

Waste, recycling and material loops



Conceptual visualization — waste becomes a resource only when collection, separation, processing, quality control and safe reuse all close the loop.

Turn settlement waste into characterized, separated and reusable material streams without confusing theoretical recycling with an operationally closed loop. Design for disassembly should therefore be treated as a material-loop requirement from the first hardware definition.

Before starting — review closed-loop ECLSS, local resources and Mars logistics because recycling performance is meaningless unless material quality and downstream use are understood. Every important symbol is defined at first use.

Mastery objectives

- map waste and recovered-material streams by composition, contamination state and intended reuse
- close material balances without confusing recovery yield with qualified reusable product
- define quality gates for recycled feedstock before it enters structural, medical or life-support use
- treat surplus, purge streams and irrecoverable fractions as explicit logistics and safety decisions

1. Waste is a set of streams, not one category

A settlement cannot manage “waste” as a single material. Polymer packaging, worn textiles, filters, food residues, metals, glass, biological sludge, medical consumables and contaminated hardware have different hazards and recovery routes. The first engineering task is a mass inventory by family, production rate and hazard class. That accounting drives storage volume, processing capacity, crew time, protective equipment and spare parts. A recycler sized only for an average daily mass can still be overwhelmed by a maintenance campaign that suddenly produces tens of kilograms of insulation, hoses and composite parts.

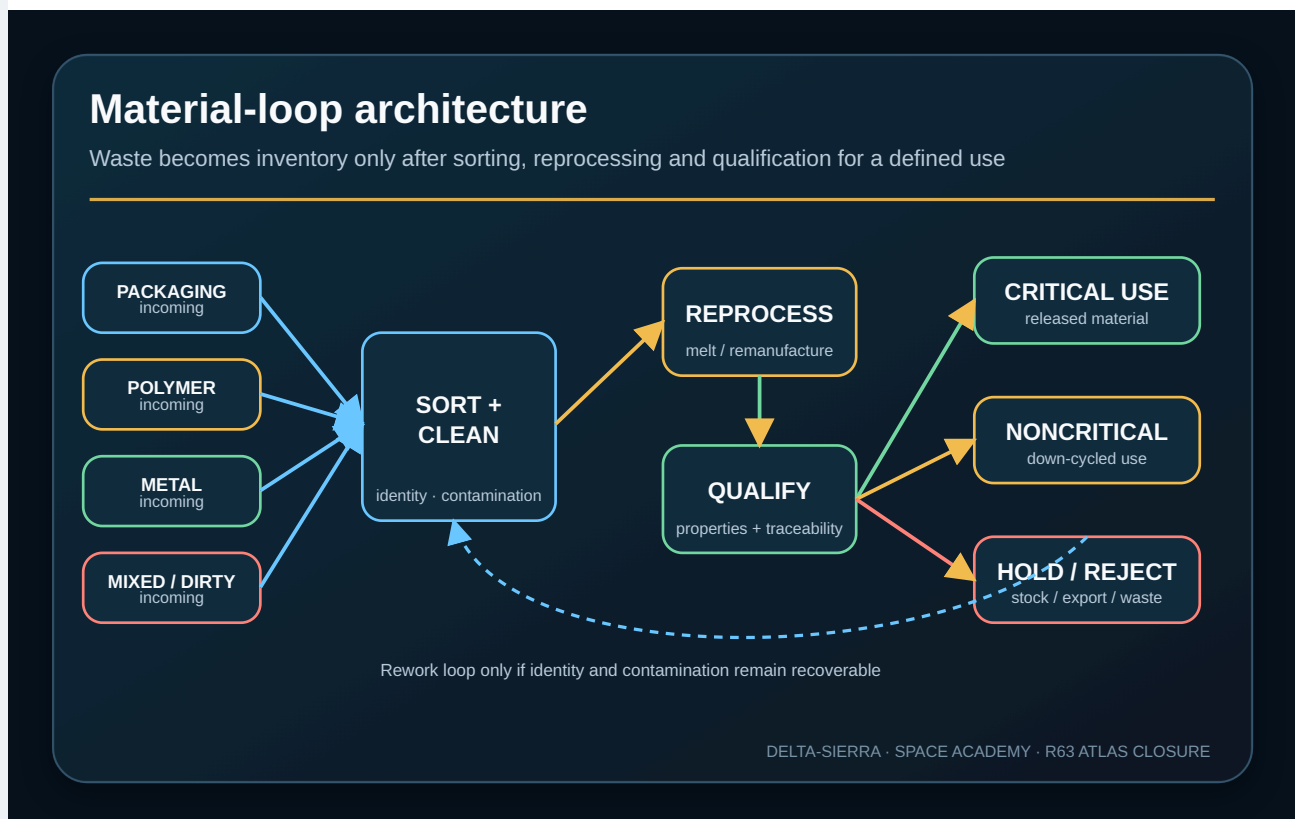
NASA documents the Refabricator as a demonstration of recycling polymers into additive-manufacturing feedstock. [NASA — Refabricator](#)

2. Priority order: avoid, reuse, repair, recycle, dispose

The most efficient waste stream is the one the architecture never creates. Packaging can become bins, panels, fixtures or feedstock. Reuse often preserves more value than destroying an item and rebuilding it from recovered material. A metal bracket that can be re-machined may be more useful than metal that is melted with energy and yield losses. Recycling therefore follows reduction, reuse and repair. Some streams will still require long-term isolation when decontamination would consume more scarce resources than the recovered material is worth.

3. Source separation and cross-contamination

High-quality recycling begins where the waste is generated. Mixing clean metal, polymer, wet food and chemicals converts four manageable streams into one complex mixture. The habitat therefore uses labeled containers, procedures and training. Biological and medical streams may need temporary containment and disinfection. Martian dust adds another complication: a textile or seal may carry abrasive or reactive particles. Separation quality is consequently an engineering function, not housekeeping trivia.



Recovered mass becomes useful only after the output is qualified for its intended downstream function. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

4. Polymers: recover a material property, not only mass

Polymers can be shredded, extruded and potentially reused in additive manufacturing, but each cycle can change viscosity, moisture, contamination and mechanical performance. The loop needs polymer-family identification and quality checks for pellet or filament feedstock. A low-load storage clip may tolerate variable recycled material; a pressure-bearing or structural component cannot be accepted without qualification. Local manufacturing therefore needs material history, not a generic bucket labeled recycled plastic.

5. Metals, glass and difficult composites

Metals retain high value but may require alloy identification, cutting, cleaning, melting or machining. Glass can become aggregate, shielding or remelt feedstock depending on quality. Composites are harder because fibers, resins, metal inserts and adhesives are bonded together. This difficulty feeds back into original design choices: demountable assemblies, marked alloys and fewer inseparable material combinations reduce recycling debt years later.

6. Organic residues, carbon and nutrients

Food residues and plant biomass contain water, carbon, nitrogen, phosphorus and micronutrients. They can support drying, biological processing or agricultural loops, but an uncontrolled biological stream can also concentrate pathogens or chemicals. “Organic” does not mean automatically safe for a crop. Food-waste-crop loops therefore connect to microbial monitoring, water quality and feedstock traceability.

7. Sometimes storage is better than immediate processing

A small settlement will not own an optimal processor for every stream. It can be rational to compact and store a clean stream for months before a campaign. This avoids running an energy-intensive machine at poor load factor and reduces crew intervention. Storage still has to manage fire, off-gassing, odor, chemistry and volume. Recycling becomes a scheduled operation like maintenance or ISRU production.

8. Measure the real closure of the loop

A recycling percentage is meaningful only when the boundary is clear. A process recovering 90% of mass but consuming a rare imported cartridge every cycle is not independent. Track recovered mass, irreversible loss, energy, water, consumables, crew hours and product quality. The useful indicator is the actual reduction in imported mass and operational risk, not the percentage of material that entered a recycler.

Deepening: imported-mass economics

The value of a loop is ultimately what it avoids importing. Compare recycler mass, spares and consumables with material saved over several years. An 800 kg machine that saves 50 kg each year is not automatically attractive, while a small shredder that converts packaging into useful feedstock every week may be. Lifetime, availability, maintenance and the diversity of recycled products belong in the calculation.

Deepening: fire, off-gassing and stored waste

Waste storage changes fire and atmosphere risk. Polymers, failed batteries and textiles can become combustible loads; some contaminated materials can off-gas or react. Storage volumes may need ventilation or isolation and monitoring compatible with habitat fire strategy. A compactor that reduces volume efficiently but hides a damaged battery from inspection can move risk rather than reduce it.

Deepening: material balance with degraded quality

A material loop has to separate recovered mass from mass that is still fit for purpose. A kilogram of polymer that no longer meets mechanical tolerances may still be valuable for less demanding parts. Several quality grades are more useful than a binary recyclable/not-recyclable label. This cascade extends material value without pretending that critical components can use unqualified feedstock. It requires batch history, simple testing and rules that connect material grade to allowed part families.

9. Worked example: polymer import avoided

A settlement uses 18 kg of polymers each week. If 70% is recoverable and the process returns 85% of that mass as acceptable feedstock, recovered production is $18 \times 0.70 \times 0.85 = 10.71$ kg per week. Over 52 weeks that is about 557 kg. Yet $18 - 10.71 = 7.29$ kg per week still has to be imported, stored or disposed. Recycling strongly reduces dependence without making it disappear.

Calculated case study: sizing annual volume for an unrecycled residue

TEACHING ASSUMPTION — After sorting and recycling, 7.29 kg of polymer remains each week. Assume a compacted bulk density of 150 kg/m^3 and a 30% storage margin.

Let m_w be weekly mass in kg/week; m_y annual mass in kg/year; ρ bulk density in kg/m^3 ; V volume in m^3 ; and m the margin, dimensionless.

$m_y = 7.29 \times 52 = 379.08 \text{ kg/year}$. $V = m_y \div \rho = 379.08 \div 150 = 2.5272 \text{ m}^3/\text{year}$. With a 30% margin: $V_{\text{plan}} = 2.5272 \times 1.30 = 3.28536 \text{ m}^3$, about $3.29 \text{ m}^3/\text{year}$.

Mass alone does not size a waste-storage area. Compaction and margin convert mass flow into volume demand; the bulk density is a teaching assumption.

10. Exercise

For a base generating each week 25 kg polymer, 12 kg metal, 30 kg organic waste and 8 kg non-recyclable material, define sorting, storage and treatment. Calculate annual masses and identify which storage saturation would create the fastest operational problem.

11. Reasoned solution

Convert every weekly flow to annual mass, then separate stable flows from maintenance peaks. Organic material needs rapid processing or sanitary containment, metal can wait for a campaign, and polymers need family separation. Non-recyclable waste needs long-term

volume. A complete answer also includes process consumables, energy and the contingency when a machine is unavailable for weeks.

12. Validation project

Build the material-flow plan for a 24-person habitat over two years: waste inventory, separation points, equipment, mass balances, buffer storage, material quality, contamination procedures, outage strategy and loop-closure indicators.

A material loop is only closed when the recovered material still has a useful destination

A Mars settlement cannot define waste only by the bin in which it is placed. Every discarded stream has mass, composition, contamination, geometry, energy content, hazard and potential reuse. The engineering task is to characterize those properties before choosing treatment. A clean aluminium offcut, a mixed polymer laminate, food residue and a solvent-soaked wipe may have similar volume but completely different recovery paths and risks.

The preferred hierarchy begins before recycling: avoid unnecessary material, reuse components, repair assemblies, recover parts, then recycle material when quality and process energy justify it. Recycling is valuable, but it can degrade polymer properties, mix alloys or create contaminated residues. The correct metric is not the percentage of objects placed in a recycling stream; it is the mass and quality that actually return to useful service.

Source separation is therefore a design feature. If metals, polymers, organics, hazardous chemicals and dust-contaminated textiles are mixed, the settlement spends crew time and energy separating them later and may lose high-quality feedstock entirely. Packaging, product design and maintenance procedures should make future disassembly and sorting easier.

Procurement becomes part of the waste system.

Storage is sometimes the safest processing step. A small rare stream may not justify running a furnace or chemical process every day. Clean dry material can be accumulated until a batch is large enough for efficient treatment. Hazardous or biologically active streams need different containment, ventilation and fire controls. “Process immediately” is not automatically more closed-loop than “store safely until the right process is available.”

Ten ideas for turning discarded mass into a managed resource inventory

1. Characterize the stream before choosing the process

Mass, material family, contamination, moisture, particle size, embedded electronics and hazardous constituents determine what treatment is feasible. A simple source code on each waste container can preserve this information. Operators should know whether the objective is direct reuse, material recovery, nutrient recovery, energy recovery or safe isolation.

Characterization prevents expensive mismatches. A shredder may be appropriate for clean single-polymer parts but can spread battery fragments or metal contamination into a feedstock that then damages extrusion equipment. Process selection follows composition, not convenience.

2. Prevention and repair usually preserve more value than recycling

Reusing a container or replacing one bearing in a pump keeps embodied manufacturing work intact. Melting or chemically reprocessing the same object consumes energy and may lose alloying elements or polymer properties. The waste hierarchy therefore starts with product longevity, modular repair and spare-part recovery.

This does not mean keeping unsafe hardware in service. Inspection and acceptance criteria decide whether a repaired part remains fit for its function. Components that cannot return to critical service may still become fixtures, jigs or noncritical feedstock rather than immediate refuse.

3. Source sorting protects feedstock quality

Clean metal separated at the point of generation is easier to remelt or machine than metal mixed with food residue, sealants and unknown fasteners. Polymer identity is especially important because incompatible families can produce weak recycled blends. Clear bins, markings and work instructions reduce downstream analysis burden.

The sorting system must remain usable during busy operations. If it requires twenty categories that crews cannot distinguish, contamination will rise. The right number of categories balances material value, hazard separation and human reliability.

4. Polymer loops lose quality unless chemistry and history are controlled

Thermoplastics can often be remelted, but heat history, oxidation, fillers and mixed resins can reduce mechanical properties. Recycled feedstock may therefore be assigned to less demanding parts unless tests demonstrate it still meets a higher requirement. A loop can remain valuable even when material cascades from high-performance to lower-performance uses.

Traceability matters because a spool labeled only “recycled plastic” says little about strength or thermal behavior. Batch records, source composition and simple coupon tests can turn secondary material into an engineering feedstock rather than an unknown convenience material.

5. Metals benefit from segregation by alloy and contamination

Metal recycling can recover high value, but mixed alloys may not meet the composition required for structural or pressure applications. Ferrous, aluminium, copper and specialty alloys should be separated when practical, and contaminated surfaces may need cleaning before remelting or machining.

If precise alloy control is unavailable, recovered metal can still serve ballast, shielding, brackets or cast noncritical components. The important step is to match material certainty with consequence. Unknown metal should not quietly enter a pressure-critical part because it was locally available.

6. Organic waste connects carbon, nutrients, hygiene and food systems

Food residues, inedible biomass and some sanitary streams contain carbon and nutrients that may support biological or chemical recovery. But they can also generate odor, gases and microbial growth. Storage and processing need temperature, moisture and contamination control so resource recovery does not become a health hazard.

Not every organic fraction belongs in the crop loop. Cleaning chemicals, pharmaceuticals or incompatible wastes may require separation. Nutrient recovery should therefore use known input streams and measured product quality rather than assuming all biological material is automatically fertilizer.

7. Hazardous waste requires a route that does not depend on future optimism

Solvents, damaged batteries, contaminated filters and reactive chemicals may accumulate faster than a settlement can safely recycle them. The plan needs compatible containers, secondary containment, ventilation where needed, inventory limits and a final treatment or long-duration storage concept.

The phrase “we will recycle it later” is not a control. The team should know the maximum safe inventory and the trigger for processing or isolation. Fire and toxic-release consequences can dominate the mass benefit of recovery.

8. Measure closure with mass balance and product quality

A loop-closing claim compares incoming material, useful recovered product, residues, losses and quality. If 100 kg of polymer waste produces 60 kg of usable filament and 40 kg of contaminated residue, the useful recovery is 60%, not 100% because every kilogram entered a recycling machine.

Quality belongs next to mass. Sixty kilograms of filament that cannot meet any defined part requirement is not equivalent to sixty kilograms of qualified feedstock. Verification can be simple for low-risk products and more demanding for structural uses.

9. Batch processing can save energy and crew time

Some processes have startup energy, cleaning effort and minimum practical batch size. Running them continuously at low load may waste energy and wear equipment. Safe accumulation followed by scheduled batches can improve efficiency while allowing maintenance and quality checks between runs.

Batch strategy requires storage capacity and fire/hygiene controls. A workshop should know how many days of each stream it can hold and what happens if the processor fails before the next planned run.

10. Waste system design should influence procurement and product architecture

Parts made from one identifiable material, fasteners that can be removed, refillable containers and standardized packaging all improve end-of-life recovery. A product that is cheap to import but impossible to repair or separate can create a persistent waste burden.

Procurement decisions therefore include end-of-life route alongside purchase mass and performance. The settlement gradually develops a materials vocabulary that favors closed, maintainable loops rather than one-way convenience.

Material-loop calculation laboratory: useful recovery and residual storage

Formula 1 — useful material-loop recovery fraction

$$R_{\text{useful}} = m_{\text{qualified}} / m_{\text{input}}$$

Starting question

What fraction of a waste stream returns as material that is actually qualified for a defined useful purpose?

Read aloud

Read: “useful recovery equals qualified recovered mass divided by input waste mass.”

Symbols, pronunciation and meaning

$m_{\text{qualified}}$ is recovered mass meeting the chosen use criteria;
 m_{input} is mass entering the process; R_{useful} is the recovery fraction.

Units

Masses use the same unit, such as kilograms; the ratio is dimensionless and can be expressed as a percentage.

Origin and status of values

Input mass comes from weighing the batch. Qualified mass comes from accepted product after excluding residues, rejects and unverified material.

Why this operation

Division compares useful output with the amount the process attempted to recover.

Substitution and calculation

If 80 kg enter and 58 kg become accepted feedstock, $R = 58/80 = 0.725 = 72.5\%$.

Calculator entry

Enter $58 \div 80$, then multiply by 100 for percent.

Mental estimate

Sixty out of eighty would be 75%, so 58 gives slightly less: 72.5% is plausible.

Independent check

Accepted mass plus all residues and losses should reconcile with input within measurement uncertainty. A missing large fraction indicates an incomplete mass balance.

Physical or operational interpretation

The process returns about three quarters of the incoming mass to a defined useful inventory; the rest still needs a managed destination.

Plain-English translation

In plain language: “recycled” does not mean “useful.” This batch closed 72.5% of the material loop at the declared quality level.

Variation / sensitivity

If better sorting raises accepted mass to 68 kg, recovery becomes 85%. If contamination reduces it to 40 kg, recovery falls to 50%.

Limit / assumption

The number depends on the acceptance criterion. Material suitable for a storage bin may not be qualified for a pressure vessel, so recovery must state the intended use.

What this does not prove

A high useful-recovery fraction does not certify material quality, durability or suitability for every end use. Qualification depends on the declared product specification, contamination controls and the mechanical or chemical demands of the next application.

Boundary case to test

The physically meaningful bookkeeping range is $0 \leq R_{\text{useful}} \leq 1$. Zero qualified mass must give zero recovery; qualified mass equal to input mass gives 100%. If $m_{\text{qualified}}$ exceeds m_{input} , the boundary or accounting is inconsistent unless additional feedstock has entered the process.

Formula 2 — annual unrecovered residue volume

$$V_{\text{residue}} = m_{\text{year}} \times (1 - R) / \rho_{\text{bulk}}$$

Starting question

How much storage volume is required for the fraction of an annual waste stream that remains unrecovered?

Read aloud

Read: "residue volume equals annual mass times unrecovered fraction divided by bulk density."

Symbols, pronunciation and meaning

m_{year} is annual input mass; R is useful recovery fraction;
 ρ_{bulk} is bulk density of stored residue; V is volume.

Units

If mass is kilograms and density kilograms per cubic metre, volume is cubic metres.

Origin and status of values

Annual mass comes from measured generation or a planning assumption. Recovery comes from demonstrated processing; bulk density depends on how residue is compacted and stored.

Why this operation

Multiplication isolates unrecovered mass. Division by density converts mass into occupied volume.

Substitution and calculation

For 1,200 kg/year, $R = 0.75$ and residue density 300 kg/m³:
residue mass = 300 kg; $V = 300/300 = 1.0 \text{ m}^3/\text{year}$.

Calculator entry

Enter $1200 \times (1 - 0.75) \div 300$.

Mental estimate

One quarter of 1,200 is 300 kg, and at 300 kg per cubic metre that is one cubic metre.

Independent check

Multiply $1.0 \text{ m}^3 \times 300 \text{ kg/m}^3 = 300 \text{ kg}$ and add recovered 900 kg to recover 1,200 kg input.

Physical or operational interpretation

Even a high recovery loop creates a residual stream that accumulates over years unless another destination exists. Storage must be designed for the unrecovered fraction.

Plain-English translation

The modeled system needs about one cubic metre of residue storage each year at the stated compaction density.

Variation / sensitivity

At 90% recovery the volume falls to 0.4 m³/year. If the residue is fluffy at 150 kg/m³, the original 300 kg occupies 2 m³.

Limit / assumption

Bulk density and recovery can vary strongly by waste type. Hazardous residues may require more container volume than the simple geometric calculation suggests.

What this does not prove

Residue volume does not establish storage safety, compatibility, containment life or hazardous-waste classification. A small volume can still dominate operations if it is toxic, biologically active, reactive or difficult to isolate.

Boundary case to test

At $R = 1$ this simplified model drives unrecovered residue mass to zero; at $R = 0$ the full annual mass remains. Bulk density must be positive: as density becomes very small the required volume grows sharply, revealing why fluffy or uncompacted residue can become a storage problem even at modest mass.

Material-loop cases: choose the highest-value safe destination

A mixed polymer bin contains unknown resins

The crew should not convert the whole bin into structural filament merely to reduce volume. Material identity can be checked by markings, procurement records or available characterization. Known compatible fractions are separated; uncertain material can be assigned to noncritical products or stored until a safer route exists.

This protects downstream printers and part quality. The failure is not that some plastic remains unrecycled; the failure would be turning a known sorting problem into hidden defects in future hardware.

A damaged battery enters the workshop waste stream

The battery is treated as a hazardous energy-containing object, not as ordinary metal scrap. It is isolated in compatible containment according to its condition, and the team evaluates heat, gas or short-circuit risk. Dismantling occurs only with an approved process and appropriate protection.

Recovery of valuable metals may be desirable, but it never justifies uncontrolled storage next to combustible polymer waste. Hazard segregation precedes resource recovery.

Recycled filament repeatedly produces weak parts

The response is to trace batch composition, thermal history, moisture, extrusion settings and test-coupon results. Recycled feedstock can be downgraded to lower-consequence uses while the cause is investigated. New material may be blended only under a documented process rather than by intuition.

This case demonstrates that a closed loop includes quality feedback. A kilogram that returns to inventory but fails every useful part is not recovered value.

Organic waste processor is offline for a week

The crew shifts to safe temporary storage with attention to moisture, odor, gas production and pests or microbial risk. Inputs that cannot be stored safely are reduced at source. Crop operations are informed if nutrient return will be delayed.

The degraded mode prevents an equipment outage from becoming a hygiene incident. Processing backlog and maximum storage duration become part of the repair priority decision.

Materials recovery practice with reasoned solutions

Exercise 1 — Calculate useful recovery

A batch receives 50 kg of sorted polymer and produces 34 kg of filament that passes the chosen acceptance check. What is useful recovery?

► Reveal the reasoned solution

Exercise 2 — Apply the waste hierarchy

A cracked storage crate can be repaired with two replaceable hinges. Why is shredding it immediately not the preferred first option?

► Reveal the reasoned solution

Exercise 3 — Choose source-sorting categories

You can support only six waste categories in a small workshop. What principles should determine them?

► Reveal the reasoned solution

Exercise 4 — Size residue storage

A stream is 900 kg/year with 80% useful recovery and residue bulk density 180 kg/m³. What annual residue volume results?

► Reveal the reasoned solution

Exercise 5 — Decide whether to batch process

A recycler needs significant startup energy and cleaning but receives only a few kilograms per day. What data would support batch operation?

► Reveal the reasoned solution

Exercise 6 — Protect alloy quality

Why should unknown mixed metal scrap not automatically become feedstock for a critical pressure component?

► Reveal the reasoned solution

Interactive beginner glossary

Each term links the waste hierarchy to an engineering decision about material value or hazard.

- waste stream — A defined flow of discarded material characterized by source, composition and quantity.
- reuse — Using an item again without converting it back into raw material.

- repair — Restoring an item or assembly so it can return to a useful function.
- recycling — Processing discarded material into feedstock for new products.
- material loop — A system in which material leaving one use is recovered for another controlled use instead of being permanently discarded.
- source sorting — Separating material where it is generated before different streams become mixed.
- feedstock — Material prepared to enter a manufacturing or processing operation.
- contamination — Unwanted material that reduces quality, creates hazard or interferes with a recovery process.
- polymer — A material made from long molecular chains; many plastics are polymers.
- thermoplastic — A polymer that can soften when heated and can often be reshaped more than once.
- alloy — A metallic material containing a controlled combination of elements.
- organic waste — Biologically derived discarded material such as food residue or crop biomass.
- hazardous waste — Discarded material requiring special control because of chemical, biological, electrical, radiological or other danger.
- secondary containment — An outer barrier intended to capture material if the primary container leaks or fails.
- bulk density — Mass of a stored material divided by the volume it occupies, including spaces between particles.
- qualified material — Recovered material that has passed the checks required for a stated use.
- downcycling — Reusing recovered material in a lower-performance application because original quality cannot be fully preserved.
- batch process — A process run on a discrete accumulated quantity rather than continuously.
- residue — Material remaining after the useful portion of a recovery process has been removed.
- mass balance — Accounting that compares all material entering, leaving and accumulating inside a defined process boundary.
- recovery fraction — The fraction of input mass recovered according to a stated criterion.
- reject — Processed material that fails the acceptance requirements for the intended product.

- traceability — The ability to reconstruct the origin and processing history of a material batch.
- coupon test — A test performed on a small representative specimen to check material or process performance.
- disassembly — Taking a product apart so components or materials can be repaired, reused or separated.
- end-of-life route — The planned destination and treatment of an item when its primary use ends.
- inventory limit — A maximum allowed amount of a stored material or hazard.
- nutrient recovery — Recovering elements useful for biological growth from waste or process streams.
- process loss — Material that leaves the useful product stream through evaporation, contamination, unrecoverable residue or other mechanisms.
- circular design — Designing products and systems so repair, reuse, separation and material recovery are practical from the beginning.

Operational review checklist

- Characterize each waste stream by material, contamination, hazard and quantity.
- Apply avoid, reuse and repair before material recycling where safe.
- Sort valuable or incompatible materials at the point of generation.
- Keep polymer identity and processing history when recycled feedstock may enter engineered parts.
- Segregate alloys when composition matters to future use.
- Keep hazardous waste routes independent from optimistic future recycling assumptions.
- Measure useful recovery after rejects, residues and quality checks.
- Account for every significant mass stream in a balance.
- Provide safe batch storage when continuous processing is inefficient.
- Treat organic waste as both a resource and a hygiene risk.
- Define maximum safe inventory for reactive, toxic or damaged materials.
- Use recovered material only in applications appropriate to its demonstrated properties.
- Record batch traceability for secondary feedstock.
- Include end-of-life route in procurement and product design.
- Size long-duration residue storage even when the headline recovery fraction is high.

Material-loop calculation laboratory: recycling percentage and backlog must be tracked together

A settlement can report a high recovery fraction while its unprocessed inventory silently grows. The two quantities answer different questions.

Recovered fraction

$$f_{\text{recovered}} = m_{\text{recovered}} / m_{\text{generated}}$$

If a teaching scenario generates 80 kg/day of a separated material stream and 68 kg/day returns to a qualified use, $f = 68/80 = 0.85$, or 85%.

Interpretation. The remaining 12 kg/day is not automatically “waste forever.” It may be stored, exported to another process, require treatment, or represent contamination losses. The calculation must state the boundary.

Backlog growth

$$\Delta m_{\text{stock}} = m_{\text{generated}} - m_{\text{processed}}$$

If generation is 80 kg/day and the processing line can handle only 68 kg/day, stock increases by 12 kg/day. After 14 days at the same imbalance, additional backlog is $12 \times 14 = 168$ kg. Storage volume, fire load, odor, contamination and handling effort may therefore become the actual constraint before nominal recycling efficiency.

► Exercise — restore balance

Engineering studio: close a material loop without hiding losses

A recycling percentage is not enough to design a settlement. Engineers need to know what enters the loop, what leaves as qualified product, what is downgraded, what becomes hazardous residue, and how much inventory accumulates while equipment is unavailable. The following teaching model turns those questions into a mass balance that a beginner can reproduce with ordinary arithmetic.

1. Start with conservation of mass

For a defined accounting period, incoming material must either leave as a useful product, remain in storage, or leave the useful loop as loss or residue. This is an accounting identity, not an efficiency claim.

$$m_{in} = m_{product} + m_{stock_change} + m_{loss}$$

Read aloud. Incoming mass equals qualified product mass plus the change in stored mass plus mass that leaves the useful loop. **m_{in}**, **m_{product}**, **m_{stock_change}** and **m_{loss}** are all measured in the same mass unit, here kilograms. Because every term is a mass, the unit check is kg = kg + kg + kg.

Teaching example. A workshop sends 100 kg of sorted polymer into a weekly accounting period. It produces 72 kg of filament that passes qualification, adds 18 kg to a waiting/rework stock, and rejects 10 kg as unusable contamination. Check: 72 + 18 + 10 = 100 kg. The identity closes, but only 72% of the input has returned immediately to a qualified use.

2. Separate process yield from useful-loop closure

A machine can have high process yield while the settlement has poor loop closure if the output cannot replace a needed imported product. Conversely, a lower-yield process may be valuable if its product has a critical destination.

$$\eta_{useful} = m_{qualified_for_demand} / m_{input}$$

Read aloud. Useful-loop efficiency equals the mass that meets an identified demand divided by input mass. The symbol η , pronounced “eta”, denotes a fraction between zero and one in this teaching definition. If 72 kg of qualified product comes from 100 kg input, $\eta_{\text{useful}} = 72 / 100 = 0.72 = 72\%$.

What this does not prove. It does not prove that the recycled product has the same lifetime, strength, fire behavior or purity as virgin material. Those properties require qualification tests appropriate to the intended use.

3. Model backlog as a rate problem

If waste generation exceeds average processing capacity, storage grows even when the recycler is functioning. Rates must therefore use the same time basis.

$$\dot{m}_{\text{stock}}/\text{dt} \approx \dot{m}_{\text{generated}} - \dot{m}_{\text{processed}}$$

Read aloud. The rate of change of stored mass is approximately generation rate minus processing rate. The dot over m is read “mass flow rate”. Here both rates use kilograms per day, so the result is also kilograms per day. If a stream generates 14 kg/day and the qualified processing line averages 11 kg/day, storage grows by 3 kg/day. Over 30 unchanged days, the additional backlog is about 90 kg.

4. Size storage for a planned outage

A buffer must cover both ordinary variability and a credible processing outage. A simple first-pass sizing equation is:

$$m_{\text{buffer}} = \dot{m}_{\text{generated}} \times t_{\text{outage}} \times (1 + f_{\text{margin}})$$

Symbols and units. $\dot{m}_{\text{generated}}$ is generation rate in kg/day; t_{outage} is outage duration in days; f_{margin} is a dimensionless planning margin. For 14 kg/day, a 12-day outage and 25% margin: $14 \times 12 = 168$ kg; $168 \times 1.25 = 210$ kg. A mental check is that 14×10 is 140 kg, so a result a little above 200 kg for twelve days plus margin is plausible.

5. Ask whether recycling actually avoids imports

The mass that matters strategically is the quantity of imported material no longer required because a local output is qualified for the same function.

$$m_{\text{import_avoided}} = m_{\text{qualified}} \times f_{\text{substitution}}$$

If 72 kg of recycled polymer is qualified, but only 60% can substitute for parts that would otherwise be imported, then $72 \times 0.60 = 43.2$ kg of import demand is avoided in that period. The remaining recycled material may still have value, but not for that particular substitution claim.

► Integrated exercise — diagnose a loop that looks “90% recycled”

Mission decision. A loop should be managed with at least four separate indicators: generation rate, qualified recovery, backlog, and actual substitution of a mission need. One headline percentage cannot safely replace them.

First-Man circularity: a waste loop is successful only when its output is trusted

Closing material loops can reduce imported mass, but the settlement should not confuse “processed” with “recovered.” Recovered material needs a destination and a quality specification. Water returned from a waste process, polymer regrind, metals from damaged parts, nutrients from biological residues and gases from processing all require checks before they re-enter a higher-value system.

Characterise

composition,
contamination,
hazardous fraction

Process

separate, clean,
convert, stabilise

Qualify

test against destination
specification

Route

reuse, lower-grade use,
storage or disposal

Quality determines whether a loop is truly closed

A kilogram of recovered polymer is not equivalent to a kilogram of flight-qualified feedstock. Repeated thermal processing can change properties; mixed polymers can contaminate a batch; embedded dust or fibres can affect a printed part. A useful hierarchy is therefore reuse at original grade when verified, down-cycle into a lower-demand application when appropriate, or quarantine/dispose when the material cannot be trusted.

This same reasoning applies to biological loops. Nutrient recovery may reduce imports, but pathogen control, trace contaminants and concentration must be managed before returning material to crops. “Natural” is not a safety classification.

Storage is part of waste engineering

Processes often create intermediate streams faster than downstream users consume them. The settlement needs tank, bin or container capacity for those streams, plus a plan for what happens when storage is full. A recycler that must run continuously can become a hidden critical load if its output cannot be buffered. Conversely, adequate storage can decouple processes and allow maintenance or power scheduling.

Exercise: choose the destination, not only the recovery rate

A polymer loop recovers 85% of incoming mass, but testing shows that only 60% of the recovered product meets the specification for pressure-adjacent structural fixtures. Another 30% is suitable for trays and covers, and 10% is contaminated beyond current cleaning capability. The correct report does not claim “85% closed-loop structural recycling.” It records several qualified output grades and routes each fraction to an appropriate use.

Each recovered material needs release criteria matched to the risk of its next use, especially for structural or life-support applications. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Operational qualification lab: close a material loop without hiding contamination

Recycling is valuable only when the recovered material is suitable for its next use. A settlement that reports a high “recycling percentage” while mixing incompatible polymers, biological waste, metals and hazardous residues has not created a useful loop. The engineering task is to

preserve identity, quality and destination as material moves from use to discard, sorting, cleaning, processing, verification and reuse.

Mass closure and quality closure are different

A mass balance can show where kilograms went. It cannot by itself show whether recovered material retained the properties needed for a pressure fitting, food-contact component or structural part. The loop therefore needs at least two ledgers: quantity and qualification. Down-cycling may still be rational; a polymer no longer suitable for a critical part may remain useful for noncritical panels or packaging. The important point is to record the loss of function honestly.

External makeup required by a recycling loop

$$\dot{m}_{\text{makeup}} = \max(0, \dot{m}_{\text{demand}} - \dot{m}_{\text{qualified, recovered}})$$

1 – Concrete question

How much new material must enter the settlement each day when only qualified recovered material can offset demand?

2 – Intuition

New supply fills the gap between what users need and what the recycling process returns at the required quality.

3 – Quantities

Measure demand and recovered output over the same boundary and time interval.

4 – Formula

Makeup flow equals the larger of zero and the demand-minus-qualified-recovery gap: $\dot{m}_{\text{makeup}} = \max(0, \dot{m}_{\text{demand}} - \dot{m}_{\text{qualified, recovered}})$.

5 – Read aloud

"m dot makeup equals the maximum of zero and m dot demand minus m dot qualified recovered."

6 – Symbols

$\dot{m}$ is mass per unit time; the qualified qualifier excludes material that fails the acceptance criteria for this use.

7 – Pronunciation

$\dot{m}$ is read "m dot."

8 – Units

Use kilograms per day, kilograms per sol or another consistent mass-rate unit.

9 – Convention

Do not count inventory already stored as recovered production during the interval; separate flow from stock.

10 – Why subtraction

Qualified recovered material offsets the same defined demand. The $\max(0, \dots)$ boundary prevents temporary surplus recovery or stock reprocessing from being mislabelled as physically negative makeup.

11 – Assumptions

Demand and qualified recovery must use the same product-quality boundary and time interval. Recovered output above current demand becomes stock or another qualified use; it does not create negative external supply.

12 – Unit check

$\text{kg/day} - \text{kg/day} = \text{kg/day}$.

13 – Numerical case

Defined demand: $\dot{m}_{\text{demand}} = 24 \text{ kg/day}$.

Qualified recovered material for the same use:

$\dot{m}_{\text{qualified, recovered}} = 19.2 \text{ kg/day}$.

Raw gap = $24 - 19.2 = 4.8 \text{ kg/day}$.

$\dot{m}_{\text{makeup}} = \max(0, 4.8) = 4.8 \text{ kg/day}$.

14 – Operations

Subtract only accepted recovered mass. Material rejected for contamination remains part of the waste problem, not the credit.

15 – Algebra check

Recovered plus makeup should equal demand: $13.5 + 4.5 = 18 \text{ kg/day}$.

16 – Mental estimate

13.5 is three quarters of 18, so external makeup should be one quarter, or 4.5.

17 – Interpretation

The loop reduces imports by 75% for this defined material use, not by 100%.

18 – What it does not prove

It does not prove energy, labour, solvent use or equipment wear make the loop beneficial overall.

19 – Sensitivity

If contamination reduces accepted output to 9 kg/day, makeup rises to 9 kg/day. If a campaign temporarily produces 21 kg/day qualified recovery against 18 kg/day current demand, makeup is $\max(0, 18-21)=0$ kg/day and the 3 kg/day surplus must be accounted as storage or another destination.

20 – Practice

Guided exercise. Calculate external makeup for 24 kg/day demand and 19.2 kg/day qualified recovery.

Detailed guided correction.

1. Raw gap = $24 - 19.2 = 4.8$ kg/day.
2. The physical makeup requirement cannot be negative, so $\max(0, 4.8) = 4.8$ kg/day.
3. Qualified recovery therefore displaces 80% of the defined virgin input for this use: $19.2/24 = 0.80$.

Autonomous exercise. A process needs 30 kg/day of grade-A polymer. Recycling returns 18 kg/day at grade A plus 7 kg/day of grade B that cannot return to the same component but can replace virgin material in non-pressure housings that otherwise demand 10 kg/day. Build a two-destination mass balance.

► Autonomous correction – open after attempting the exercise

21 – Mission decision

Use makeup flow and recovery-time benefit to prioritise which loops deserve local equipment and which materials should simply remain imported and stockpiled.

Design for reversibility and traceability

Bins, labels and software records should preserve material family and hazard status from the moment an item is discarded. Cleaning chemicals and lubricants can contaminate an otherwise recyclable stream. A maintenance change can therefore alter the recycling system even when the recycler itself has not changed. Qualification samples should be linked back to batches so a failed part does not force the rejection of every kilogram ever recycled.

Qualification drill

Create a materials map for one week of settlement operation. Include food packaging, printed polymer parts, aluminium offcuts, a contaminated filter, biological waste and a failed battery. Decide which streams can share handling equipment and which must remain separated. For one polymer loop, state the acceptance tests required before the material can return to a pressure-critical part, and identify a lower-risk destination if it fails that grade.

Source context. NASA Refabricator and life-support work show the relevance of reuse and closed loops; the mass-flow values are a teaching scenario. [NASA — Refabricator](#).

R61 circular-material assurance: close loops by quality class, contamination history and destination

A material loop is not closed merely because mass re-enters a machine. Recovered material must be suitable for a defined destination, and the settlement must know what contaminants, thermal histories and mechanical degradation it carries. Circularity therefore needs a quality ledger alongside the mass ledger.

Create material quality classes before recycling begins

Separate streams that can safely return to life-critical use from those suitable only for noncritical fabrication, shielding, packaging or energy recovery. Define acceptance tests for each class. Mixing an unknown polymer or alloy into a high-value feedstock can reduce the usable yield of the entire batch. Source separation is therefore a production-control function, not merely housekeeping.

Primary-source bridge — NASA Refabricator. NASA's Refabricator work is a primary example of recycling and reuse in spaceflight. R61 extends the lesson by requiring destination-specific quality release rather than counting recycled mass alone. [Official source](#).

Track impurity accumulation across repeated loops

Small contaminants can concentrate when material is repeatedly reprocessed. Build a simple impurity history for streams where quality matters: input source, number of cycles, known additives, measured properties and disposition. When a batch falls outside the qualified envelope, downgrade it deliberately to a less demanding use or quarantine it rather than quietly blending it into fresh feed.

Backlog is a risk inventory

Waste waiting for processing occupies volume, can create odour or biological hazards, ties up containers and may block access routes. Report backlog not just in kilograms but by hazard and storage limit. A two-week backlog of clean packaging is different from a two-day backlog of wet biological material. The processing queue should therefore prioritise consequence as well as mass.

Primary-source bridge — ECLSS. NASA ECLSS material provides primary context for regenerative resource loops. R61 distinguishes life-support recovery from broader settlement material recycling so quality boundaries are not blurred. [Official source](#).

Use material passports for high-value recovered feedstock

A recovered batch should carry a record of origin, processing route, test results, contamination events and approved destinations. This can be as simple as a database record linked to the batch identifier. The objective is to make later failures traceable: if printed parts begin cracking, engineers can identify whether they share feedstock history rather than treating each failure as independent.

Do not let local recycling hide imported dependency

A loop that recovers 95% of polymer mass may still depend on imported filters, catalysts, lubricant, test coupons, cleaning agents or replacement heaters. Record these enabling consumables in the same autonomy model. A circular process is only as independent as the consumables and expertise required to keep it qualified.

Qualification drill — a high recovery rate produces weak parts

A polymer loop reports 93% mass recovery, but tensile coupons from recent batches are trending downward. The correct response is to stop releasing that feedstock for structural or pressure-related use, preserve batch history, inspect contamination and thermal-cycle data, and redirect material to a lower consequence class if it passes that class's acceptance criteria. Recovery percentage remains useful, but it cannot overrule product qualification.

Design products for recovery before they become waste

Material circularity improves when products use separable materials, identifiable polymers or alloys, accessible fasteners and replaceable wear surfaces. Procurement and local design should therefore consider end-of-life handling. A product that saves a few grams but permanently bonds several incompatible materials can impose a larger future cost on a closed settlement.

Quarantine capacity is part of recycling capacity

When a recovered batch is suspect, the settlement needs somewhere safe to store it without contaminating qualified material. Size quarantine space for plausible investigation and reprocessing delays, label it clearly, and prevent automated inventory systems from counting quarantined stock as usable feed. Otherwise pressure to free storage can quietly turn uncertain material into production input.

Loop performance should be reported as a Sankey-like loss story

For training and operations, show where mass goes: useful recovered product, downgraded product, purge, contamination loss, unrecoverable residue and stored backlog. This prevents a headline recovery percentage from hiding the destinations that actually determine autonomy. Even without a graphical Sankey diagram, the mass destinations should reconcile to the input within measurement uncertainty.

A settlement should route each stream according to quality, processing cost, hazard and autonomy value rather than chasing recovery percentage alone. Pedagogical synthesis by Delta-Sierra from the primary sources cited in this course; schematic, not to scale.

Primary sources and bridges

- [NASA — Environmental Control and Life Support Systems](#)
- [NASA — 3D-Printed Habitat Challenge](#)