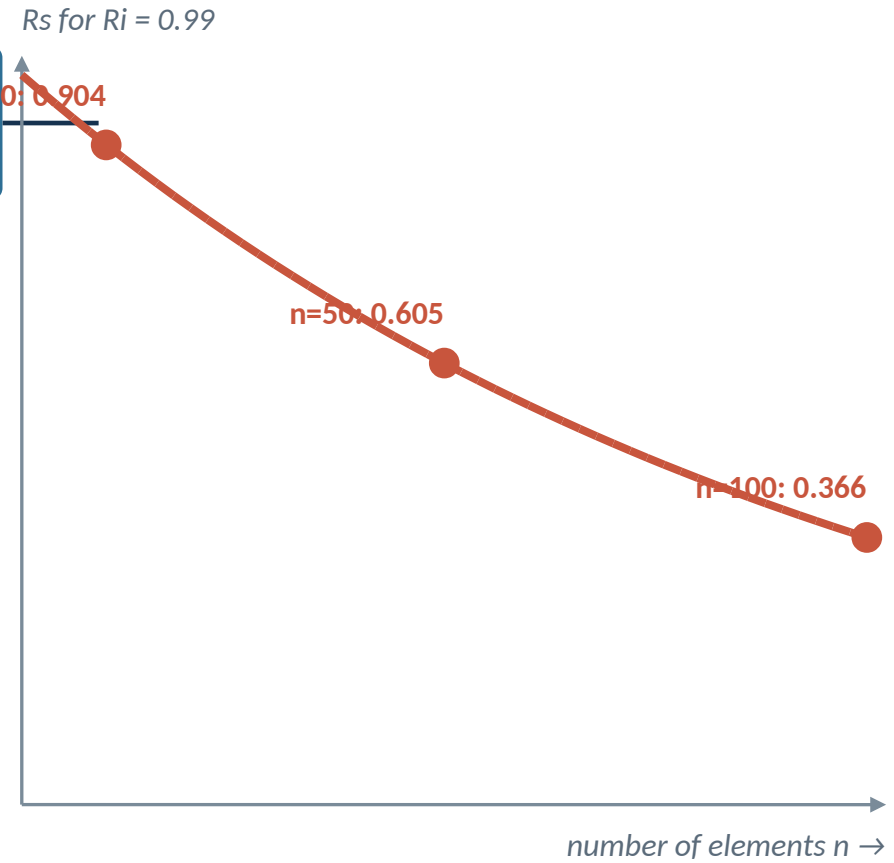


$$R_s = R_1 \cdot R_2 \cdot \ldots \cdot R_n$$

$$\textit{exponential: } \lambda_s = \lambda_1 + \lambda_2 + \ldots + \lambda_n$$

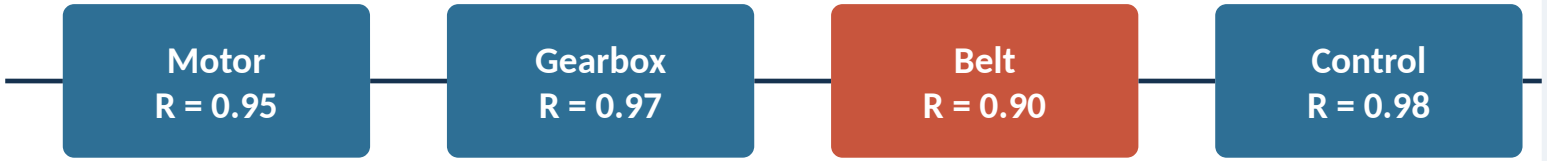
The system is **always less reliable than its weakest element**.

For exponential elements, **failure rates add up**: MTTFs = 1 / Σλi.



EXAMPLE

A conveyor line in series



one-year reliabilities

Rs $0.95 \cdot 0.97 \cdot 0.90 \cdot 0.98$

Rs ≈ 0.813

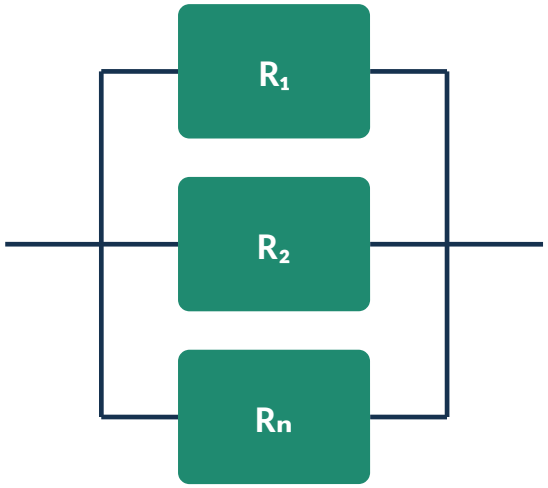
Second part – exponential failure rates: $\lambda = 2 \cdot 10^{-5}$, $1 \cdot 10^{-5}$ and $5 \cdot 10^{-5}$ 1/h → **$\Sigma\lambda = 8 \cdot 10^{-5}$ 1/h → MTTF ≈ 12 500 h**.

The line works one year without failure with probability **81%** – lower than any single element.

The **belt** (0.90) is the weakest link – improving it gives the biggest effect.

Better belt R = 0.97 → Rs ≈ 0.876.

Parallel system – active redundancy



$$F_s = F_1 \cdot F_2 \cdot \ldots \cdot F_n$$

$$R_s = 1 - \Pi(1 - R_i)$$

The system fails only if **all** elements fail. Both elements work at the same time (**active** redundancy).

Pumps (R = 0.9 each)	R system	F system
1 pump	0.900	1 in 10
2 in parallel	0.990	1 in 100
3 in parallel	0.999	1 in 1 000

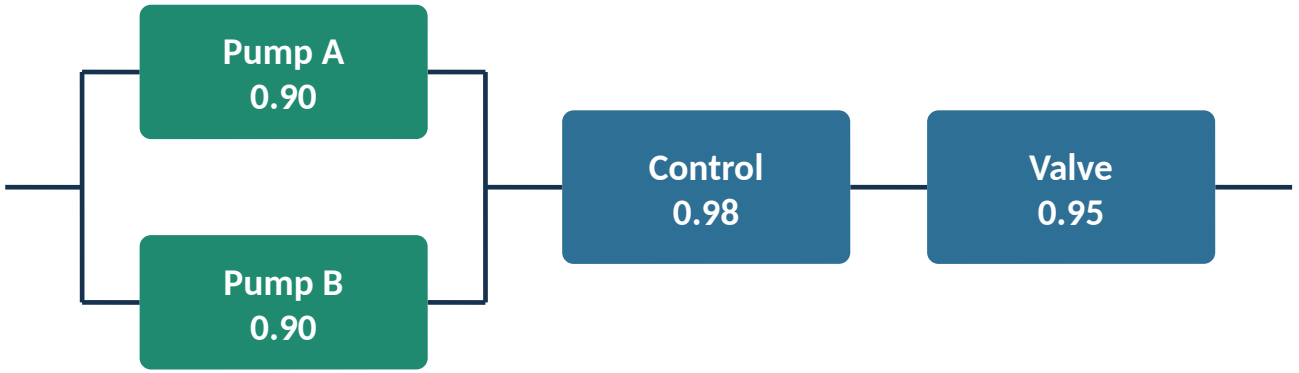
Redundancy improves reliability **very strongly** – but with **diminishing returns**: the second pump gives +0.09, the third only +0.009.

Cost, space, energy and maintenance grow with every extra element.

Watch out for **common-cause failures** – one power supply or one dirty tank can stop all pumps at once.

EXAMPLE

Series–parallel systems – reduce step by step



Step 1: pumps in parallel	$1 - (0.1 \cdot 0.1) = 0.99$
Step 2: whole system in series	$0.99 \cdot 0.98 \cdot 0.95$
Rs	≈ 0.922

Method: replace each parallel or series group by **one equivalent block**, then repeat.

Here the redundant pumps are **no longer** the weakest part – the **valve** (0.95) is.

Improving the strongest part makes almost no difference!

k-out-of-n systems – voting and capacity

The system works if **at least k of n** elements work. Examples: a plant needs **2 of 3** compressors for full capacity; a safety system trips if **2 of 3** sensors agree (voting – fewer false trips).

$$2\text{-out-of-3: } R_s = 3R^2 - 2R^3$$

(identical elements, each with reliability R)

R of one element	1 of 1	2 of 3	1 of 2 (parallel)
0.90	0.900	0.972	0.990
0.80	0.800	0.896	0.960

2-out-of-3 is a compromise: more reliable than one element, less than full parallel – but it can **tolerate one failure** and also **detect a wrong sensor**.

Typical in safety instrumented systems, aircraft and power plants.

Standby redundancy – the spare waits

In **standby** redundancy the second unit is switched on only when the first fails (e.g. a backup pump or a diesel generator). With a perfect switch and identical exponential units:

$$R_s = e^{-\lambda t} \cdot (1 + \lambda t)$$

EXAMPLE: λt = 0.1

One unit	$e^{-0.1} \approx 0.905$
Active parallel	$1 - (0.095)^2 \approx 0.991$
Cold standby	$0.905 \cdot 1.1 \approx 0.995$

Type	Spare during operation	Note
Hot standby	running, unloaded	fast switch-over; spare also ages
Warm standby	partly energised	compromise
Cold standby	switched off	spare does not age – but the switch and start-up may fail!

Hidden failure risk: test standby units regularly (failure-finding – Lecture 2).

Common-cause failures – the enemy of redundancy

A **common-cause failure (CCF)** stops several redundant elements **at the same time** from one cause: one power supply, one dirty oil tank, the same wrong maintenance on both units, flooding, fire, a software bug.

EXAMPLE: two pumps, F = 0.10 each; 10% of failures are common-cause (β = 0.1)

Independent part	$F_{ind} = 0.09,\ F_{CCF} = 0.01$
Both fail independently	$0.09^2 = 0.0081$
System F	$0.0081 + 0.01 \approx 0.018$
System R	≈ 0.982 (not 0.990!)

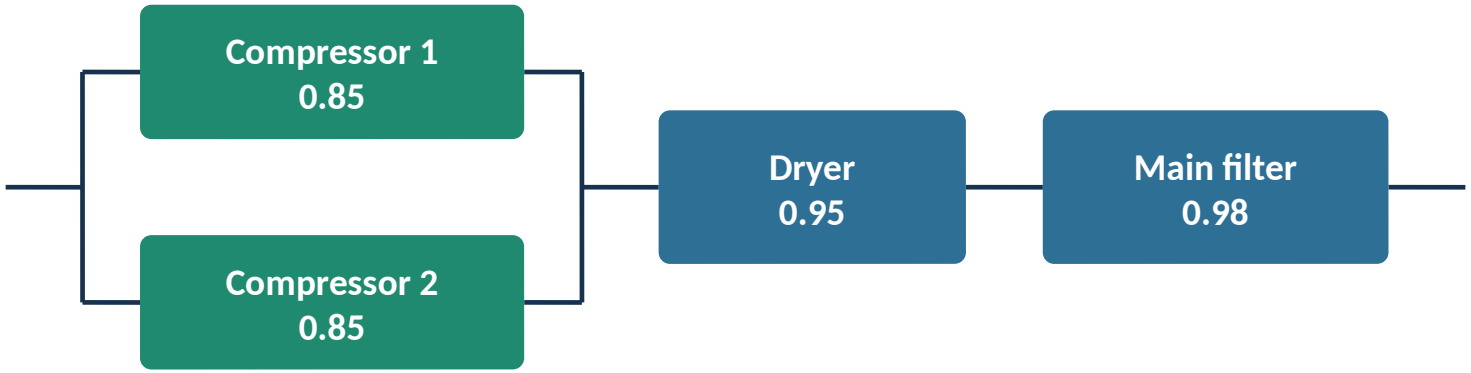
Even a small CCF share **dominates** the result.

Defences: **diversity** (different types or suppliers), **separation** (different rooms, power feeds), **staggered maintenance** (not the same technician on both units on the same day), testing.

EXERCISE

ACTIVITY

Your turn: compressed-air supply



one compressor is enough for the plant; one-year reliabilities

Work in pairs – 7 minutes:

1. Calculate the system reliability Rs.
2. The budget allows ONE improvement: a 3rd compressor OR a 2nd dryer in parallel. Which is better?

EXERCISE

ANSWERS

Compressed-air supply – solution

Compressors (parallel)	$1 - 0.15^2 = 0.9775$
System now	$0.9775 \cdot 0.95 \cdot 0.98 \approx 0.910$
+ 3rd compressor	$(1 - 0.15^3) \cdot 0.95 \cdot 0.98 \approx 0.928$
+ 2nd dryer	$0.9775 \cdot (1 - 0.05^2) \cdot 0.98 \approx 0.956$

The **2nd dryer** is much better: 0.956 vs 0.928.

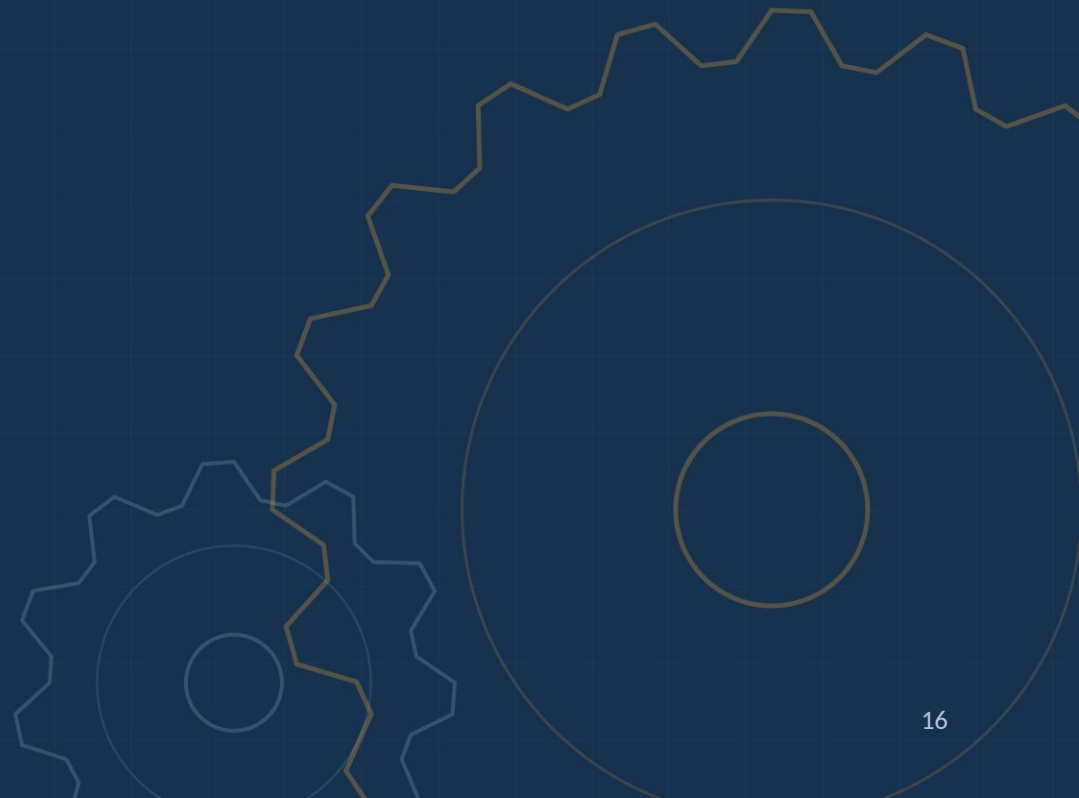
The dryer was the **weakest single element** in series; the compressors were already redundant.

Lesson: improve the **weakest link** – and look at the structure before buying.

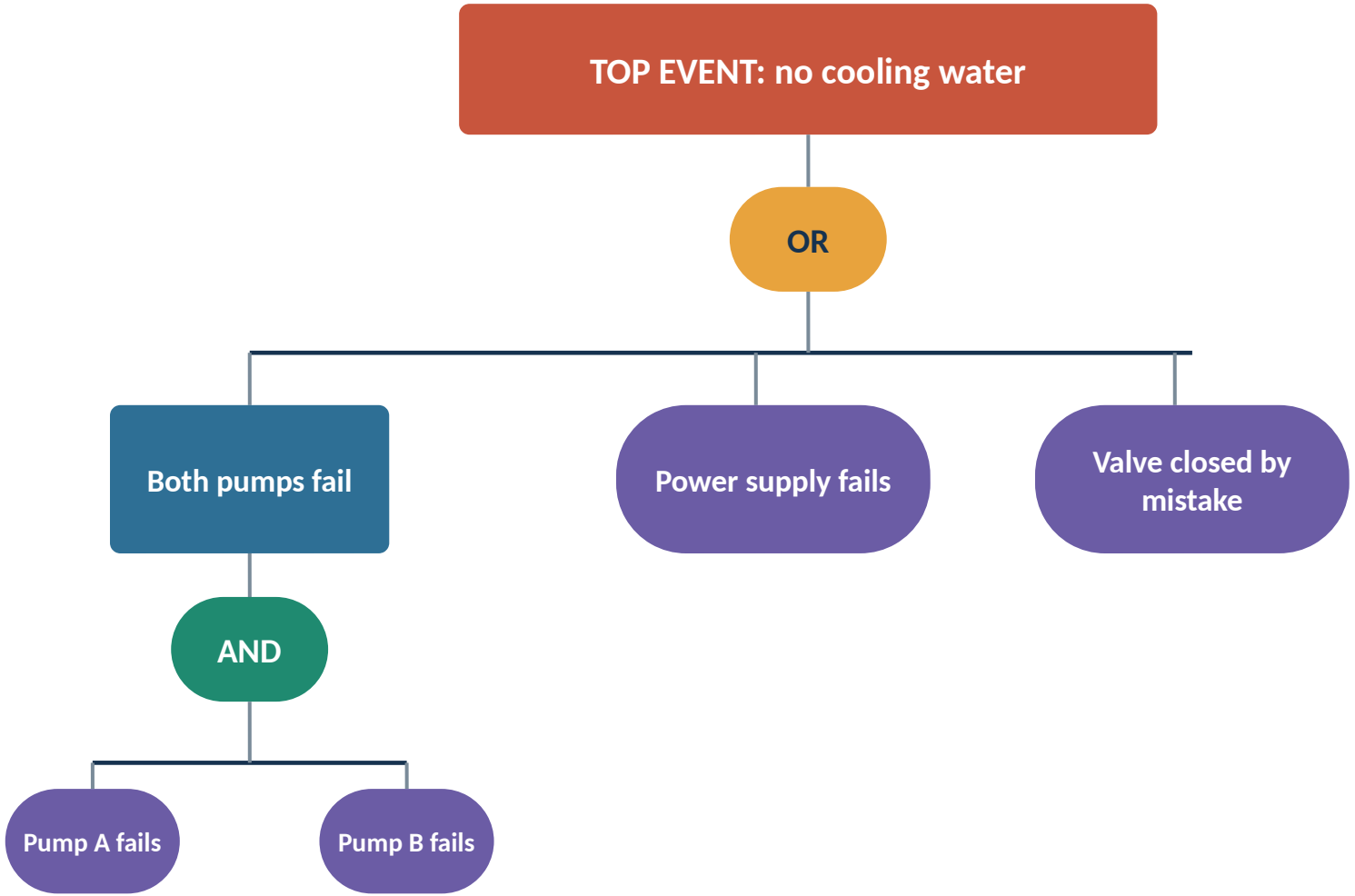
02

Fault tree analysis (FTA)

Top-down: from an undesired event to its causes



What is a fault tree?



FTA (IEC 61025) starts from an **undesired top event** and goes **down** to its causes.

OR gate – any input causes the output.

AND gate – all inputs must occur.

Basic events (circles) – failures with known probability.

AND = parallel in the RBD; OR = series.

EXAMPLE

Calculating the fault tree

$$AND:\ P = P_1 \cdot P_2 \cdot \ldots$$

$$OR:\ P = 1 - \Pi(1 - P_i) \approx \Sigma P_i$$

(the approximation ΣP is good when all P are small)

The **power supply** contributes most (0.01 of 0.0145) – a **single point of failure**. Redundant pumps do not help if both need the same power!

DATA (one year): P(pump) = 0.05 each, P(power) = 0.01, P(valve error) = 0.002

Both pumps (AND)	$0.05 \cdot 0.05 = 0.0025$
Top event (OR)	$\approx 0.0025 + 0.01 + 0.002$
P(top)	$\approx 0.0145 \approx 1.5\%$

Improvement: a second power feed or a diesel-driven pump.

Minimal cut sets – the weak points

A **cut set** is a combination of basic events that causes the top event. A **minimal cut set** cannot be reduced further.

Minimal cut set	Order	Probability	Meaning
{power supply fails}	1	0.010	single point of failure – one event is enough
{valve closed by mistake}	1	0.002	single point of failure – human error
{pump A fails, pump B fails}	2	0.0025	two independent failures needed

Rules: **first-order cut sets** (single points of failure) are the most dangerous – remove them by redundancy, interlocks or procedures. Check **common causes** that can hit several events at once.

EXERCISE

ACTIVITY

Fault tree: the car does not start

Work in pairs for **6 minutes**. Top event: **the car does not start in the morning** (probabilities per winter month):

Basic event	Probability
Battery flat	0.020
Starter motor fails	0.005
Fuel pump fails	0.004
Fuel tank empty	0.006



1. Draw the fault tree (OR / AND gates). Hint: fuel pump and empty tank form an intermediate event “no fuel delivered”.
2. Calculate P(top event).
3. You buy a jump-starter booster (it fails with P = 0.1). How does the tree change? New P(top)?

EXERCISE

ANSWERS

Fault tree: the car – solution

No fuel (OR)	$0.004 + 0.006 = 0.010$
Top event (OR)	$0.020 + 0.005 + 0.010 \approx 0.035$
With booster: battery AND booster	$0.020 \cdot 0.1 = 0.002$
New top event	$0.002 + 0.005 + 0.010 \approx 0.017$

The booster adds an **AND gate** – redundancy for the battery.

The risk falls by half (3.5% → 1.7%).

Now the **fuel** branch (0.010) is the biggest contributor – the next improvement should go there.

COMPARISON

RBD, FTA and FMEA – which tool when?

	RBD	FTA	FMEA
Direction	system structure	top-down (from effect to causes)	bottom-up (from causes to effects)
Starts from	functions and their logic	one undesired top event	each component / process step
Result	system reliability	probability of the top event, cut sets	list of failure modes, risks, actions
Strength	redundancy decisions	combinations of failures, human errors	completeness – nothing is forgotten
Standard	IEC 61078	IEC 61025	IEC 60812, AIAG-VDA

In practice they are combined: FMEA finds failure modes, FTA analyses the critical top events, RBD calculates system reliability.

QUIZ

Quiz 1 – system reliability

1 **Three elements in series, R = 0.9 each. System reliability is about...**

A) 0.90 | B) 0.73 | C) 0.81 | D) 0.999

2 **Two elements in parallel, R = 0.9 each. System reliability is...**

A) 0.81 | B) 0.90 | C) 0.99 | D) 1.80

3 **In a series system with exponential elements, the failure rates...**

A) multiply | B) add up | C) cancel out | D) do not matter

4 **In a fault tree, an AND gate corresponds in an RBD to...**

A) series | B) parallel | C) standby only | D) nothing

5 **A first-order minimal cut set is...**

A) a single point of failure | B) always harmless | C) a parallel element | D) a test procedure

ANSWERS

Quiz 1 – answers

1 Three elements in series, R = 0.9 each. System reliability is about...

A) 0.90 | **B) 0.73** | C) 0.81 | D) 0.999

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03

FMEA and FMECA

Failure Mode and Effects Analysis – find problems before they happen



What is FMEA?

FMEA – Failure Mode and Effects Analysis – a systematic, **bottom-up** team method: for each component or process step we ask **how it can fail, what the effect is, why it happens, and how we detect or prevent it**.

History

US military procedure (1949), NASA Apollo programme (1960s), automotive industry (1970s – today).

Types

Design FMEA (product), **Process FMEA** (manufacturing), and FMEA for maintenance (equipment – part of RCM).

Standards

IEC 60812; in automotive the **AIAG-VDA FMEA Handbook** (2019).

The FMEA worksheet

Item / function	Failure mode	Effect	S	Cause	O	Current controls	D	RPN / AP	Actions
what does it do?	*how can it fail?*	*what happens?*	*how bad?*	*why?*	*how often?*	*prevention / detection now*	*will we find it?*	*priority*	*what will we do?*

S – Severity	how serious is the effect for the user, safety, environment (1–10)
O – Occurrence	how likely is the cause (1–10)
D – Detection	how likely is it that current controls detect the failure before it reaches the customer or causes the effect (1 = sure, 10 = impossible)

Note: for D a HIGH number means BAD detection.

Rating scales (simplified)

Rank	Severity S	Occurrence O	Detection D
9–10	safety or legal problem, without warning	very high – almost certain	cannot be detected
7–8	machine stops, major loss of function	high – repeated failures	low chance of detection
4–6	reduced performance, customer notices	moderate – occasional failures	moderate chance
2–3	minor effect, few notice it	low – few failures	high chance of detection
1	no effect	remote – failure unlikely	almost certain detection

Each company or standard defines detailed criteria – use the same scale in the whole team.

Risk priority number and action priority

$$RPN = S \times O \times D$$

range 1 – 1 000

The classic **RPN** ranks failure modes – the highest RPN first.

Problem: S = 10, O = 2, D = 2 gives RPN = 40, while S = 4, O = 5, D = 5 gives 100. The first (a safety problem!) looks less important.

AIAG-VDA (2019) replaced RPN with **Action Priority (AP)**: High / Medium / Low.

AP gives **severity** the first place, then occurrence, then detection.

Rule in every method: **high severity always gets attention**, regardless of the product.

Actions first reduce **O** (prevent the cause), then improve **D** (detect it). S changes only by design changes.

EXAMPLE

FMEA example: a hydraulic press

Failure mode	Effect	Cause	S	O	D	RPN	Action
Hose bursts	oil jet, injury, fire risk	ageing, abrasion	9	4	3	108	hose replacement plan, guards
Pump delivers low pressure	press force too low, scrap	pump wear, dirty oil	6	5	4	120	oil analysis, filtration
Pressure switch fails (stuck)	over-pressure not stopped	contamination, ageing	8	2	8	128	periodic function test (failure-finding)

By RPN the **pressure switch** is first – a **hidden failure** (D = 8). But the **hose** has the highest severity (S = 9, injury) – with Action Priority it would be **High** as well. **Both** need action; after the actions, the team re-rates S, O and D.

GROUP EXERCISE

ACTIVITY

FMEA: an office coffee machine

Work in groups of 3–4 for **10 minutes**. For each failure mode: give **S, O, D**, calculate **RPN**, and propose **one action**.

Failure mode	Effect	Cause	S	O	D	RPN	Action
Water heater does not heat	cold coffee	scale (limescale) on the heater					
Grinder blocked	no coffee	foreign object in beans					
Water leaks onto the floor	slip hazard, electrical risk	cracked hose					

Discuss: which failure mode needs action first – and why?

GROUP EXERCISE

ANSWERS

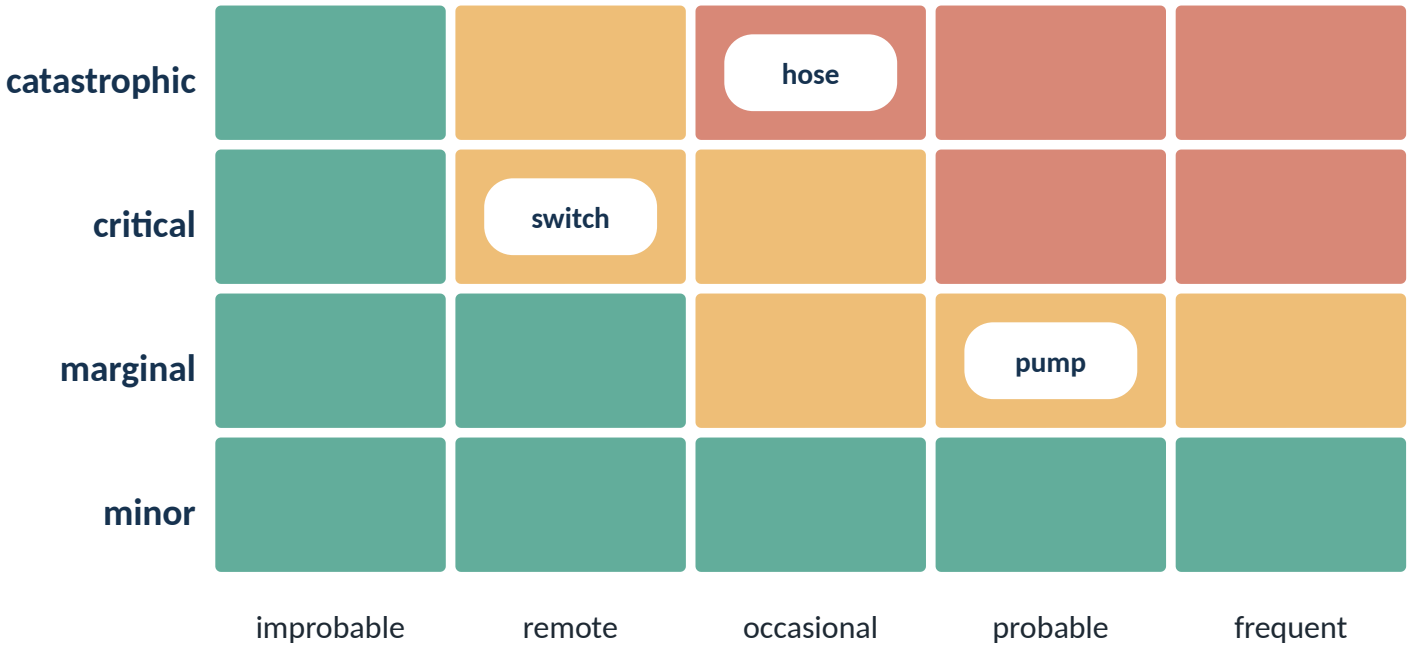
Coffee machine FMEA – example solution

Failure mode	S	O	D	RPN	Action
Heater does not heat (scale)	4	6	2	48	automatic descaling reminder; water filter
Grinder blocked	5	3	3	45	bean inspection, sieve, overload protection
Water leak on the floor	8	3	6	144	leak sensor with automatic shut-off valve; drip tray; hose replacement every 2 years

The **leak** has the highest severity (safety) and poor detection → **first priority**. A leak sensor improves **D**; a better hose reduces **O**. Your numbers may differ – the discussion is the value of FMEA.

FMECA – adding criticality

FMECA (Failure Mode, Effects and **Criticality** Analysis) adds a quantitative criticality – the **probability or frequency** of each failure mode – shown in a **criticality matrix**.



The press example placed in the matrix.

Red zone – unacceptable: act now.

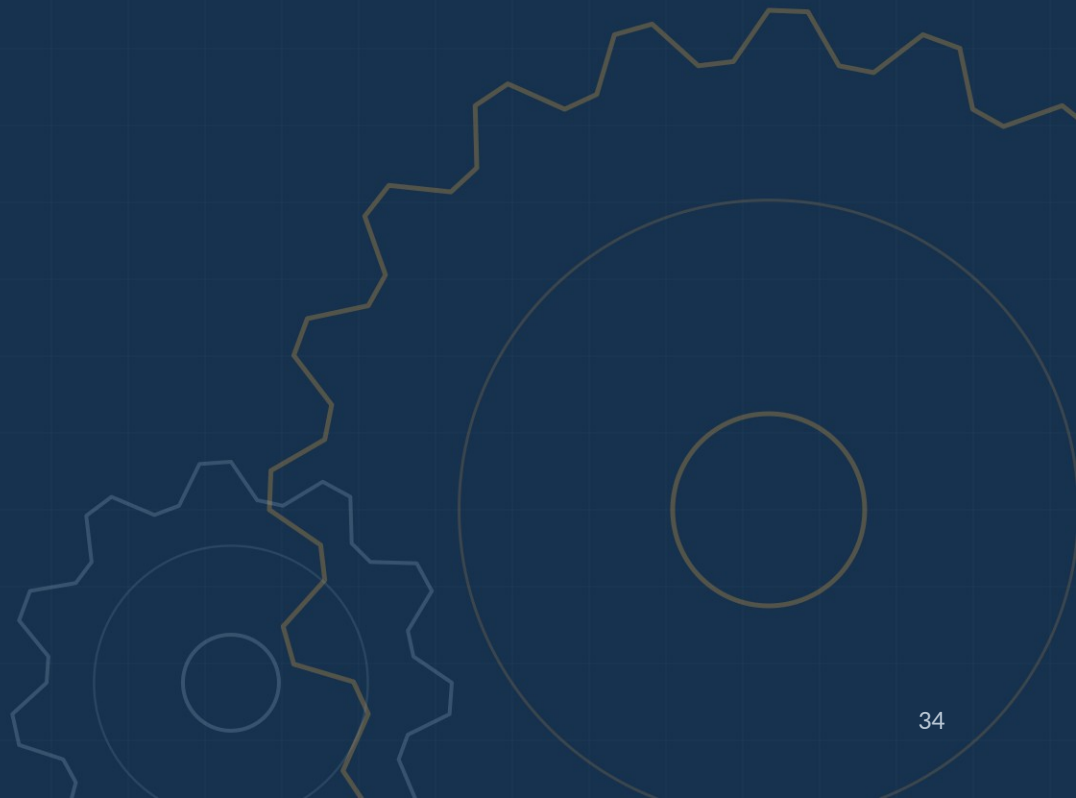
FMECA is used in aerospace, defence, nuclear – and in **RCM** (questions 1–5).

The matrix is the same idea as the **risk matrix** from Lecture 1.

04

Root cause analysis (RCA)

Fix the cause – not only the broken part



Three levels of causes

FMEA looks **forward** (what could fail). **Root cause analysis** looks **backward**: why did this failure happen – and how do we stop it from happening again?

Physical root cause

the failure mechanism – e.g. bearing fatigue due to overload. Fixing it: replace the bearing.

Human root cause

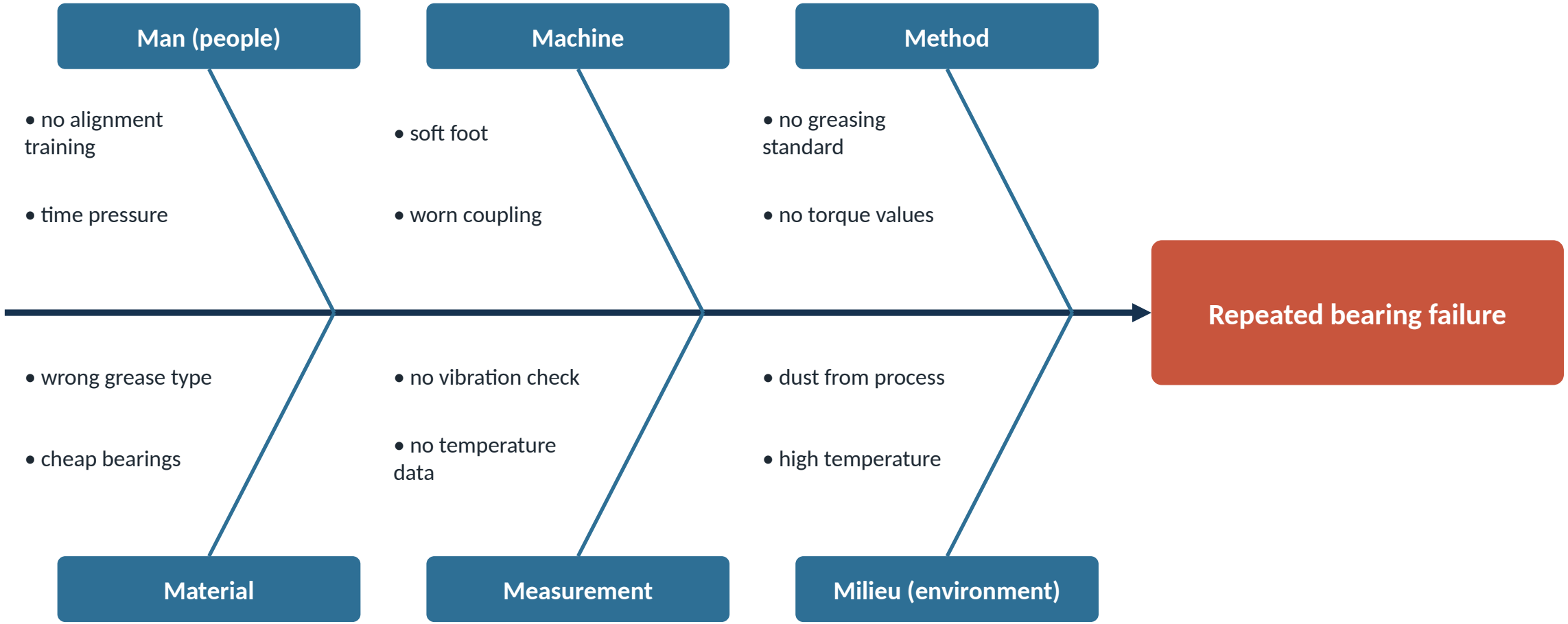
a human action or decision – e.g. the coupling was misaligned during assembly.

Latent (organisational) root cause

the system that allowed it – e.g. no alignment tool, no procedure, no training. Fixing it prevents **many** future failures.

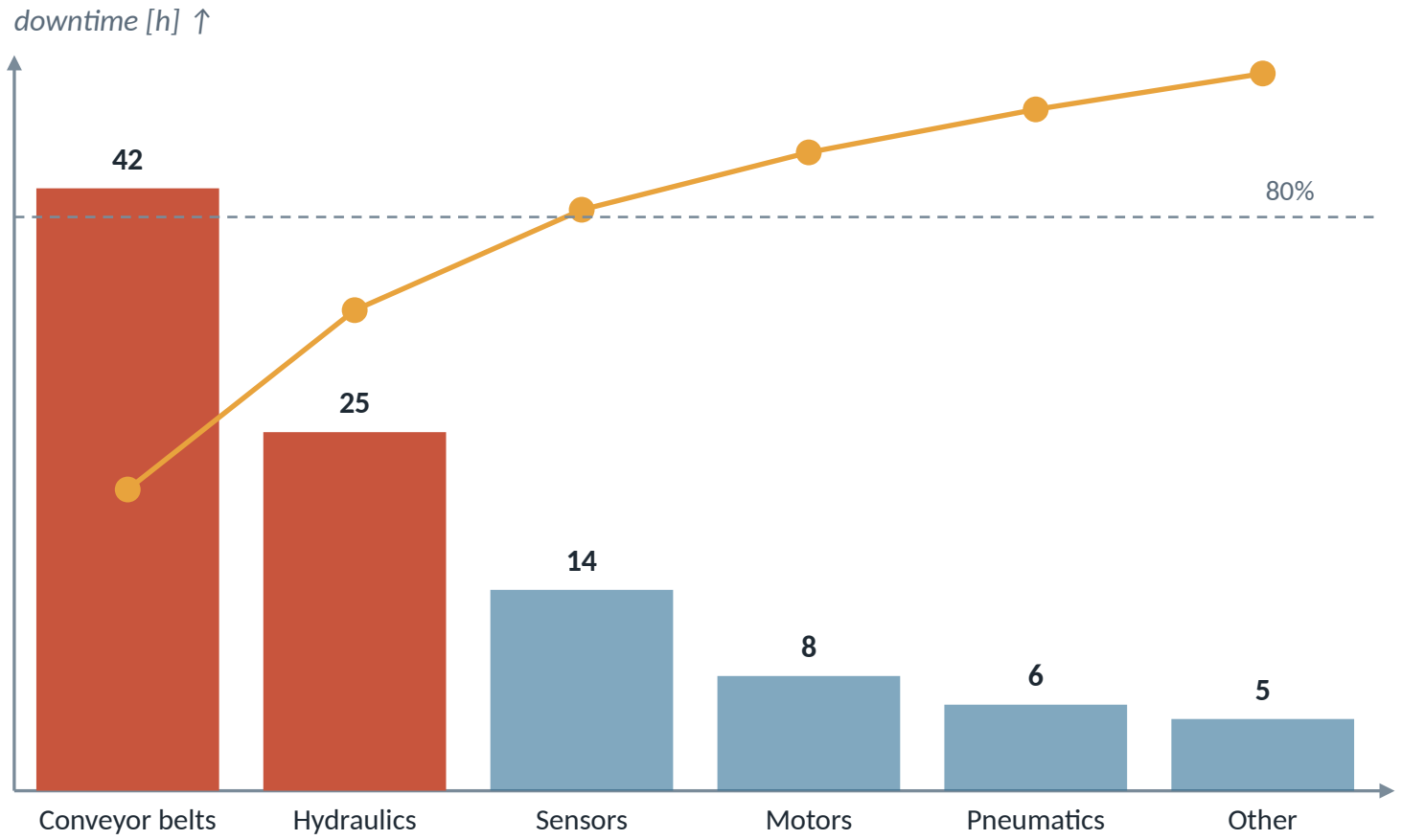
If we fix only the physical cause, the failure **will come back**. Remember the conveyor bearing from Lecture 1.

The Ishikawa (fishbone) diagram



6M categories help the team not to forget any group of causes. Then verify the most likely causes with data or 5 Whys.

Pareto analysis – the vital few



Sort causes from the largest to the smallest and add the **cumulative %** (orange line).

Here belts and hydraulics = **67%** of downtime; with sensors **81%**.

Pareto principle (80/20): a few causes create most of the losses – focus RCA there.

Use downtime or cost – not only the number of failures.

Collecting evidence – the 5 Ps

Good RCA needs facts, collected **before** the evidence disappears (cleaned, scrapped, forgotten):

- **Parts** – keep the failed parts – do not clean them; label and photograph them
- **Position** – where was everything? Photos of the scene, settings, positions of valves and switches
- **People** – short interviews with operators and technicians – facts, not blame
- **Paper** – work orders, logs, trends from monitoring, maintenance history, procedures
- **Paradigms** – beliefs and habits – “we always do it this way” (remember the iceberg)

CASE STUDY

Case study: pump seals that fail every two months

Problem	Mechanical seals of a process pump fail every 6–8 weeks. Each time the seal is replaced. Cost: parts, labour, product loss.
Evidence	Seal faces show uneven wear on one side; vibration 1× and 2× with high axial values after each repair.
Analysis	Fishbone + 5 Whys: misalignment after each repair → no laser tool, alignment “by eye” → no procedure, no training.
Actions	laser alignment tool bought; alignment procedure with tolerances; training; vibration check after every repair.
Result	Seal life grows from 2 months to more than 18 months.

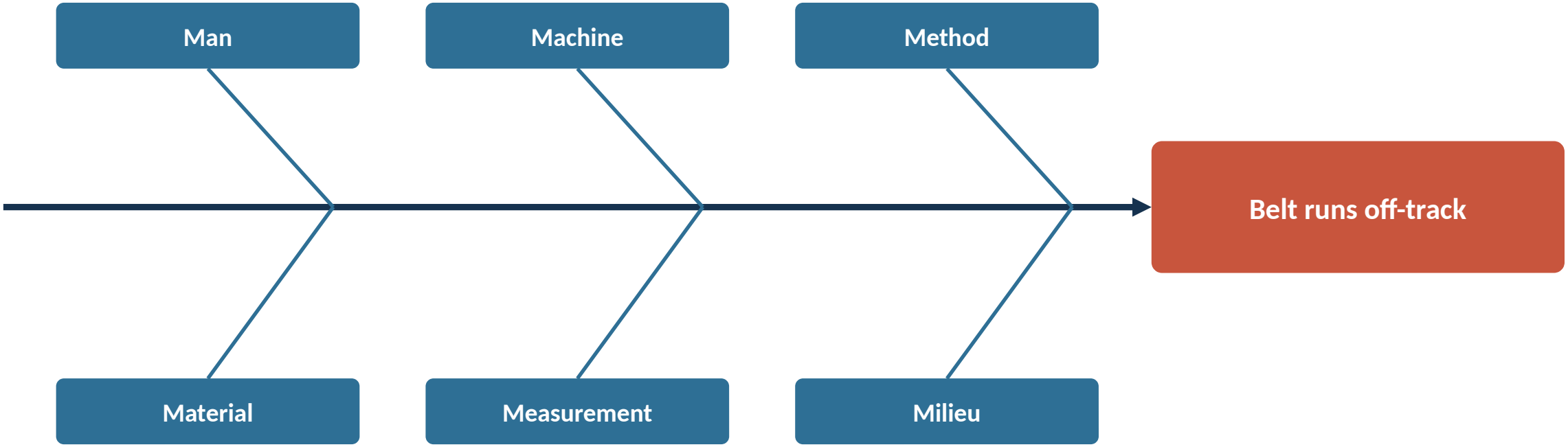
Illustrative case. The physical cause was the seal; the root cause was the alignment process.

GROUP EXERCISE

ACTIVITY

Fishbone: the conveyor belt that keeps running off-track

Work in groups of 3–4 for **10 minutes**. A long conveyor belt in a packaging plant keeps **running off-track** (mistracking) – several times per shift. Operators adjust it by hand.



Find at least 2 possible causes per category – then choose the 2 most likely and say how you would verify them.

GROUP EXERCISE

ANSWERS

Belt mistracking – example causes

Category	Possible causes	How to verify
Man	wrong tensioning after repair; adjusting the wrong roller	check work orders; observe adjustment
Machine	misaligned or worn rollers; seized idler; frame not square	measure alignment; spin each idler
Method	no procedure for belt tensioning and splicing	check documentation
Material	bad splice (not square); belt stretched unevenly	inspect the splice; measure belt edges
Measurement	no regular inspection of rollers; no tension measurement	check the inspection plan
Milieu	product spillage builds up on rollers; humidity	look at roller surfaces; cleaning records

Most frequent real causes: material build-up on rollers, a non-square splice and a seized idler.

05

Methods of reliability improvement

Design, manufacturing, operation and maintenance



Where can we improve reliability?

Design

simplification (fewer parts), derating and safety margins, redundancy, robust design, better materials, design for maintainability.

Manufacturing

quality control, process capability, burn-in and run-in tests to remove early failures ($\beta < 1$).

Operation

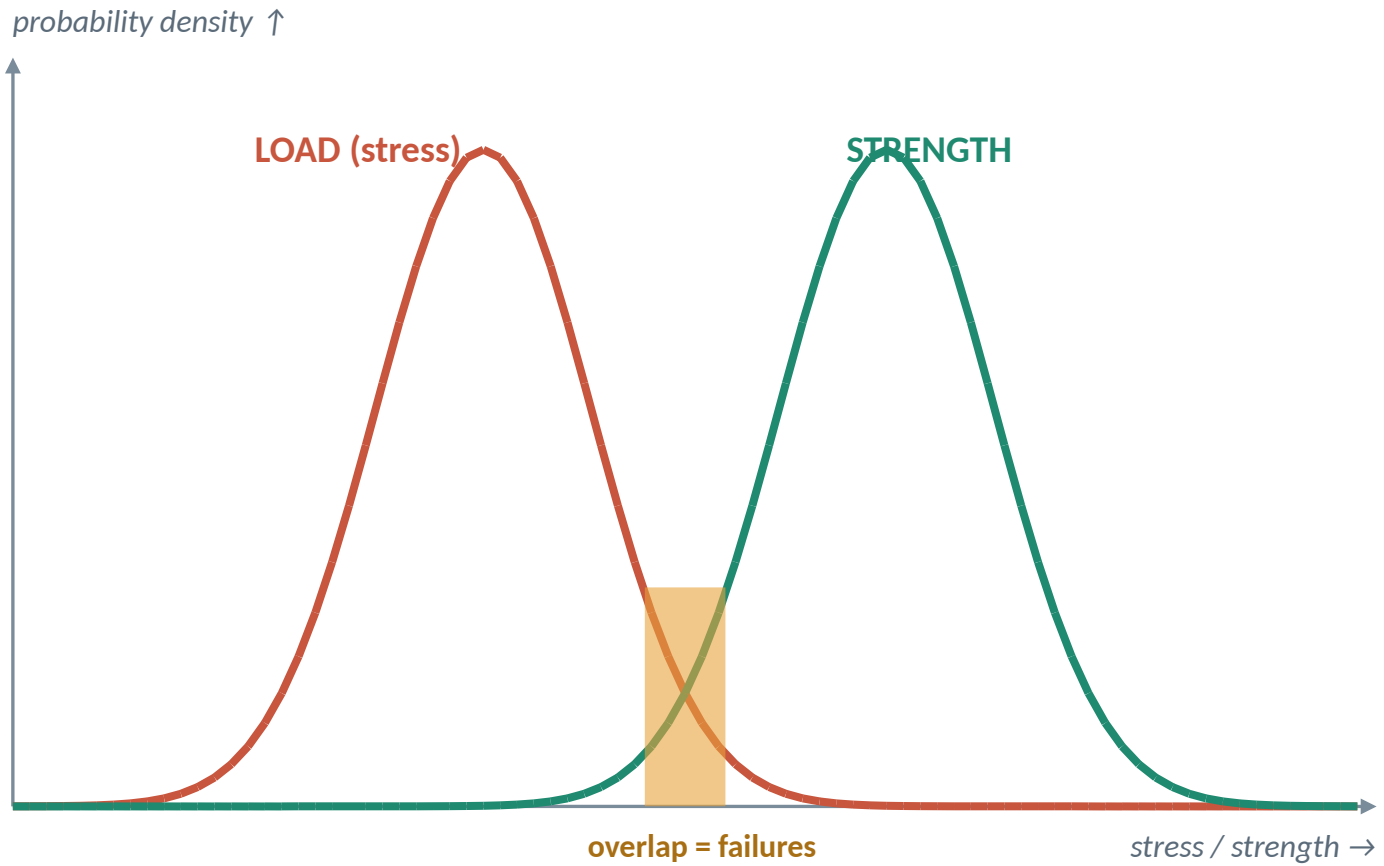
correct operating conditions and loads, training of operators, clear procedures – avoid overload and misuse.

Maintenance

the right strategy (RCM), condition monitoring, correct lubrication and alignment, good repair quality, RCA.

The earlier the improvement, the cheaper it is: a change on paper costs little, a change in the field costs a lot.

Load–strength interference and derating



Both load and strength **vary** – they are distributions, not single numbers.

Failures happen in the **overlap**: a high load meets a weak part.

Improve by: a larger **safety margin** (distance between means), **less scatter** (quality, controlled loads), and **derating** – using components below their rated values (e.g. a motor at 80% of rated power).

Wear and ageing move strength **to the left** over time.

Design for maintainability – and mistake-proofing

Accessibility
service points reachable without dismantling; inspection windows

Modularity
replace a whole module quickly, repair it in the workshop – lower MTTR

Standard parts
common bearings, seals, fasteners – fewer spare parts, faster supply

Built-in diagnostics
sensors, test points, error codes – fast fault finding

Poka-yoke
mistake-proofing: parts that fit only one way, coloured connectors, different hose couplings for different oils

Clear marking
labels for lubrication points, flow directions, torque values

FRACAS – the closed loop of improvement



FRACAS – Failure Reporting, Analysis and Corrective Action System.

It is the **PDCA cycle** (Plan–Do–Check–Act) applied to failures.

In aviation and defence it is mandatory; in industry it is the basis of **continuous reliability improvement**.

Without step 4 we never know if the action worked.

QUIZ

Quiz 2 – failure analysis

1 **FMEA is mainly a...**

A) top-down method | B) bottom-up method | C) cost calculation | D) vibration method

2 **RPN for S = 7, O = 3, D = 5 equals...**

A) 15 | B) 35 | C) 105 | D) 21

3 **In FMEA, D = 10 means...**

A) the failure is always detected | B) the failure cannot be detected | C) very high severity | D) ten failures per year

4 **The categories Man, Machine, Method, Material, Measurement, Milieu belong to...**

A) Pareto analysis | B) the Ishikawa diagram | C) FTA | D) Weibull plot

5 **Fixing only the broken part usually addresses...**

A) the latent root cause | B) the physical cause | C) all causes | D) the human cause

ANSWERS

Quiz 2 – answers

1 **FMEA is mainly a...**

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SUMMARY

Key takeaways from today

Series: **Rs = ∏Ri** – weaker than the weakest element; λ values add up.

Parallel: **Rs = 1 − ∏(1 − Ri)** – strong effect, diminishing returns, beware common causes.

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

FMEA: **S, O, D**; RPN or Action Priority – severity first.

RCA: physical → human → **latent** cause; tools: 5 Whys, Ishikawa, Pareto, 5 Ps.

Improve early (design), reduce scatter, derate, design for maintainability, close the **FRACAS** loop.

REVIEW

Review questions



1. Calculate the reliability of a series system and of a parallel system of three elements with R = 0.95.
2. Explain why an RBD describes a function and not the physical layout. Give an example.
3. Draw a simple fault tree with AND and OR gates. What is a minimal cut set?
4. Describe the FMEA worksheet. What are S, O, D and the RPN? What are the limits of RPN?
5. What are the physical, human and latent root causes? Describe the Ishikawa diagram and Pareto analysis.
6. Name four methods of reliability improvement in design and two in maintenance.

Thank you for your attention

Next: laboratory today 13:30 (R11) · next block 27 Jan 2027 – Lecture 7 and course review

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