

Excavation, metallurgy, manufacturing and quality control on Mars

Move from a geological resource to a usable part: excavate, separate, transform, manufacture, measure and qualify without pretending that a 3D printer is an entire industrial base.

Before starting — Prerequisites: modules 00 to 28 are recommended depending on the topic. Every important symbol is defined at first use.

Mastery objectives

- explain quantities, units, assumptions and uncertainty
- repeat simple calculations without a black box
- identify interfaces, limits and degraded modes
- turn the result into an operational or architecture decision

1. A resource is not yet a construction material

Martian regolith contains minerals, but a scoop of soil is not directly a beam, wire or pressure vessel. Material must be characterized, excavated, transported, separated, processed and then verified.

Every step has yield. Low concentration or contamination can multiply energy demand. Industrial design should start from the required final product and work backward to the raw tonnage that must be handled.

2. Excavation: production, traction and wear

Terrestrial excavators use vehicle mass to create traction. Reduced gravity changes that logic. Counter-rotating drums and other architectures aim to reduce reaction forces. On Mars, abrasive dust, temperature and maintenance may matter as much as nominal bucket capacity.

The useful metric is kilograms delivered to the process per available hour, not volume moved during one ideal demonstration.

3. Beneficiation and separation

Before metallurgy, feedstock can be concentrated by particle size, density, magnetism or chemistry. Beneficiation reduces the amount of material that must be heated or chemically processed.

A Mars plant must remain maintainable. Gaining a few percent purity with a machine that cannot be repaired may be a poor trade.

4. Metallurgy: energy, atmosphere and waste

Producing metal requires breaking chemical bonds, melting or reducing oxides and controlling process atmosphere. Energy demand can dominate. Metallurgy also creates slag, gases, dust and waste heat that must be integrated into the industrial habitat.

The product then needs composition and microstructure appropriate to its use. Approximate local metal may serve as ballast but not necessarily as a pressure part or engine component.

5. Additive and subtractive manufacturing

Additive manufacturing deposits or fuses material layer by layer. It can reduce tooling and enable complex shapes, but it does not eliminate machining, heat treatment or inspection. Critical surfaces and tolerances may still require subtractive finishing.

The real question is not “can we print the part?” but “can we produce a part whose properties, dimensions and defects are known and acceptable?”

6. Metrology: measure before you trust

Metrology is the science of measurement. A Mars base needs standards, calibration procedures and ways to verify dimensions, mass, temperature, pressure and electrical quantities. Without traceability, two workshops can make nominally identical parts that do not fit.

Measurement instruments also drift. Cross-checks and stable references are therefore part of industrial resilience.

7. Qualifying a locally made part

A critical part should be traceable to material lot, manufacturing parameters, operator or robot, machine, measurements and tests. Qualification may use visual and dimensional inspection, penetrant, ultrasound, radiography or material coupons depending on risk.

Not every part requires the same evidence. Criticality classes reserve expensive verification for functions where failure threatens crew or mission.

8. Worked example: work backward from final demand to raw tonnage

A base needs 500 kg of a material. Useful ore is 12% of excavated mass. Separation recovers 80% of that fraction and metallurgical conversion yields 70%. Overall yield is $0.12 \times 0.80 \times 0.70 = 0.0672$.

Required raw mass is $500 / 0.0672 \approx 7,440$ kg. A small upstream yield loss can therefore multiply excavation and power requirements.

9. Mass balance: distinguish contained resource from recovered resource

A common mistake is to treat the quantity of a resource contained in feedstock as the quantity a plant can actually deliver. Extraction chains always have losses: material not excavated, water remaining bound in solids, imperfect condensation, leakage, purge or off-specification product.

Teaching assumption. A unit processes mass $M = 1,000$ kg of regolith. The assumed water mass fraction is $f = 5\%$, or 0.05. The theoretical contained water is $M_{\text{water,th}} = M \times f = 1,000 \times 0.05 = \mathbf{50 \text{ kg}}$. We multiply because 5% means five hundredths of the total mass.

Now assume total recovery efficiency $\eta = 70\%$, or 0.70. Recovered water is $M_{\text{water,rec}} = M_{\text{water,th}} \times \eta = 50 \times 0.70 = \mathbf{35 \text{ kg}}$. The remaining 15 kg have not been “destroyed”; in this simplified model they represent resource that does not reach the product tank.

Operational translation. If a settlement needs 350 kg of recovered water, ten identical batches are required in this model, meaning 10,000 kg of regolith processed. The next engineering question is not another decimal place but how much energy, machine time, wear parts and storage capacity those ten tonnes require.

Progressive exercise

Repeat with 15% grade, 75% recovery and 85% metallurgical yield to produce 1,200 kg. Also calculate energy if the process requires 8 kWh per kilogram of final product.

Reasoned correction

The fraction of feed that becomes final product is $0.15 \times 0.75 \times 0.85 = 0.095625$. Producing 1,200 kg therefore requires about $1,200 / 0.095625 = 12,549$ kg of incoming material, roughly 12.55 tonnes. At 8 kWh per kilogram of final product, process energy is 9,600 kWh, or 9.6 MWh. This excludes excavation, crushing, pumping, auxiliary heating, maintenance and storage. The calculation mainly shows why grade, recovery and metallurgical yield multiply: modest losses at each stage can sharply increase both mined mass and energy demand.

Mini-project

Design a Mars micro-factory for non-pressure hardware: excavation, sorting, feedstock, manufacturing, machining, metrology, quality control, waste storage, maintenance and criteria for deciding that a part must still come from Earth.

From raw ground to a part you are willing to trust

A Mars settlement does not obtain useful hardware simply because useful elements exist in the regolith. The industrial chain begins with excavation, but every later step can lose material, consume energy or introduce defects. A realistic production plan therefore follows one kilogram of desired finished product backward through machining or additive manufacturing, metallurgical yield, beneficiation recovery and ore grade. This reverse view prevents a common mistake: sizing a mine from the mass of the final part instead of from the much larger mass of material that must be handled upstream.

Industrial autonomy is also a quality problem. A locally produced bracket may have the right shape and still fail because its alloy chemistry, porosity, heat treatment, surface condition or dimensional tolerance is wrong. On Earth, these uncertainties are absorbed by mature supply chains, accredited laboratories and specialist subcontractors. On Mars, the settlement must decide which measurements are essential, which defects are acceptable, what can be repaired, and which components remain too safety-critical for local production until the process is qualified.

The engineering objective is not maximum local production at any price. It is a controlled progression from low-consequence items toward more demanding parts. Early workshops can make fixtures, covers, ducts, tools and replacement geometry while importing bearings, seals, sensors and high-performance alloys. As metrology, feedstock control and process knowledge improve, the boundary of local manufacture can move. That boundary should be evidence-driven rather than ideological.

Four industrial ideas that connect the whole chain

Ore grade

Ore grade is the fraction of the excavated feed that contains the desired resource or mineral. A deposit containing 12% useful mineral does not yield 120 kg of finished product from each tonne of soil, because separation and downstream processing are never perfect. Grade is therefore only the first multiplier in the mass balance.

Recovery

Recovery measures how much of the desired material present in the feed is actually captured by a separation or extraction step. Losses can leave valuable material in tailings, dust, slag or process water. Recovery must be measured on the real feed and operating conditions, not copied from an optimistic laboratory value.

Process yield

Process yield is the fraction of material entering a manufacturing or metallurgical step that emerges as acceptable product. Cutting chips, rejected prints, oxidation, machining allowance and failed heat treatment all reduce yield. Some losses can be recycled, but recycling still consumes handling time and energy.

Traceability

Traceability connects a finished part to its feedstock batch, process parameters, machine, operator or software revision, inspections and any rework. Without traceability, a later failure cannot be linked to a cause and the settlement cannot know which apparently identical parts may share the same defect.

Calculation laboratory

Formula 1 — raw feed required for a target mass

Canonical quantitative mini-lessons

This block is the module quantitative reference; exercise values are pedagogical and must be replaced by mission data before any real decision.

Required raw mass

$$M_{\text{raw}} = M_{\text{product}} / (\text{grade} \times \text{recovery} \times \text{yield_proc})$$

1 — Concrete question

What does “ $M_{\text{raw}} = M_{\text{product}} / (\text{grade} \times \text{recovery} \times \text{yield_proc})$ ” compute in “Required raw mass”?

2 — Intuition without symbols

Working backward from final product to raw feed requires accounting for every loss in the chain.

3 — Quantities

M_{raw} : raw mass to process [kg]; M_{product} : qualified product mass [kg]; grade: useful grade [sans dimension];
recovery: process recovery [sans dimension]; yield_proc: manufacturing yield [sans dimension]

4 — Formula

$$M_{\text{raw}} = M_{\text{product}} / (\text{grade} \times \text{recovery} \times \text{yield_proc})$$

5 — Read aloud

Read “ $M_{\text{raw}} = M_{\text{product}} / (\text{grade} \times \text{recovery} \times \text{yield_proc})$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

M_{raw} : raw mass to process [kg]; M_{product} : qualified product mass [kg]; grade: useful grade [sans dimension];
recovery: process recovery [sans dimension]; yield_proc: manufacturing yield [sans dimension]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

M_{raw} [kg]; M_{product} [kg]; grade [sans dimension]; recovery [sans dimension]; yield_proc [sans dimension]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $M_{\text{product}} = 100$ kg, grade = 0.2 sans dimension, recovery = 0.8 sans dimension, yield_proc = 0.9 sans dimension: $M_{\text{raw}} = 100 / (0.2 \times 0.8 \times 0.9) = 694.44$ kg.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Size excavation and storage for raw mass, not just finished product mass.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $M_{\text{product}} = 50$ kg, grade = 0.1 sans dimension, recovery = 0.7 sans dimension, yield_proc = 0.8 sans dimension: $M_{\text{raw}} = 50 / (0.1 \times 0.7 \times 0.8)$?

Detailed guided correction — open after trying

With $M_{\text{product}} = 50$ kg, grade = 0.1 sans dimension, recovery = 0.7 sans dimension, yield_proc = 0.8 sans dimension: $M_{\text{raw}} = 50 / (0.1 \times 0.7 \times 0.8) = 892.86$ kg. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $M_{\text{product}} = 200$ kg, grade = 0.25 sans dimension, recovery = 0.85 sans dimension, yield_proc = 0.95 sans dimension: $M_{\text{raw}} = 200 / (0.25 \times 0.85 \times 0.95)$?

Autonomous correction — open after trying

With $M_{\text{product}} = 200$ kg, grade = 0.25 sans dimension, recovery = 0.85 sans dimension, yield_proc = 0.95 sans dimension: $M_{\text{raw}} = 200 / (0.25 \times 0.85 \times 0.95) = 990.71$ kg. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Size excavation and storage for raw mass, not just finished product mass.

Contained resource

$$M_{\text{contained}} = M_{\text{raw}} \times \text{grade}$$

1 — Concrete question

What does " $M_{\text{contained}} = M_{\text{raw}} \times \text{grade}$ " compute in "Contained resource"?

2 — Intuition without symbols

Grade converts raw mass into theoretically available material before recovery losses.

3 — Quantities

$M_{\text{contained}}$: contained useful mass [kg]; M_{raw} : raw mass [kg]; grade: useful grade [sans dimension]

4 — Formula

$$M_{\text{contained}} = M_{\text{raw}} \times \text{grade}$$

5 — Read aloud

Read " $M_{\text{contained}} = M_{\text{raw}} \times \text{grade}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

$M_{\text{contained}}$: contained useful mass [kg]; M_{raw} : raw mass [kg]; grade: useful grade [sans dimension]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$M_{\text{contained}}$ [kg]; M_{raw} [kg]; grade [sans dimension]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate, fraction or specific quantity into a total.

11 — Assumptions

Factors must belong to the same scenario and their units must combine correctly.

12 — Independent check

Dividing the result by a non-zero factor should recover the product of the others.

13 — Numerical case

With $M_{\text{raw}} = 500$ kg, grade = 0.2 sans dimension: $M_{\text{contained}} = 500 \times 0.2 = 100$ kg.

14 — Why the calculation works

Multiplication converts a rate, fraction or specific quantity into a total.

15 — Verification

Dividing the result by a non-zero factor should recover the product of the others.

16 — Mental estimate

Estimating each factor separately quickly predicts product scale.

17 — Interpretation

Do not confuse contained resource with resource actually recoverable.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

A relative change in one factor transfers directly to the product when the others stay fixed.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $M_{\text{raw}} = 800$ kg, grade = 0.12 sans dimension: $M_{\text{contained}} = 800 \times 0.12$?

Detailed guided correction — open after trying

With $M_{\text{raw}} = 800$ kg, grade = 0.12 sans dimension: $M_{\text{contained}} = 800 \times 0.12 = 96$ kg. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $M_{\text{raw}} = 1000$ kg, grade = 0.3 sans dimension: $M_{\text{contained}} = 1000 \times 0.3$?

Autonomous correction — open after trying

With $M_{\text{raw}} = 1000$ kg, grade = 0.3 sans dimension: $M_{\text{contained}} = 1000 \times 0.3 = 300$ kg. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Do not confuse contained resource with resource actually recoverable.

Recovered mass

$M_{\text{recovered}} = M_{\text{contained}} \times \text{recovery}$

1 — Concrete question

What does “ $M_{\text{recovered}} = M_{\text{contained}} \times \text{recovery}$ ” compute in “Recovered mass”?

2 — Intuition without symbols

Recovery applies actual process efficiency to the material present in feedstock.

3 — Quantities

$M_{\text{recovered}}$: recovered mass [kg]; $M_{\text{contained}}$: contained mass [kg]; recovery: recovery fraction [sans dimension]

4 — Formula

$M_{\text{recovered}} = M_{\text{contained}} \times \text{recovery}$

5 — Read aloud

Read “ $M_{\text{recovered}} = M_{\text{contained}} \times \text{recovery}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

$M_{\text{recovered}}$: recovered mass [kg]; $M_{\text{contained}}$: contained mass [kg]; recovery: recovery fraction [sans dimension]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

$M_{\text{recovered}}$ [kg]; $M_{\text{contained}}$ [kg]; recovery [sans dimension]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate, fraction or specific quantity into a total.

11 — Assumptions

Factors must belong to the same scenario and their units must combine correctly.

12 — Independent check

Dividing the result by a non-zero factor should recover the product of the others.

13 — Numerical case

With $M_{\text{contained}} = 100$ kg, recovery = 0.8 sans dimension: $M_{\text{recovered}} = 100 \times 0.8 = 80$ kg.

14 — Why the calculation works

Multiplication converts a rate, fraction or specific quantity into a total.

15 — Verification

Dividing the result by a non-zero factor should recover the product of the others.

16 — Mental estimate

Estimating each factor separately quickly predicts product scale.

17 — Interpretation

Compare recovered mass with production demand before committing a processing campaign.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

A relative change in one factor transfers directly to the product when the others stay fixed.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $M_{\text{contained}} = 96$ kg, recovery = 0.75 sans dimension:
 $M_{\text{recovered}} = 96 \times 0.75$?

Detailed guided correction — open after trying

With $M_{\text{contained}} = 96$ kg, recovery = 0.75 sans dimension: $M_{\text{recovered}} = 96 \times 0.75 = 72$ kg. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $M_{\text{contained}} = 300$ kg, recovery = 0.9 sans dimension:
 $M_{\text{recovered}} = 300 \times 0.9$?

Autonomous correction — open after trying

With $M_{\text{contained}} = 300$ kg, recovery = 0.9 sans dimension: $M_{\text{recovered}} = 300 \times 0.9 = 270$ kg. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Compare recovered mass with production demand before committing a processing campaign.

Process energy

$$E_{\text{process}} = e_{\text{spec}} \times M_{\text{product}}$$

1 — Concrete question

What does “ $E_{\text{process}} = e_{\text{spec}} \times M_{\text{product}}$ ” compute in “Process energy”?

2 — Intuition without symbols

Specific energy turns production mass into total energy demand.

3 — Quantities

E_{process} : process energy [kWh]; e_{spec} : specific energy [kWh/kg]; M_{product} : produced mass [kg]

4 — Formula

$$E_{\text{process}} = e_{\text{spec}} \times M_{\text{product}}$$

5 — Read aloud

Read “ $E_{\text{process}} = e_{\text{spec}} \times M_{\text{product}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

E_{process} : process energy [kWh]; e_{spec} : specific energy [kWh/kg]; M_{product} : produced mass [kg]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

E_{process} [kWh]; e_{spec} [kWh/kg]; M_{product} [kg]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate, fraction or specific quantity into a total.

11 — Assumptions

Factors must belong to the same scenario and their units must combine correctly.

12 — Independent check

Dividing the result by a non-zero factor should recover the product of the others.

13 — Numerical case

With $e_{\text{spec}} = 12$ kWh/kg, $M_{\text{product}} = 100$ kg: $E_{\text{process}} = 12 \times 100 = 1200$ kWh.

14 — Why the calculation works

Multiplication converts a rate, fraction or specific quantity into a total.

15 — Verification

Dividing the result by a non-zero factor should recover the product of the others.

16 — Mental estimate

Estimating each factor separately quickly predicts product scale.

17 — Interpretation

Verify process energy can be supplied without degrading life-critical loads.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

A relative change in one factor transfers directly to the product when the others stay fixed.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $e_{\text{spec}} = 8 \text{ kWh/kg}$, $M_{\text{product}} = 50 \text{ kg}$: $E_{\text{process}} = 8 \times 50$?

Detailed guided correction — open after trying

With $e_{\text{spec}} = 8 \text{ kWh/kg}$, $M_{\text{product}} = 50 \text{ kg}$: $E_{\text{process}} = 8 \times 50 = 400 \text{ kWh}$. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $e_{\text{spec}} = 20 \text{ kWh/kg}$, $M_{\text{product}} = 200 \text{ kg}$: $E_{\text{process}} = 20 \times 200$?

Autonomous correction — open after trying

With $e_{\text{spec}} = 20 \text{ kWh/kg}$, $M_{\text{product}} = 200 \text{ kg}$: $E_{\text{process}} = 20 \times 200 = 4000 \text{ kWh}$. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Verify process energy can be supplied without degrading life-critical loads.

Processing time

$$t_{\text{process}} = M_{\text{raw}} / q_{\text{feed}}$$

1 — Concrete question

What does “ $t_{\text{process}} = M_{\text{raw}} / q_{\text{feed}}$ ” compute in “Processing time”?

2 — Intuition without symbols

Feed rate converts raw tonnage into campaign duration.

3 — Quantities

t_{process} : processing time [h]; M_{raw} : raw mass [kg]; q_{feed} : feed rate [kg/h]

4 — Formula

$$t_{\text{process}} = M_{\text{raw}} / q_{\text{feed}}$$

5 — Read aloud

Read “ $t_{\text{process}} = M_{\text{raw}} / q_{\text{feed}}$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

t_{process} : processing time [h]; M_{raw} : raw mass [kg]; q_{feed} : feed rate [kg/h]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

t_{process} [h]; M_{raw} [kg]; q_{feed} [kg/h]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $M_{\text{raw}} = 500 \text{ kg}$, $q_{\text{feed}} = 25 \text{ kg/h}$: $t_{\text{process}} = 500 / 25 = 20 \text{ h}$.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

Include availability, maintenance and cleaning before promising calendar completion.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $M_{\text{raw}} = 800$ kg, $q_{\text{feed}} = 40$ kg/h: $t_{\text{process}} = 800 / 40$?

Detailed guided correction — open after trying

With $M_{\text{raw}} = 800$ kg, $q_{\text{feed}} = 40$ kg/h: $t_{\text{process}} = 800 / 40 = 20$ h. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $M_{\text{raw}} = 1200$ kg, $q_{\text{feed}} = 60$ kg/h: $t_{\text{process}} = 1200 / 60$?

Autonomous correction — open after trying

With $M_{\text{raw}} = 1200$ kg, $q_{\text{feed}} = 60$ kg/h: $t_{\text{process}} = 1200 / 60 = 20$ h. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

Include availability, maintenance and cleaning before promising calendar completion.

Quality yield

$$Y_{\text{quality}} = n_{\text{accepted}} / n_{\text{produced}}$$

1 — Concrete question

What does " $Y_{\text{quality}} = n_{\text{accepted}} / n_{\text{produced}}$ " compute in "Quality yield"?

2 — Intuition without symbols

Manufacturing is useful only when parts actually pass qualification criteria.

3 — Quantities

Y_{quality} : accepted fraction [sans dimension]; n_{accepted} : accepted parts [part]; n_{produced} : produced parts [part]

4 — Formula

$$Y_{\text{quality}} = n_{\text{accepted}} / n_{\text{produced}}$$

5 — Read aloud

Read " $Y_{\text{quality}} = n_{\text{accepted}} / n_{\text{produced}}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

Y_{quality} : accepted fraction [sans dimension]; n_{accepted} : accepted parts [part]; n_{produced} : produced parts [part]

7 — Pronunciation

Say subscripts, powers, parentheses and Greek letters explicitly so the relation can be reconstructed without seeing the page.

8 — Units

Y_{quality} [sans dimension]; n_{accepted} [part]; n_{produced} [part]

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division relates a quantity to a coherent capacity, duration or reference.

11 — Assumptions

Numerator and denominator must describe the same scenario and the denominator must remain positive.

12 — Independent check

Multiplying the result by the denominator should reconstruct the numerator.

13 — Numerical case

With $n_{\text{accepted}} = 92$ part, $n_{\text{produced}} = 100$ part: $Y_{\text{quality}} = 92 / 100 = 0.92$.

14 — Why the calculation works

Division relates a quantity to a coherent capacity, duration or reference.

15 — Verification

Multiplying the result by the denominator should reconstruct the numerator.

16 — Mental estimate

Comparing numerator and denominator scales predicts the result.

17 — Interpretation

A drop in quality yield should trigger process analysis before increasing volume.

18 — What the result does not prove

The calculation proves neither that inputs are exact nor that the model remains valid outside the declared scenario; both require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls as the denominator rises.

20 — Guided and autonomous exercises

Guided exercise. Recalculate this scenario: With $n_{\text{accepted}} = 45$ part, $n_{\text{produced}} = 50$ part: $Y_{\text{quality}} = 45 / 50$?

Detailed guided correction — open after trying

With $n_{\text{accepted}} = 45$ part, $n_{\text{produced}} = 50$ part: $Y_{\text{quality}} = 45 / 50 = 0.9$. The decision must then be checked against the module margins and assumptions.

Autonomous exercise. Recalculate this scenario: With $n_{\text{accepted}} = 180$ part, $n_{\text{produced}} = 200$ part: $Y_{\text{quality}} = 180 / 200$?

Autonomous correction — open after trying

With $n_{\text{accepted}} = 180$ part, $n_{\text{produced}} = 200$ part: $Y_{\text{quality}} = 180 / 200 = 0.9$. The decision must then be checked against the module margins and assumptions.

21 — Mission decision

A drop in quality yield should trigger process analysis before increasing volume.

Starting question

How much excavated feed must enter the chain to deliver a specified mass of acceptable product?

Read aloud

Say: “feed mass equals final mass divided by grade times recovery times yield.”

Symbols, pronunciation and meaning

m_{feed} is raw excavated mass; m_{final} is acceptable finished mass; g is ore grade; R is recovery; Y is downstream process yield.

Units

The two masses use the same mass unit, such as kilograms. Grade, recovery and yield are dimensionless fractions between zero and one.

Origin and status of values

Grade comes from sampling and assay; recovery from separation tests; yield from controlled production records. A training example must be labelled as such.

Why this operation

Multiplying the three fractions gives the fraction of raw feed that survives the full chain. Dividing by that fraction works backward to the required feed.

Substitution and calculation

For 100 kg final product, $g = 0.20$, $R = 0.80$ and $Y = 0.75$: $0.20 \times 0.80 \times 0.75 = 0.12$, then $100 / 0.12 = 833.3$ kg of raw feed.

Calculator entry

Enter $100 \div (0.20 \times 0.80 \times 0.75)$. Keep the parentheses so the denominator is evaluated as one chain efficiency.

Mental estimate

Only about one eighth of the feed survives, so the raw mass should be roughly eight times the final mass. 833 kg is consistent with that estimate.

Independent check

Multiply 833.3 kg by 0.12. Recovering about 100 kg confirms the arithmetic and the direction of the calculation.

Physical or operational interpretation

The result sizes excavation, haulage, crushers, separators and waste handling, not merely the final printer or machine tool.

Plain-English translation

In ordinary language: producing 100 kg of good material may require handling more than 800 kg of Martian feed under these assumptions.

Variation / sensitivity

If recovery rises from 0.80 to 0.90 while everything else stays constant, required feed falls to about 741 kg. Upstream improvements can therefore save large amounts of work.

Limit / assumption

The formula collapses several stages into one product of fractions. Real plants may have recycle loops, multiple products, variable grade and time-dependent availability.

Formula 2 — specific process energy to daily electrical demand

Starting question

What average electrical power is implied by a planned production mass and a known specific process energy?

Read aloud

Read: "average power equals mass times specific energy divided by operating time."

Symbols, pronunciation and meaning

m is processed mass, e is energy per unit mass, and t is the time over which that energy must be supplied.

Units

If e is in kilowatt-hours per kilogram, $m \times e$ is kilowatt-hours. Dividing by hours gives kilowatts.

Origin and status of values

Specific energy should come from test data for the actual process and material. It must include declared boundaries: furnace only, or furnace plus pumps, gas handling and auxiliaries.

Why this operation

The multiplication produces total energy for the batch; division distributes that energy across the available operating time.

Substitution and calculation

For 50 kg at 6 kWh/kg processed during 10 h: energy = $50 \times 6 = 300$ kWh; average power = $300 / 10 = 30$ kW.

Calculator entry

Type $50 \times 6 \div 10$. Check that the displayed unit is interpreted as kilowatts, not kilowatt-hours.

Mental estimate

A 300 kWh batch spread over ten hours should average a few tens of kilowatts, so 30 kW is plausible.

Independent check

Multiply 30 kW by 10 h; recovering 300 kWh verifies the time conversion.

Physical or operational interpretation

This average is a planning quantity. The electrical system may still need to survive much higher furnace start-up or heater peak loads.

Plain-English translation

The workshop needs about 30 kW continuously for ten hours to supply the stated batch energy, before other loads are added.

Variation / sensitivity

Doubling the allowed processing time halves average power but does not reduce total energy. That trade can be useful when solar or reactor capacity is constrained.

Limit / assumption

Thermal losses, idle periods and peak demand are hidden by the average. Power electronics and cables must be sized from the real load profile.

Mission reasoning: making local industry dependable rather than impressive

Excavation is a vehicle problem as much as a digging problem

Low gravity reduces weight but not mass. A loaded bucket still has inertia, while reduced normal force limits traction. Excavators therefore need anchoring, counter-rotation strategies, careful bucket geometry or slow cuts that respect available reaction force. Dust intrusion and abrasive grains can dominate wear. Production planning must include blade life, bearings, seals, cleaning and the time needed to recover a disabled machine.

Beneficiation deserves its own instrumentation

Separation is where the settlement can avoid heating or chemically processing useless mass. Screens, magnets, density methods or electrostatic separation may concentrate a target fraction before high-energy processing. The plant should measure feed rate, product grade and tailings composition so operators can see whether a change in soil or equipment condition is quietly destroying recovery.

Metallurgy couples chemistry to the power system

Reduction, melting and heat treatment require controlled temperature and atmosphere. A furnace schedule therefore belongs in the settlement energy plan. Gas purity, refractory life, slag composition and cooling capacity matter as much as nominal furnace temperature. If the power system enters a constrained mode, the safest response may be to delay a batch rather than interrupt it halfway and lose both material and hardware.

Manufacturing needs a route card, not only a CAD file

A digital geometry file does not specify feedstock condition, machine setup, layer strategy, cutting tool, post-processing, heat treatment or inspection. A route card records the sequence that turns material into a qualified part. When a process changes, the part may need requalification even if the geometry is unchanged. This discipline prevents undocumented workshop improvisation from entering safety-critical systems.

Quality control decides what can be trusted locally

Inspection should be proportional to consequence. A storage-bin handle may need only dimensional checks; a pressure fitting may require material verification, leak testing and non-destructive examination. The settlement should define acceptance criteria before production. Otherwise a team under schedule pressure can rationalize defects after the part already exists, which is the opposite of controlled qualification.

Workshop exercises — reason from material need to qualified hardware

Exercise A — Feed-mass chain

A crew needs 60 kg of acceptable metal. The useful fraction in the feed is 25%, separation recovery 70% and process yield 80%. Estimate the raw feed requirement and identify which parameter would be most valuable to improve first.

Reveal the reasoned solution

The combined fraction is $0.25 \times 0.70 \times 0.80 = 0.14$. Required feed is $60 / 0.14 \approx 429$ kg. Improving any multiplier helps, but the best engineering choice depends on cost. Raising grade through better beneficiation can reduce every downstream load; raising recovery can reduce tailings loss; raising yield can reduce remelt and machining waste. The calculation tells you sensitivity, not which modification is cheapest.

Exercise B — Power-window planning

A furnace batch needs 480 kWh. The settlement can allocate only 40 kW to industry during the daylight production window. Can the batch finish in eight hours?

Reveal the reasoned solution

At 40 kW for eight hours the available energy is 320 kWh, so the answer is no. The batch requires $480 / 40 = 12$ h at that average power. The operational choices are to extend the window, increase allocated power, split the process if metallurgy permits it, or reschedule another large load.

Exercise C — Inspection level

Classify three locally made items: a tool rack, an oxygen-line bracket and a pressure-vessel closure. Propose progressively stronger acceptance evidence.

Reveal the reasoned solution

The rack can usually be accepted by dimensions and visual inspection. The oxygen-line bracket deserves material identity, dimensions and load or proof evidence appropriate to its function. A pressure closure is higher consequence and should demand controlled material, process records, dimensional inspection, leak or pressure proof, and non-destructive examination where justified. The principle is consequence-based assurance.

Exercise D — Traceability break

A batch of printed pump housings cracks after installation, but the workshop did not record powder lot or heat-treatment cycle. What has been lost?

Reveal the reasoned solution

The settlement has lost the ability to bound the suspect population and correlate failures with a process cause. Every similar housing may now require inspection or replacement. Traceability would have allowed engineers to isolate one batch, one machine configuration or one heat-treatment excursion and learn from it.

Exercise E — Repair or remake

A machined sealing face is out of tolerance by 0.15 mm. Explain the questions that must be answered before rework.

Reveal the reasoned solution

First ask whether enough material remains for corrective machining, whether the repair changes geometry or strength, whether the sealing specification allows the new surface finish, and whether the repaired part can still be inspected against an approved acceptance criterion. Rework is an engineering process, not permission to make the drawing fit the part.

Exercise F — Process bottleneck

A plant can excavate 2 tonnes per day but the separator can accept only 1.2 tonnes and the furnace only 0.8 tonne. Which throughput controls finished production?

Reveal the reasoned solution

The furnace is the current bottleneck at 0.8 tonne per day before considering grade, recovery and yield. Increasing excavation alone would mostly build inventory. Capacity improvement should target the constraining stage or deliberately add buffer storage if a later expansion is planned.

Interactive beginner glossary

These terms form the minimum vocabulary for discussing a Martian production chain without confusing raw resources, processing performance and evidence of quality.

- ore grade — The proportion of a raw feed that contains the desired mineral, element or useful phase before recovery losses are considered.
- beneficiation — Physical or chemical preparation that concentrates a useful fraction and rejects unwanted material before more expensive processing.
- recovery — The fraction of desired material present in the feed that a process successfully captures in its intended product stream.
- tailings — Material rejected by a separation or extraction process; it may still contain unrecovered resource and must be handled safely.
- mass balance — An accounting method that tracks material entering, leaving, accumulating or being lost within a defined process boundary.
- process yield — The fraction of input material that becomes acceptable output after manufacturing, trimming, rejection and other losses.
- slag — A non-metallic by-product formed during many metallurgical operations and used to carry separated impurities away from metal.
- refractory — A heat-resistant lining or component used to protect furnaces and process vessels from high temperature and chemical attack.
- feedstock — Prepared material supplied to a manufacturing process, such as powder, wire, pellets, plate, bar or a concentrated mineral.
- additive manufacturing — Production by building geometry layer by layer from digital information rather than removing most material from a larger blank.
- subtractive manufacturing — Production by removing material through machining operations such as milling, turning, drilling or grinding.
- heat treatment — Controlled heating and cooling used to change microstructure, hardness, strength, ductility or residual stress in a material.
- metrology — The science and practice of measurement, including calibration, uncertainty, standards and traceability of measuring equipment.
- calibration — Comparison of an instrument against a known reference so its indication and uncertainty are understood.
- tolerance — The permitted variation around a specified dimension, property or performance value.
- surface finish — A description of the small-scale texture and condition of a manufactured surface that can affect sealing, wear and fatigue.
- porosity — Voids or pores inside a material; excessive porosity can reduce strength, leak tightness or fatigue life.
- non-destructive examination — Inspection that searches for defects without intentionally destroying the component being accepted for use.

- qualification — Evidence that a process, design or item can meet defined requirements under the conditions for which it is intended.
- acceptance test — A check performed on a particular delivered or manufactured item to decide whether it meets its release criteria.
- traceability — The recorded link from a finished item back to material batches, process settings, inspections, revisions and responsible operations.
- route card — A controlled record describing the manufacturing and inspection steps that a part must follow through the workshop.
- lot — A defined group of material or parts produced under common conditions and treated as one traceable population.
- rework — Controlled additional processing intended to bring a nonconforming item back into compliance with an approved requirement.
- repair — An approved action that restores usable function but may not return the item exactly to its original drawing condition.
- nonconformance — A documented condition in which a product, process or measurement fails to meet a specified requirement.
- scrap — Material or hardware removed from intended service because it cannot economically or safely be accepted, repaired or reworked.
- recycle loop — A process path that sends recoverable waste or off-cuts back into an earlier production stage instead of discarding them.
- specific energy — Energy required per unit of processed mass, often used to compare industrial process demand.
- industrial availability — The fraction of scheduled time during which a machine or process is capable of performing its required production function.

Operational depth: how a settlement grows an industrial capability

Start with consequence classes

Local manufacture should be introduced by consequence class. Low-risk hardware builds operator skill and exposes dust, calibration and software problems without threatening life support. Higher-consequence products are added only after the process demonstrates stability and the inspection system can detect the defects that matter.

Design products for the workshop you actually have

A Mars design should consider available machine envelope, tooling, inspection capability and feedstock. A part that is elegant on Earth may be impossible to make or verify locally. Design-for-manufacture can replace exotic geometry with modular pieces, accessible fasteners and tolerances that match the settlement metrology base.

Protect standards and reference artefacts

Calibration standards are infrastructure. If every measuring device drifts together, the workshop can produce consistent but wrong parts. Reference artefacts, redundant measurement methods and periodic cross-checks help detect that common-mode error. Sensitive standards also need thermal and contamination control.

Treat scrap as information

A rejected part is not merely wasted material. Its fracture, porosity, dimensional error or surface defect provides evidence about process health. Recording the failure and linking it to parameters can improve future yield. Melting scrap immediately may destroy the evidence before engineers understand why the part failed.

Separate production pressure from acceptance authority

The people responsible for meeting a schedule should not be able to erase an acceptance criterion because a part is urgently needed. A small settlement may not have independent departments, but it can still separate roles in procedure: one person produces, another reviews evidence, and deviations are explicitly authorized.

Plan the industrial chain as part of resilience

A workshop adds resilience only if it can function after the failures it is meant to mitigate. Spare printer nozzles, cutting tools, furnace controls, filters, lubricants and calibration gear are therefore part of the industrial spare strategy. A capability that depends on one irreplaceable imported component is not yet autonomous.

Operational review checklist

- Define the final part mass and consequence class before sizing the upstream process.
- Measure feed grade and process recovery rather than assuming laboratory values.
- Include waste, recycle loops and rejected product in the mass balance.
- Check both total process energy and peak electrical demand.
- Record material lot, machine configuration and process parameters for traceability.
- Declare tolerances and acceptance criteria before the part is manufactured.
- Match inspection method to the defect that could cause the relevant failure.
- Keep calibration references and measurement uncertainty under configuration control.
- Document rework or repair so later failures remain traceable.
- Expand local manufacturing only when production evidence and quality evidence mature together.

Primary sources and pathways

- [NASA JSC — In-Situ Resource Utilization](#)
- [NASA — Advanced Manufacturing Technologies](#)
- [NASA-STD-6030 — Additive Manufacturing Requirements for Spaceflight Systems](#)

FR ↔ EN parity matrix

Required raw mass	Masse brute nécessaire
Contained resource	Ressource contenue
Recovered mass	Masse récupérée
Process energy	Énergie de procédé
Processing time	Temps de traitement
Quality yield	Rendement qualité