

Choose the Greener Route: Combining the Best of Three Process Designs

Learning target: I can analyze mass data from three ways of making the same product, check each against criteria and constraints, identify the strongest feature of each design, and combine those features into a new route that sends more reactant atoms into useful products.

Transfer and design

About 45 min

Pairs

MS-ETS1-3 · assesses

MS-ETS1-2 · practice

MS-PS1-5 · supports

engineering design

data analysis

writing

Standards connections

MS-ETS1-3 (assesses, analyzing test data from several designs to combine their best characteristics): Students compare simulated batch data from three process routes, identify which characteristic of each performs best against the criteria, and design a combined route whose predicted performance they calculate. This is the PE's task as written. The code is listed for grades 6-8 in the California sequence and is paired with this lesson's engineering spread.

MS-ETS1-2 (practice): Checking each route against the same criteria and constraints in a table is the systematic evaluation this PE describes; here it is a step toward the combination task rather than the final product.

MS-PS1-5 (supports): The mass accounting only works because atoms are conserved: reactant mass in must equal product plus by-product plus waste out. Students verify that sum for each route before judging efficiency, but the atom model itself is background here.

Purpose: extend · **Time:** about 45 minutes · **Format:** pairs

Answers with reasoning

The design brief — Every batch must make **200 kg of Product P**. The plant manager wants the route that wastes the fewest atoms, because every kilogram of waste costs money to dispose of and ends up in a landfill. **Criteria** (what a good route does): makes 200 kg of P per batch; sends as much reactant mass as possible into useful products; costs no more than **\$850 per batch**; sends no more than **80 kg per batch** to the landfill. **Constraints** (limits you cannot change): the plant has room for at most five reaction steps; adding a capture tank to collect a by-product costs **\$40 per batch** extra; a catalyst must be recovered after each batch or it becomes waste.

Substance Q is a by-product: a substance that forms along with P in some routes. Q is not P, but another factory will buy Q as a reactant for its own process. In Routes A and B, Q is currently thrown away with the other waste. In Route C, Q is captured in a tank and sold. A catalyst is a substance that helps a reaction happen but is not used up, so it can be recovered and used again.

Test batches for three routes to Product P (teaching dataset)

Simulated teaching dataset: the numbers are invented to be realistic, not measured.

Route	Reaction steps	Reactants in (kg)	Product P out (kg)	By-product Q out (kg)	Other waste out (kg)	Q captured and sold?	Cost per batch (\$)
A: original route (no catalyst)	6	500	200	0	300	no Q is made	900
B: catalyst route	3	260	200	50	10	no, Q is thrown away	700
C: capture route (no catalyst)	5	340	200	110	30	yes, captured	800

Simulated data for teaching. Masses are per batch. 'Other waste' means everything that is not P and not Q. In Route B, the catalyst is recovered and is not counted in any column.

How to measure efficiency — Efficiency here means the percentage of the reactant mass that ends up in useful products: $\text{efficiency} = (\text{mass of useful products} \div \text{mass of reactants in}) \times 100$. Count P as useful always. Count Q as useful only if it is captured and sold; Q that is thrown away is waste. This works because atoms are conserved: every reactant atom ends up in P, in Q or in other waste, so the three 'out' columns must add up to the 'in' column.

Part A: Check the data and compute efficiency

1. For each route, add P out + Q out + other waste out and compare the sum with reactants in. Show all three sums. What law says these must match, and why?

Answer: Route A: $200 + 0 + 300 = 500 \text{ kg} = 500 \text{ kg in}$. Route B: $200 + 50 + 10 = 260 \text{ kg} = 260 \text{ kg in}$. Route C: $200 + 110 + 30 = 340 \text{ kg} = 340 \text{ kg in}$. The law of conservation of matter: atoms are not created or destroyed in a reaction, so every reactant atom ends up in one of the products or in the waste, and the masses out must add up to the mass in.

Why: The check establishes that the dataset is internally consistent and that efficiency is really a question of where the atoms go. Students must name the law and the atom reason.

Also acceptable: Accept 'mass in equals mass out because atoms are conserved.'

2. Calculate the efficiency of each route counting only P as useful. Show each division and round to the nearest whole percent.

Answer: Route A: $200 \div 500 = 0.400 \rightarrow 40\%$. Route B: $200 \div 260 = 0.769 \rightarrow 77\%$. Route C: $200 \div 340 = 0.588 \rightarrow 59\%$.

Why: Counting only P, the catalyst route wins because it needs the least reactant mass to make the same 200 kg of P.

Also acceptable: Accept 76.9% and 58.8% unrounded.

3. Now count captured Q as useful. Which route's efficiency changes? Calculate its new efficiency. Explain in one sentence why the other two routes do not change.

Answer: Only Route C changes, because it is the only route that captures and sells Q. Route C: $(200 + 110) \div 340 = 310 \div 340 = 0.912 \rightarrow 91\%$. Route A makes no Q, and Route B throws its Q away, so their useful-product mass is unchanged.

Why: This is the lesson's key engineering move: a by-product that is used is no longer waste, so the same atoms now count as useful.

Also acceptable: Accept 91.2%.

4. Calculate the landfill mass per batch for each route. Landfill mass = all waste that is not sold. (Careful: in Route B, is Q landfilled?)

Answer: Route A: 300 kg (no Q, all other waste). Route B: 50 kg of Q + 10 kg other = 60 kg, because Route B's Q is thrown away. Route C: 30 kg (Q is sold, so only the other waste is landfilled).

Why: The trap is Route B: its Q is made but not captured, so it is landfill. Students who write 10 kg for Route B have missed the 'Q captured and sold?' column.

Also acceptable: None; the Route B value must be 60 kg.

Part B: Judge each route against the criteria

5. Complete the table with yes/no and numbers. Then circle the route that meets the most criteria and constraints.

Answer: Route A: 200 kg yes; \$900 no; 300 kg landfill no; 40%; 6 steps no. Route B: yes; \$700 yes; 60 kg yes; 77%; 3 steps yes. Route C: yes; \$800 yes; 30 kg yes; 91%; 5 steps yes. Circle: Route B and Route C both meet every yes/no criterion and constraint; Route C has the higher efficiency and lower landfill, Route B the lower cost and fewer steps. Either may be circled with that explanation; Route A fails three.

Why: Routes B and C each pass all the yes/no checks, which is exactly why the combination question matters: neither dominates the other on the numbers.

Also acceptable: Accept either B or C circled if the student notes the other also passes.

- All fifteen cells correct
- Route A identified as failing cost, landfill and steps
- Circled route justified

6. No single route is best at everything. For each of Routes B and C, name the one characteristic that performs best (the thing it does better than the other routes) and the data that show it. Then say what Route A tells you even though it fails.

Answer: Route B's best characteristic: the catalyst, which cuts the route to 3 steps and needs only 260 kg of reactants for 200 kg of P (the least of the three), giving the lowest cost (\$700). Route C's best characteristic: capturing and selling Q, which turns 110 kg of would-be waste into a useful product and gives the lowest landfill (30 kg) and the highest efficiency (91%). Route A fails, but it shows the baseline: without a catalyst or capture, 300 of every 500 kg of reactant atoms become waste, so it tells you how much the other two features are worth.

Why: The PE asks students to identify the best characteristic of each design from the data; the answer must tie each feature to numbers.

Also acceptable: Accept 'lowest cost' as B's feature if the student connects it to the catalyst and fewer steps.

- Catalyst (or fewest steps and least reactant mass) named for B with data
- Q capture named for C with data
- Route A used as a baseline

Part C: Design the combined route

7. Design Route D by combining the best characteristic of Route B with the best characteristic of Route C. Describe Route D in two sentences. Then predict its numbers per batch, assuming the reaction data do not change: reactants in, P out, Q captured, landfill mass, number of steps, cost (remember the capture tank), and efficiency counting captured Q. Show every calculation.

Answer: Route D: use Route B's three-step catalyst route, and add Route C's capture tank so that the Q made in Route B is collected and sold instead of thrown away. Predicted numbers, using Route B's reaction data: reactants in 260 kg; P out 200 kg; Q captured 50 kg; landfill = other waste only = 10 kg; steps 3; cost \$700 + \$40 capture tank = \$740; efficiency counting captured Q = $(200 + 50) \div 260 = 250 \div 260 = 0.962 \rightarrow 96\%$. Conservation check: $200 + 50 + 10 = 260$ kg.

Why: Combining the catalyst (fewest reactant atoms needed) with capture (the by-product atoms become useful) beats both: 96% versus 91% for C and 77% for B; 10 kg landfill versus 30 and 60; \$740 versus \$800 and \$700.

Also acceptable: Accept 96.2%. A student who also proposes checking how completely the catalyst is recovered has gone beyond the data; credit the idea but keep the predicted numbers as above.

8. Write your recommendation to the plant manager. State which route to build, compare Route D's efficiency, landfill mass and cost with the best single route using your numbers, explain why combining two solutions beat each one alone, and connect the result to the law of conservation of matter: where do the atoms that used to become waste go now?

Answer: Model response: Build Route D, the catalyst route with a capture tank for Q. Route D is predicted to send 96% of reactant mass into useful products, compared with 91% for Route C, the best single route, and 77% for Route B. It sends only 10 kg per batch to the landfill, against 30 kg for C and 60 kg for B, and costs \$740, under the \$850 limit and below C's \$800. It uses 3 steps, well inside the 5-step limit. Combining beat each route alone because the two features fix different problems: the catalyst reduces how many reactant atoms are needed in the first place, and the capture tank rescues the atoms that still end up in Q. Neither route had both. Atoms are conserved, so the atoms that Route B used to send to the landfill as Q do not disappear in Route D; they go into the tank and then to the factory that uses Q as a reactant. Efficiency went up not because fewer atoms exist, but because more of the same atoms now end up somewhere useful.

Why: Full credit requires a clear recommendation, three numerical comparisons with the best single route, an explanation of why the features combine rather than compete, and the conservation connection that waste atoms are redirected, not eliminated.

Also acceptable: A student who recommends Route C because its numbers are measured while D's are predicted has made a defensible engineering argument; credit the reasoning if the comparison numbers are correct and the student says what test would justify switching to D.

- Recommends Route D
- Compares efficiency, landfill and cost with numbers against the best single route
- Explains that the two features solve different problems
- Uses conservation of matter: the former waste atoms now go into a useful product

9. Name two things that could make the real Route D perform worse than your prediction, and say what test you would run before building the full-size plant.

Answer: Any two: the capture tank might not collect all 50 kg of Q (some could escape or be contaminated); the catalyst might not be fully recovered each batch, and any lost catalyst becomes waste and must be replaced, adding cost; the buyer might pay less for Q than expected or stop buying; adding the tank might change the reaction conditions and the P output. Test: run several small pilot batches of Route D and measure the actual P, Q and waste masses and the cost before building the full plant; compare the measured efficiency with the predicted 96%.

Why: The predicted numbers assume the reaction data do not change; a pilot test is the standard check before scaling up.

Also acceptable: Accept 'the data are simulated; real batches vary' as one reason if paired with a specific test.

- Two realistic reasons
- A pilot or small-scale test proposed with what would be measured

Scoring rubric

Criterion	4 • Exemplary	3 • Proficient	2 • Developing	1 • Beginning
Data analysis and calculations	All conservation sums, efficiencies and landfill masses correct with work shown; Route B's thrown-away Q correctly counted as landfill.	One calculation error or one missing step of work; the Route B landfill trap is handled correctly.	Several errors, or Route B's Q counted as useful or omitted from landfill.	Calculations missing or unrelated to the data.

Evaluation against criteria and constraints	Criteria table complete and correct; the best characteristic of each route is identified with the data that show it; Route A is used as a baseline.	Table correct; best characteristics named but with thin data support.	Table has errors, or routes are ranked by one criterion only.	No systematic comparison.
Combined design	Route D combines the catalyst and the capture tank; all predicted numbers correct including the \$40 tank cost and the 96% efficiency; conservation sum checked.	Correct combination; one predicted number wrong (often the cost without the tank or Q left out of efficiency).	Combination named but numbers not predicted, or a 'combination' that is just one route renamed.	No combined design.
Justification	Recommendation compares three numbers with the best single route, explains why the two features combine rather than compete, and uses conservation of matter to say where the former waste atoms go.	Recommendation with numbers, but the conservation connection or the why-combining-works explanation is missing.	Recommendation with a general reason and no numbers.	No recommendation or one contradicted by the data.

Teacher notes

The routes, substances and numbers are fictional and labeled as a teaching dataset; they are patterned on the lesson's ibuprofen story (a six-step route near 40 percent, a three-step catalytic route near 77 percent, and a by-product recovered as a useful product), but the chapter's accuracy notes apply: the textbook's own figures are inconsistent (75 versus 77 percent) and its history is simplified, so this sheet does not claim to reproduce it. Efficiency here is defined as the share of reactant mass that becomes useful product, which is what chemists call atom economy; it is a mass-accounting quantity, not a reaction speed and not the yield of a real batch. Expected numbers: efficiencies 40, 77, 59 (P only) and 91 for C with Q; landfill 300, 60, 30 kg; Route D 96 percent, 10 kg landfill, \$740. The most common error is counting Route B's Q as useful or forgetting that it is landfilled. No atomic masses are used anywhere; the conservation check uses only the given masses, which keeps MS-PS1-5 in a supporting role.

Scaffold offered to students: A worked line for Route A

Route A, step by step. Conservation check: $200\text{ kg} + 0\text{ kg} + 300\text{ kg} = 500\text{ kg}$, which equals the 500 kg of reactants in, so the data obey the law. Efficiency counting P only: $200 \div 500 = 0.40$, which is 40 percent. Landfill: Route A makes no Q, so everything that is not P goes to the landfill: 300 kg. Criteria: 200 kg of P, yes; cost \$900, which is more than \$850, no; landfill 300 kg, which is more than 80 kg, no. Do the same four steps for Routes B and C, and watch Route B's Q: it is made but thrown away, so it counts as landfill and not as useful product.

Extension: What if Q loses its buyer?

Suppose the factory that buys Q closes, so Q can no longer be sold. Recalculate Route D's efficiency and landfill mass with Q counted as waste, and decide whether Route D still beats Route B. Then propose a Route E: a change that would use Q inside your own plant (for example, as a reactant in one of your own steps) and explain, using atoms, why reusing a by-product inside the plant has the same effect on efficiency as selling it. Finally, explain why 100 percent efficiency is the ceiling and what it would mean for the waste column.