O SCALE MODEL RAILROADING
SYSTEMS ENGINEERING WORKSHOP

A 1–2 Day Intensive for Sophomore Systems & Industrial Engineering Students

Integrating Lean Operations · Queueing Theory · Human Factors ·
Process Optimization · Systems Thinking & Engineering Economics

O Scale STEM Education Initiative

Workshop Title	Precision Operations: Systems Engineering Through O Scale Model Railroading
Target Students	Sophomore Systems & Industrial Engineering (IE/SE) — Year 2, core curriculum
Prerequisites	Introduction to Industrial Engineering; Probability & Statistics I; Engineering Economy (concurrent OK)
Format	1-Day Intensive (8 hrs) or 2-Day Workshop (4 hrs/day); modular — sessions can be taught independently
Team Size	4–5 students per team; roles rotate each session
ABET Coverage	Student Outcomes (1)(2)(3)(4)(5)(6)(7) — broadest single-lab ABET coverage in the IE curriculum
IE/SE Threads	Lean & Waste Elimination · Queueing Theory · Human Factors & Ergonomics · Engineering Economics · Systems Thinking & Simulation
Session 1	The Railroad as a System — Systems Thinking, VSM & Waste Identification (Day 1, AM)
Session 2	Flow, Throughput & Queueing — Little's Law, Bottleneck Analysis & Takt Time (Day 1, PM)
Session 3	Human Factors & Workstation Design — Ergonomics, Error Analysis & Poka-Yoke (Day 2, AM)
Session 4	Engineering Economics & Decision Analysis — ROI, Life-Cycle Cost & Make-vs-Buy (Day 2, PM)
Capstone Activity	System Redesign Sprint — Teams apply all four threads to optimize layout operations
Equipment Scale	O Scale (1:48) — all process metrics scaled to prototype railroad equivalents
Contact	O Scale STEM Education Initiative

Why O Scale for Systems Engineering? The model railroad is not a toy — it is a scaled manufacturing and logistics system. It has raw material inputs (cars to be switched), processing stations (interchange tracks, yards), throughput constraints (locomotive tractive effort, track capacity), human operators (the crew), quality defects (derailments, missed switches), and economic constraints (capital cost, operating cost, return on investment). Every concept in the sophomore IE curriculum has a direct, observable, measurable analog on the layout. O Scale is chosen because its larger size makes workstation ergonomics, component handling, and process observation practical in a classroom setting.

ABET Student Outcomes Coverage

This workshop provides evidence for the broadest ABET coverage of any single laboratory activity in the typical sophomore IE curriculum. The following table maps each ABET Student Outcome (2019 Criteria) to specific workshop activities.

ABET Outcome	Statement	How This Workshop Addresses It
(1)	Identify, formulate, and solve complex engineering problems	Teams formulate the bottleneck identification problem as a queueing network, solve for throughput using Little's Law, and verify experimentally
(2)	Apply engineering design within realistic constraints	Session 4 requires teams to make a capital investment recommendation subject to a defined budget constraint and required payback period
(3)	Communicate effectively (written, oral, visual)	Each session ends with a structured team debrief; the capstone requires a 10-minute management briefing with VSM before/after
(4)	Recognize ethical and professional responsibilities	Human factors session explicitly addresses operator fatigue, error-inducing design, and the engineer's responsibility to design for human capability
(5)	Function effectively on a team with diverse roles	Roles rotate each session: Timekeeper, Data Recorder, Process Observer, Operator, Analyst — no student holds the same role twice
(6)	Develop and conduct experiments; analyze data	Every session includes a timed, repeated-measures experiment with statistical analysis of results (mean, standard deviation, confidence intervals)
(7)	Acquire and apply new knowledge as needed	Students research one real railroad operations case study per session and connect it to their experimental findings

Master Workshop Schedule

Day 1 Schedule

Time	Duration	Activity	IE/SE Concept
8:00 AM	30 min	Welcome, safety briefing, team formation, role assignment	Team dynamics, professional norms
8:30 AM	15 min	Layout orientation — physical walkthrough of O Scale system	System boundary definition
8:45 AM	75 min	SESSION 1: Systems Thinking & Value Stream Mapping	VSM, waste taxonomy, systems thinking
10:00 AM	15 min	Break + team data review	—
10:15 AM	90 min	SESSION 2: Flow, Throughput & Queueing Analysis	Little's Law, bottleneck, takt time
11:45 AM	45 min	Lunch + individual reflection journal entry	Metacognition
12:30 PM	30 min	Day 1 debrief — teams present VSM findings (5 min each)	Technical communication
1:00 PM	—	Day 1 close (1-day format ends here)	—

Day 2 Schedule

Time	Duration	Activity	IE/SE Concept
8:00 AM	15 min	Day 1 recap quiz (individual, 5 questions)	Retrieval practice, accountability
8:15 AM	90 min	SESSION 3: Human Factors & Workstation Design	Ergonomics, error analysis, poka-yoke
9:45 AM	15 min	Break	—
10:00 AM	90 min	SESSION 4: Engineering Economics & Decision Analysis	NPV, IRR, life-cycle cost, make vs. buy
11:30 AM	30 min	Capstone Sprint briefing — teams receive redesign scenario	Problem framing
11:45 AM	45 min	Lunch	—
12:30 PM	60 min	Capstone Sprint — team design & implementation	System integration
1:30 PM	30 min	Capstone presentations — 10 min per team (management briefing format)	Professional communication
2:00 PM	30 min	Instructor debrief, individual reflection, workshop close	Synthesis

Materials — Full Workshop

Item	Qty / Team	Notes
O Scale operating layout (minimum 4×8 ft, with at least 3 distinct track sections / sidings)	1	Pre-built by instructor or model railroad club; should include at least one switch/turnout and one passing siding
O Scale locomotive (DCC or DC, reliable runner)	1	Diesel preferred — more visible mechanical action than steam
O Scale freight cars (assorted types, minimum 10)	10	Include boxcars, flatcars, hoppers — variety supports classification exercise
Stopwatch / phone timers	1 per team	For cycle time and throughput measurements
Digital kitchen scale (capacity 2 kg, 1g resolution)	1	For car weight measurement in engineering economics session
Tape measure and ruler	1 each per team	For workstation dimension measurement (human factors)
Sticky notes (3 colors: yellow, pink, green)	2 pads each per team	For VSM waste identification exercise
A3 / 11×17 paper (for VSM drawing)	4 sheets per team	Landscape orientation; teams draw current-state and future-state VSM
Markers (thick, 4 colors)	1 set per team	For VSM drawing
Engineering logbooks (quad-ruled, bound)	1 per student	Professional documentation practice — kept by student throughout
Printed data collection worksheets (one per session)	1 set per student	Provided by instructor; see each session
Laptop or tablet with spreadsheet software	1 per team	For queueing calculations and economic analysis
Index cards (for poka-yoke design exercise)	20 per team	Session 3 error-proofing prototyping
Small whiteboard or flip chart	1 per team	For team scratchpad during capstone sprint

DAY 1 · SESSION 1

The Railroad as a System

Systems Thinking, Value Stream Mapping & Waste Identification

Duration	75 minutes
IE/SE Threads	Systems Thinking · Lean Manufacturing · Value Stream Mapping (VSM) · Toyota Production System waste taxonomy
ABET Outcomes	(1) Formulate and solve problems; (3) Communicate effectively; (6) Conduct experiments and analyze data
Key Concepts	System boundary, value-added vs. non-value-added activity, the 8 wastes (TIMWOODS), current-state VSM, future-state VSM, cycle time, lead time, process efficiency
Driving Question	Where does value actually get created in this railroad system — and where is time, energy, and capacity being wasted?
Industry Link	Union Pacific, BNSF, and CSX all use lean process mapping derived from Toyota Production System principles to optimize car dwell time, locomotive utilization, and crew efficiency

Instructor Background

Value Stream Mapping was developed by Toyota and popularized in the US by Womack and Jones's "Lean Thinking" (1996). It is now standard practice in railroad operations: Class I railroads publish metrics including car dwell time (average time a freight car sits idle between movements), velocity (network miles per day), and train speed — all of which are direct VSM outputs. The Association of American Railroads (AAR) publishes these metrics weekly. Students will observe, measure, and map the model layout's value stream before proposing improvements.

Real Railroad Context: In 2023, the AAR reported average freight car dwell times of 22–26 hours across Class I railroads. Industry analysis suggests 60–70% of that dwell time is non-value-added (waiting in yards, waiting for crews, waiting for locomotive availability). The model layout exhibits the same waste patterns in miniature — and improvements students identify mirror real railroad efficiency initiatives.

Session 1 Sequence

Phase 1: System Boundary Definition (10 min)

Before observing anything, teams formally define their system:

1. Draw a rectangle on A3 paper. Label: SYSTEM BOUNDARY.
2. Identify and list all INPUTS entering the system boundary (cars to be moved, locomotive, crew, electrical power, instructions/waybills).
3. Identify all OUTPUTS leaving the system (cars delivered to destination track, cycle time consumed, energy used).

4. Identify all EXTERNAL ACTORS that interact with the system but are outside it (the "customer" — define who receives value; the "supplier" — define where cars originate).

This step is non-negotiable: systems thinking begins with boundary definition. A team that cannot define the system boundary cannot analyze it rigorously.

Phase 2: Observation Run & Time Study (20 min)

The instructor runs a defined switching operation on the layout (e.g., move 4 cars from the yard track to 3 destination tracks, returning the locomotive to its starting position). Teams observe and record:

Activity Observed	Start Time	End Time	Value-Added? (Y/N/Maybe)
Locomotive traveling empty to pick up car			
Coupling locomotive to car			
Moving loaded car to destination			
Uncoupling at destination			
Locomotive returning empty			
Waiting (locomotive idle, no task)			
Re-doing a missed coupling (defect rework)			

After the run, teams calculate:

- Total cycle time (first movement to last car delivered)
- Value-added time (only activities that directly move a car to its destination)
- Process Efficiency = Value-Added Time / Total Cycle Time × 100%

> **Benchmark:** World-class manufacturing processes target process efficiency of 25–40%. Most processes before improvement run at 5–15%. What does your railroad score? How does it compare to AAR-published Class I railroad metrics?

Phase 3: Waste Identification using TIMWOODS (20 min)

The 8 wastes of lean (TIMWOODS) apply directly to railroad operations. Teams use sticky notes (one waste per note) to identify every instance of waste observed:

Letter	Waste Type	Railroad / Layout Example	Observed Instance (team fills in)
T	Transportation	Locomotive traveling empty between switching moves	

I	Inventory	Cars waiting in yard with no movement plan	
M	Motion	Crew walking to remote switch panel instead of DCC	
W	Waiting	Locomotive idle while operator reads waybills	
O	Overproduction	Pulling 5 cars when only 3 are needed this cycle	
O	Over-processing	Coupling/uncoupling the same car multiple times	
D	Defects	Derailment requiring re-do; missed coupling attempt	
S	Skills (unused)	Operator knowledge of better switch sequence not applied	

Phase 4: Current-State VSM Drawing (15 min)

Using standard VSM iconography (process boxes, inventory triangles, push arrows, information flows), teams draw a current-state VSM of the switching operation on A3 paper. Required elements:

- Customer demand box (upper right): how many cars must be delivered per cycle?
- Supplier box (upper left): where do cars originate?
- Process boxes for each major activity, labeled with: cycle time (CT), value-added time (VAT), and operator count
- Inventory triangles between each process with count and wait time
- Information flow arrow showing how the operator knows what to do (waybill, verbal instruction, DCC command)
- Timeline at the bottom: lead time (top) vs. value-added time (bottom) — the gap is waste

Phase 5: Future-State VSM & Kaizen Bursts (10 min)

Teams identify the top 3 improvements and draw a future-state VSM showing the system after improvements. Each improvement is marked with a "kaizen burst" (starburst symbol) on the VSM. For each improvement, teams estimate:

- Reduction in cycle time (seconds)
- Change in process efficiency (percentage points)
- Implementation difficulty (Low / Medium / High)

Systems Thinking Synthesis: Ask teams: "If you implemented your highest-impact improvement, what would change elsewhere in the system? Would the bottleneck move? Would a downstream process become overloaded?" This introduces the concept of local vs. global optimization — a key systems engineering insight that students will formalize in Session 2.

Session 1 Assessment

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
System Boundary	All inputs, outputs, and external actors correctly identified; boundary is precise and defensible; distinction between system and environment is clear	Most elements correct; one input or output missed; boundary mostly clear	System boundary drawn but several elements missing; customer/supplier not distinguished	System boundary not defined; observation begun without formal framing
Time Study & Process Efficiency	All activities timed accurately; value-added classification correctly applied to all; process efficiency calculated correctly with formula shown	Most activities timed; 1–2 value-added classification errors; efficiency calculated	Activities timed but value-added classification inconsistent; efficiency calculated with errors	Time study incomplete; process efficiency not calculated
TIMWOODS Analysis	All 8 waste types identified with at least one specific layout example each; observations linked to real railroad industry examples	6–7 waste types identified with specific examples; 1–2 generic or missing	4–5 waste types identified; examples are generic; no industry connection	Fewer than 4 waste types; examples unclear or incorrect
VSM Drawing Quality	Current-state VSM has all required elements; standard iconography used; timeline shows lead time vs. value-added time gap; future-state shows 3 improvements with kaizen bursts	Current-state complete; future-state shows 2 improvements; iconography mostly correct	Current-state mostly complete; future-state missing or has only 1 improvement	VSM is a flowchart; standard iconography not used; no timeline
Quantified Improvement	Each future-state improvement has a specific, calculated estimate of time	2 of 3 improvements quantified; difficulty rated	1 improvement quantified; others descriptive only	No quantification of improvements

	saved and efficiency gain; implementation difficulty rated and justified			

DAY 1 · SESSION 2

Flow, Throughput & Queueing

Little's Law, Bottleneck Analysis & Takt Time

Duration	90 minutes
IE/SE Threads	Queueing Theory · Bottleneck Analysis · Theory of Constraints (TOC) · Throughput Analysis · Takt Time
ABET Outcomes	(1) Formulate and solve problems; (6) Design and conduct experiments, analyze and interpret data
Key Concepts	Little's Law, arrival rate (λ), service rate (μ), utilization (ρ), queue length (Lq), waiting time (Wq), takt time, drum-buffer-rope, throughput accounting
Required Math	Algebra; basic statistics (mean, standard deviation); ratio and proportion; optional: M/M/1 queueing formulas for advanced teams
Driving Question	Why does the yard always seem to back up even when the locomotive seems busy? Where exactly is the constraint — and what happens to the whole system when we fix it?

Instructor Background

Little's Law ($L = \lambda W$, published by John D.C. Little in 1961) is arguably the most useful equation in operations research. It applies to any stable system — manufacturing, healthcare, transportation, computing — and requires no assumptions about arrival distributions or service time distributions. It is universally valid. Railroad operations are a natural queueing system: cars (customers) arrive at yards (servers) at some rate λ, receive service (switching, classification, inspection), and depart at rate μ. When λ approaches μ, utilization $\rho \to 1$ and queue lengths grow unboundedly.

Industry Application: Union Pacific's "Unified Plan 2020" (UP2020) was a precision scheduled railroading (PSR) initiative directly grounded in queueing theory principles. By reducing car dwell time (W in Little's Law) from 26 hours to 21 hours, UP reduced total cars-in-system (L) by nearly 20% — freeing thousands of cars for redeployment without purchasing new equipment. The financial impact exceeded $500M in efficiency gains.

Theoretical Framework

Little's Law

$$L = \lambda \times W$$

Where: L = average number of items in the system (cars on layout); λ = average arrival rate (cars entering the switching queue per minute); W = average time each item spends in the system (car dwell time, minutes). Students measure all three and verify the relationship holds.

Utilization & Queue Build-Up

$$\rho = \lambda / \mu \quad \text{[utilization, must be < 1 for stable system]}$$
$$L_q = \rho^2 / (1 - \rho) \quad \text{[M/M/1: average queue length]}$$
$$W_q = \rho / (\mu - \lambda) \quad \text{[M/M/1: average waiting time in queue]}$$

As $\rho \rightarrow 1$ (system approaches 100% utilization), Lq and Wq grow without bound. This is why a railroad yard that is "busy 95% of the time" has massive backlogs — the math guarantees it. Students observe this directly by increasing car arrival rate until the yard overloads.

Takt Time

$$\text{Takt Time} = \text{Available Production Time} / \text{Customer Demand}$$

Takt time defines the rhythm of production required to meet demand. If the customer requires 10 cars delivered in 60 minutes, takt time = 60/10 = 6 minutes per car. Every process step must be capable of completing in ≤ 6 minutes, or it is a bottleneck by definition.

Theory of Constraints — The 5 Focusing Steps

Eliyahu Goldratt's Theory of Constraints (TOC) provides a systematic process for improving throughput:

5. IDENTIFY the system's constraint (bottleneck).
6. EXPLOIT the constraint — get maximum throughput from it without capital investment.
7. SUBORDINATE everything else to the constraint — all other processes run at the constraint's pace.
8. ELEVATE the constraint — if steps 1–3 are insufficient, invest to increase constraint capacity.
9. REPEAT — once the constraint is broken, find the new constraint.

Students apply all five steps to the layout in Experiment 2B.

Session 2 Experiments

Experiment 2A — Little's Law Verification (25 min)

Teams run the layout in a defined configuration for 10 minutes. One team member counts and timestamps every car that enters the switching queue (arrival) and every car that is successfully delivered (departure). Calculate:

10. λ = total arrivals / 10 minutes
11. μ = total deliveries / 10 minutes
12. $\rho = \lambda / \mu$ (utilization)
13. L = average count of cars in system (count every 30 seconds, average the counts)
14. $W = L / \lambda$ (from Little's Law — predicted average dwell time)
15. Verify: measure actual average dwell time by tracking 5 individual cars from arrival to delivery. Compare measured W to Little's Law prediction. Calculate percent error.

Metric	Symbol	Measured	Calculation / Source

		Value	
Arrival rate	λ		Total arrivals ÷ 10 min
Service (delivery) rate	μ		Total deliveries ÷ 10 min
Utilization	ρ		λ ÷ μ
Avg. cars in system	L		Count every 30 sec; average
Predicted avg. dwell time	W		L ÷ λ (Little's Law)
Measured avg. dwell time	W_actual		Track 5 cars individually
Percent error	—		|W - W_actual| / W_actual × 100%

Experiment 2B — Bottleneck Identification & TOC (35 min)

Teams redesign the layout operation to simulate a multi-stage production system with 3 process stages:

- Stage 1 — Classification: locomotive sorts incoming cars by type (all boxcars to Track A, all hoppers to Track B, all flatcars to Track C). Measure cycle time per car.
- Stage 2 — Inspection: one team member physically inspects each car for a defined defect (a colored sticker on the underside = defective). Inspect and record. Measure time per car.
- Stage 3 — Delivery: locomotive delivers approved cars to the final destination track in the correct sequence. Measure time per car.

Teams measure cycle time for each stage across 10 cars. Calculate:

- Stage utilization for each stage assuming takt time = (slowest stage cycle time)
- System throughput = 1 / (slowest stage cycle time) — identify the bottleneck
- Apply TOC Step 2 (exploit): what can the team do immediately, without new equipment, to speed up the bottleneck stage?
- Implement the improvement and re-measure. Calculate throughput increase.
- Apply TOC Step 3 (subordinate): adjust the non-bottleneck stages to feed the bottleneck at exactly its rate. Observe the effect on work-in-process (cars waiting between stages).

> **Drum-Buffer-Rope Connection:** In TOC, the bottleneck is the drum (it sets the beat), the buffer is inventory placed just before the bottleneck to prevent it from starving, and the rope is the communication signal that limits release of new work into the system to match the drum rate. Have students identify the drum, buffer, and rope in their layout operation.

Experiment 2C — Takt Time Analysis (20 min)

The instructor announces a "customer demand": 8 cars must be delivered within 20 minutes. Teams calculate takt time, then evaluate whether each stage is capable of meeting takt time. For any stage that cannot meet takt time:

16. Calculate the capacity gap: how many additional seconds of capacity are needed per car?

17. Propose a specific countermeasure (additional operator, process simplification, parallel processing).
18. Estimate the countermeasure's cost in time, effort, and any capital required.
19. Re-run the simulation with the countermeasure implemented. Did throughput meet takt time? If not, why?

Session 2 Assessment

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Little's Law Verification	All metrics correctly measured and calculated; percent error < 15%; deviation explained by specific system characteristics (variable service time, batch arrivals)	All metrics calculated; percent error 15–30%; general explanation offered	λ, μ, L measured; W calculated; no comparison to measured dwell time	Little's Law formula stated but not verified experimentally
Bottleneck Identification	Bottleneck correctly identified using cycle time data; supported by utilization calculation; TOC Steps 1–3 explicitly applied and documented	Bottleneck correctly identified; TOC Steps 1–2 applied; Step 3 partially applied	Bottleneck identified by observation rather than data; TOC referenced but not formally applied	Bottleneck not correctly identified; no quantitative support
Throughput Improvement	Improvement implemented and measured; throughput increase quantified; new bottleneck location identified after improvement	Improvement implemented; throughput increase measured; new bottleneck not identified	Improvement proposed and implemented; throughput change not measured	Improvement proposed but not implemented or measured
Takt Time Analysis	Takt time correctly calculated; all stages evaluated against takt; capacity gap quantified for constrained stages; countermeasures proposed with	Takt time correct; stages evaluated; capacity gap calculated for one stage; countermeasure proposed	Takt time calculated; stages evaluated qualitatively; no quantified capacity gap	Takt time formula stated but not applied to specific stages

	cost estimates			
Statistical Rigor	All measurements repeated minimum 3 times; mean and standard deviation reported; confidence interval stated; outliers identified and treated appropriately	Mean and standard deviation reported for primary metrics; outliers noted	Mean reported; no standard deviation; no repeated measures	Single measurement taken for each metric; no statistical analysis

DAY 2 · SESSION 3

Human Factors & Workstation Design

Ergonomics, Cognitive Load, Error Analysis & Poka-Yoke

Duration	90 minutes
IE/SE Threads	Human Factors & Ergonomics · Cognitive Engineering · Error Analysis (SHERPA / FMEA) · Poka-Yoke (Error-Proofing) · Workstation Design
ABET Outcomes	(1) Formulate problems; (4) Professional and ethical responsibilities; (5) Team effectiveness; (6) Experiment design and data analysis
Key Concepts	Anthropometric data, reach envelope, cognitive load, situation awareness, human error taxonomy (slips, lapses, mistakes, violations), SHERPA, poka-yoke types (contact, fixed-value, motion-step)
Driving Question	This layout was designed for the equipment — but was it designed for the human operator? How does workstation design affect error rate, fatigue, and throughput?
Industry Link	Cab ergonomics is a regulated discipline in the railroad industry. FRA regulations (49 CFR Part 229) specify minimum cab dimensions, control reach distances, display visibility, and noise levels. Poorly designed locomotive cabs are directly linked to operator fatigue and accidents.

Instructor Background

Human factors engineering (HFE) addresses the fit between human capabilities and system demands. In the railroad industry, the consequences of human error can be catastrophic: the 2008 Chatsworth collision (25 deaths) was caused by an engineer distracted by text messages — a failure of attention management and system design that failed to alert the operator. Modern positive train control (PTC) systems are, at their core, human factors engineering solutions: they provide a technological backup for human cognitive limitations.

> **Ethical Dimension:** Engineers who design systems operated by humans bear a professional responsibility to design for human capability, not assume human infallibility. This session explicitly raises the ethical obligation: when an operator makes an error on a poorly designed system, how much responsibility lies with the designer vs. the operator? This connects directly to ABET Outcome (4).

Session 3 Sequence

Phase 1: Anthropometric Workstation Analysis (20 min)

Teams measure the existing layout workstation (the area where the operator stands to control the layout) against published anthropometric standards. Using a tape measure, record:

Measurement	Actual (in)	Standard (in)	Compliant? / Gap

Standing work surface height (top of layout fascia)		34–38	
Maximum forward reach to farthest control		24 (5th %ile female)	
Maximum lateral reach to farthest switch		18	
Clear floor space for operator stance		24 × 36 min.	
Control panel viewing angle from operator eye height		15–45° below horizontal	
Aisle width behind operator (egress clearance)		28 min.	

Teams calculate the percentage of the user population (using standard normal distribution tables) that can reach the farthest control given the measured maximum reach distance. This directly applies their probability and statistics coursework.

Phase 2: Human Error Analysis using SHERPA (25 min)

Systematic Human Error Reduction and Prediction Approach (SHERPA) is a task analysis method that identifies potential human errors for each step in a task. Teams apply SHERPA to the car switching task from Sessions 1 and 2.

For each task step, teams classify potential error types:

- Action errors: wrong action performed (e.g., throwing wrong switch)
- Checking errors: check not performed or performed incorrectly (e.g., not verifying track is clear)
- Retrieval errors: information recalled incorrectly (e.g., wrong destination track remembered)
- Communication errors: instruction misunderstood or not received (e.g., waybill misread)
- Selection errors: wrong item selected (e.g., wrong car coupled)

Task Step	Error Type	Error Description	Consequence	Proposed Recovery / Poka-Yoke
Read waybill for next car				
Couple locomotive to car				
Throw switch for destination track				
Move car to destination				
Uncouple at destination				
Return loco to ready				

position				

Phase 3: Poka-Yoke Design Sprint (25 min)

Poka-yoke (mistake-proofing) is a technique for preventing errors by making incorrect actions impossible or immediately obvious. There are three types:

- Contact method: physical or electrical detection of incorrect condition (e.g., a limit switch that detects if a switch is thrown before the locomotive has cleared)
- Fixed-value method: ensures a fixed number of actions are completed (e.g., a checklist with physical checkboxes that must be marked before proceeding)
- Motion-step method: ensures the correct sequence is followed (e.g., a system that physically cannot proceed to step 3 until step 2 is confirmed)

Teams select the top 2 errors from their SHERPA analysis and design a poka-yoke solution for each. They prototype the solution using index cards, tape, and available materials, then implement and test it during a live switching run. Record:

- Error type targeted
- Poka-yoke type (contact / fixed-value / motion-step)
- Implementation description and materials
- Test results: did the error still occur? How many attempts before error was prevented?
- Operator reaction: did the poka-yoke slow down normal operations? By how much?

Design Trade-off Discussion: Poka-yoke solutions that prevent errors often slow down the process. This is a fundamental design trade-off in human factors engineering: reliability vs. speed. Teams quantify this trade-off: if the poka-yoke adds 5 seconds per cycle but prevents a 90-second recovery from an error that occurs 1 in 10 cycles, is it net positive? Calculate the expected time per cycle with and without the poka-yoke. This is a direct application of expected value from their probability course.

Phase 4: Cognitive Load & Situation Awareness Assessment (10 min)

Teams run the switching operation under two conditions: (A) normal operation with waybills; (B) added cognitive load — the operator must simultaneously track and verbally report the current DCC speed step every 15 seconds. Record error rate and cycle time for both conditions.

Calculate:

- Error rate (errors per car) under each condition
- Cycle time increase due to cognitive loading (%)
- Connect to Endsley's Situation Awareness model (Level 1: Perception; Level 2: Comprehension; Level 3: Projection) — which SA level was degraded by the added cognitive load?

Session 3 Assessment

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
Anthropometric Analysis	All 6 measurements taken; each compared to published standard; population percentile calculated for reach distance using z-score; compliance gaps quantified	All measurements taken; most compared to standard; reach percentile estimated	4–5 measurements taken; comparisons made without standard reference cited	Measurements taken without comparison to standards; no percentile calculation
SHERPA Analysis	All 6 task steps analyzed; error type correctly classified for each; consequences identified; all entries are specific and credible	5 of 6 steps analyzed; classifications mostly correct; consequences identified	3–4 steps analyzed; some classifications incorrect; consequences vague	SHERPA table partially completed; error types not correctly classified
Poka-Yoke Design	Two poka-yokes designed, implemented, and tested; type correctly classified; expected value calculation performed; trade-off quantified; test results reported	Two poka-yokes designed and implemented; expected value calculated; one type misclassified	One poka-yoke designed and implemented; no expected value calculation	Poka-yoke concept described but not implemented or tested
Ethical Reasoning	Team clearly articulates designer responsibility vs. operator responsibility using specific examples from SHERPA analysis; references a real railroad accident in which design contributed to error	Team articulates designer responsibility with one specific example; references real-world context	Team discusses ethics generally without connecting to specific analysis findings	Ethics discussion is generic; not connected to human factors or specific findings
Cognitive Load	Error rate and	Error rate and	Measurements	Only one

Experiment	cycle time measured for both conditions; statistical comparison performed (t-test or confidence interval); SA level correctly identified and explained	cycle time measured; comparison performed; SA level identified	taken; comparison is visual rather than statistical	condition measured; no comparison performed

DAY 2 · SESSION 4

Engineering Economics & Decision Analysis

NPV, IRR, Life-Cycle Cost & Make-vs-Buy

Duration	90 minutes
IE/SE Threads	Engineering Economics · Decision Analysis · Life-Cycle Costing · Make-vs-Buy Analysis · Sensitivity Analysis
ABET Outcomes	(1) Formulate and solve problems; (2) Engineering design with constraints; (3) Written communication; (6) Analyze and interpret data
Key Concepts	Time value of money, Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period, Life-Cycle Cost (LCC), Break-Even Analysis, sensitivity analysis, decision trees, make-vs-buy criteria
Required Math	Algebra; geometric series (annuity formulas); basic spreadsheet skills; expected value from probability
Driving Question	You have identified three improvements from Sessions 1–3. You have a budget of $5,000 and must choose which improvement to fund. Which investment delivers the greatest return — and how confident are you in that conclusion?

Instructor Background

Engineering economics is the formal framework for evaluating capital investment decisions under constraints. Every improvement identified in Sessions 1, 2, and 3 has an associated cost (implementation) and benefit (throughput increase, error reduction, labor savings). The systems engineer's job is to prioritize these investments rigorously rather than intuitively. In the railroad industry, capital allocation decisions (new locomotives vs. track maintenance vs. yard technology vs. crew scheduling software) routinely involve NPV and IRR analysis across multi-decade planning horizons.

> **Industry Scale:** BNSF Railway spends approximately $3.5 billion per year on capital expenditures. Each major investment — new locomotives, positive train control, intermodal terminals — is supported by a formal Net Present Value analysis comparing projected cash flows over 20–30 year asset life cycles. The analytical tools students apply in this session are identical to those used in BNSF's capital planning department.

Theoretical Framework

Time Value of Money — Core Formulas

$$\text{Future Value:}\quad FV = PV \times (1 + i)^n$$

$$\text{Present Value:}\quad PV = FV / (1 + i)^n$$

$$NPV = \Sigma\, [C_t / (1+i)^t] - C_0 \quad [\text{sum from } t=1 \text{ to } n]$$

$$\text{Payback Period} = \text{Initial Investment} / \text{Annual Net Cash Flow}$$

$$\text{Break-Even:}\quad Q^* = \text{Fixed Cost} / (\text{Revenue per unit} - \text{Variable Cost per unit})$$

Where: PV = present value; FV = future value; i = discount rate (MARR — Minimum Attractive Rate of Return); n = number of periods; C_t = net cash flow in period t; C_0 = initial investment.

Life-Cycle Cost Analysis

```
LCC = C_acquisition + C_operating + C_maintenance + C_disposal - C_salvage
```

All costs discounted to present value. A lower acquisition cost does not necessarily mean lower LCC. Students calculate LCC for two alternative DCC system configurations and discover that the cheaper upfront system may have higher total cost over a 10-year operating life.

Session 4 Case Studies

Case Study 4A — Investment Prioritization (30 min)

Teams are presented with the three improvements identified in earlier sessions, with cost and benefit data provided (or estimated from their own observations):

Improvement Option	Initial Cost ($)	Annual Benefit ($)	Life (yrs)	MARR (%)	NPV (calculate)
A: DCC Upgrade (eliminate manual switching errors)	1,800	420	10	8	
B: Ergonomic Fascia Redesign (reduce operator fatigue errors)	650	180	7	8	
C: Automated Car Identification System	3,200	750	12	8	

For each option, teams calculate:

20. NPV using the annuity present value factor: $PV = A \times [(1-(1+i)^{-n})/i]$
21. Payback Period
22. IRR (estimated by trial and error or spreadsheet IRR function)
23. Rank the three options. Which maximizes NPV? Which has shortest payback? Do they agree?
24. Budget constraint: if the budget is $4,000, which combination of investments maximizes total NPV? (This is a 0/1 knapsack problem — an integer programming concept introduced conceptually.)

Case Study 4B — Make vs. Buy Analysis (20 min)

The team must decide whether to build a custom car classification system in-house (using team labor and purchased components) or purchase a commercial alternative.

Factor	Make (In-House)	Buy (Commercial)
Development / Acquisition Cost	$800 (40 hrs × $20/hr)	$1,200
Annual Operating Cost	$50 (maintenance parts)	$150 (software subscription)
Annual Support Cost	$200 (in-house labor)	$0 (vendor included)
Risk of Failure	High (first build)	Low (proven product)
Customizability	Full	Limited
Time to Implement	8 weeks	2 weeks
Strategic Advantage	Builds internal capability	No internal learning

Teams calculate 5-year LCC for each option, weight the non-quantifiable factors using a weighted scoring model (assign weights and scores to risk, customizability, strategic advantage), and make a final recommendation with stated assumptions and sensitivity analysis.

Case Study 4C — Sensitivity Analysis & Decision Under Uncertainty (20 min)

NPV calculations depend on assumed values (annual benefit, discount rate, asset life) that are uncertain. Sensitivity analysis asks: "How much would our conclusion change if a key assumption is wrong?"

Teams perform a one-at-a-time (OAT) sensitivity analysis on the top-ranked investment from Case Study 4A:

25. Vary the annual benefit by ±20%, ±40%. At what benefit level does NPV = 0 (break-even)?
26. Vary the MARR from 5% to 15% in 2.5% steps. Plot NPV vs. MARR. Identify the IRR (MARR at which NPV = 0).
27. Vary asset life from the assumed value ±2 years. How sensitive is the NPV to asset life?
28. Construct a tornado diagram: rank the three variables by their impact on NPV. Which assumption matters most? Which matters least?

> **Decision Rule:** A well-reasoned engineering economics recommendation always states: (1) the recommended alternative; (2) the assumptions under which it is preferred; (3) the conditions under which a different alternative would be preferred; and (4) the key risks. Students must include all four elements in their written recommendation.

Session 4 Assessment

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
NPV / IRR Calculations	All three NPV calculations correct using annuity formula; IRR found for top alternative;	All NPVs correct; IRR found; payback calculated; ranking present but	NPVs calculated with minor arithmetic errors; payback calculated; no IRR	NPV formula stated but not correctly applied; payback only

	payback calculated; ranking addresses disagreements between metrics	disagreements not discussed		
Make vs. Buy Analysis	5-year LCC calculated for both options; weighted scoring model includes at least 4 factors with justified weights; recommendation states assumptions and limitations	LCC calculated; weighted scoring with 3 factors; recommendation present but assumptions not stated	LCC calculated without present value discounting; scoring model present; recommendation made	Make vs. buy comparison is qualitative only; no LCC calculation
Sensitivity Analysis	All three variables tested over specified ranges; break-even point identified for annual benefit; NPV vs. MARR plotted; tornado diagram constructed and interpreted	Two variables tested; break-even found; NPV vs. MARR plotted; no tornado diagram	One variable tested; no break-even; no graphical output	Sensitivity analysis described but not performed
Written Recommendation	Recommendation includes all four required elements; assumptions stated quantitatively; switch conditions specified; risks ranked by impact	Recommendation includes 3 of 4 elements; assumptions stated; risks mentioned	Recommendation clear but lacks assumption statement or risk discussion	Recommendation stated without supporting analysis or conditions
Budget Optimization	Correctly identifies the NPV-maximizing portfolio subject to budget constraint; recognizes this as an integer problem; considers at least 3 feasible combinations	Identifies correct portfolio; considers 2 combinations	Selects highest-NPV single investment; does not consider combinations	Does not apply budget constraint to portfolio selection

CAPSTONE · SESSION SPRINT

System Redesign Sprint

Integrating All Four IE Threads into a Management-Ready Recommendation

Duration	90 minutes total: 60 min design sprint + 30 min presentations (10 min per team)
Format	Teams receive a new client scenario they have NOT seen before; all deliverables produced in the sprint window
Deliverables	(1) Revised Current-State VSM with quantified waste; (2) Throughput and bottleneck analysis with Little's Law; (3) Top 2 human error risks with poka-yoke solutions; (4) Investment recommendation with NPV for top improvement; (5) 10-minute management briefing presentation
Presentation Format	Management briefing style: team presents to "executive panel" (instructor + invited guests); strict 10-minute limit; 5-minute Q&A; professional communication is assessed

Capstone Client Brief

> **Client Brief — Pocono Valley Short Line Railroad:** The Pocono Valley Short Line serves three industrial customers: a coal preparation plant (6 cars per day), a lumber yard (4 cars per day), and a cement distributor (3 cars per day). Operations currently run 8 hours per day with one locomotive and a 2-person crew. The railroad's general manager has requested a Systems Engineering Assessment addressing: (1) current process efficiency and primary waste sources; (2) throughput capacity and the location of the primary constraint; (3) the top 2 human error risks and recommended error-proofing solutions; and (4) a prioritized list of capital improvements with NPV analysis, ranked by return, within a $10,000 capital budget. The general manager needs a 10-minute briefing suitable for presentation to the railroad's board of directors.

Capstone Scoring

Criterion	4 – Exemplary	3 – Proficient	2 – Developing	1 – Beginning
VSM & Waste Analysis	Current-state VSM complete with timeline; process efficiency calculated; top 3 wastes quantified (time or cost); future-state improvements identified with estimated impact	VSM complete; process efficiency calculated; top 3 wastes identified but not quantified	VSM present; process efficiency calculated; wastes listed without quantification	VSM incomplete or missing; process efficiency not calculated
Throughput & Queueing	Little's Law applied with all	Little's Law applied;	Little's Law stated;	Throughput discussed

	three variables estimated or calculated; bottleneck identified with quantitative support; TOC Steps 1–3 applied; takt time calculated for stated demand	bottleneck identified; takt time calculated; TOC Steps 1–2 applied	bottleneck identified qualitatively; takt time calculated	without applying Little's Law or TOC framework
Human Factors	Top 2 errors identified using SHERPA taxonomy; poka-yoke type specified for each; expected value calculation determines net benefit; ethical responsibility addressed	2 errors identified; poka-yoke solutions proposed; expected value calculated; ethics mentioned	2 errors identified; solutions proposed; no expected value or ethics discussion	1 error identified; no formal poka-yoke design; no expected value
Economic Analysis	NPV calculated for at least 2 improvements; IRR or payback calculated; budget-constrained portfolio selected; sensitivity of top recommendation demonstrated	NPV for 2 improvements; payback calculated; portfolio selected within budget	NPV for 1 improvement; portfolio selection made without budget optimization	Economic analysis is qualitative; no NPV calculations
Management Briefing	Briefing is within time limit; professional tone and format; all four IE threads clearly represented; findings supported by specific numbers; Q&A answered confidently with reference to data	Briefing within time; professional; all four threads present; most claims supported by numbers; Q&A mostly answered	Briefing within time; 3 of 4 threads present; some numerical support; some Q&A answered	Over time or under time by >2 min; fewer than 3 threads; minimal numerical support; Q&A not answered

Appendix A — IE/SE Concept Quick Reference

Concept	Formula / Tool	Layout Application
Process Efficiency	VA Time / Total Lead Time × 100%	Ratio of car-moving time to total cycle time
Little's Law	$L = \lambda \times W$	Cars in system = arrival rate × average dwell time
Utilization	$\rho = \lambda / \mu$	Fraction of time locomotive is actively working
Takt Time	Available Time / Demand	Minutes per car to meet the daily delivery requirement
NPV	$\Sigma\ C_t/(1+i)^t - C_0$	Present value of throughput improvement over asset life
Payback Period	C_0 / Annual Benefit	Years to recover investment in DCC or ergonomic upgrade
LCC	Acquisition + Operating + Maintenance − Salvage	Total cost of a DCC system or switch machine over 10 years
Break-Even	Fixed Cost / (Revenue − Variable Cost)	Cars per year needed to justify investment in automation
Poka-Yoke (Contact)	Physical detection device	Limit switch detecting switch position before locomotive moves
Poka-Yoke (Fixed-Value)	Count enforcement	Checklist: 6 waybills processed before shift closes
TIMWOODS	8-waste taxonomy	T=empty loco travel; W=loco idle; D=derailment rework; etc.
SHERPA	Task × Error Type matrix	Systematic error prediction for each switching task step

Appendix B — Suggested Reading & Industry Resources

- Womack & Jones, "Lean Thinking" (1996) — foundational VSM and waste elimination theory
- Goldratt, "The Goal" (1984) — Theory of Constraints as a novel; highly readable for sophomores
- Little, J.D.C. (1961), "A Proof for the Queuing Formula: $L = \lambda W$" — Operations Research 9(3), 383–387 — the original paper; one page
- Endsley, M.R. (1995), "Toward a Theory of Situation Awareness in Dynamic Systems" — Human Factors 37(1) — SA model foundation
- Park, C.S., "Fundamentals of Engineering Economics" (4th ed.) — recommended IE economics textbook reference
- AAR Weekly Railroad Traffic & Performance Reports — free at railroads.org/rail-traffic — real λ, W, L data for Class I railroads

- FRA Safety Data (safety.fra.dot.gov) — human error causes of railroad accidents; real SHERPA source material

Appendix C — Role Descriptions (Rotate Each Session)

Role	Responsibilities	Skills Practiced
Timekeeper	Manages all timing; calls start/stop; tracks cycle times; ensures team stays on schedule	Time management, data accuracy, professional coordination
Data Recorder	Records all measurements in engineering logbook; maintains data table; calculates metrics	Technical documentation, quantitative accuracy, attention to detail
Process Observer	Watches layout operations; identifies waste, errors, and improvement opportunities; does not operate equipment	Observation skills, systems thinking, critical analysis
Operator	Controls the locomotive and switches during experiments; follows process exactly as defined (no improvisation)	Procedural discipline, manual control, awareness of human factors in own performance
Analyst / Reporter	Leads quantitative analysis; prepares team's debrief slides or summary; speaks for team during presentations	Quantitative reasoning, synthesis, professional communication

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O Scale Systems & Industrial Engineering Workshop
Sophomore Systems & Industrial Engineering Workshop | O Scale Model Railroading