

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

Name _____

Date _____

Period _____

Directions

You are a junior engineer at a company that makes Product P, an ingredient in sunscreen. Three routes to P have been tested. The batch data are a teaching dataset, invented to be realistic; the routes and substances are fictional. Read the brief, the criteria and constraints, and the data. Work through the questions in order: first check that the data obey the law of conservation of matter, then calculate efficiency, then judge each route, then design the combined route and justify it. Show every calculation with units. Work with a partner on the calculations, but write your justification yourself.

You will need: This worksheet, Pencil, Calculator

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?

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

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.

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?)

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.

Makes 200 kg of P?	Cost $\leq$ \$850?	Landfill $\leq$ 80 kg?	Efficiency (useful products, %)	Steps $\leq$ 5?
Route A				
Route B				
Route C				

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.

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.

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?

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.

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.

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.