

Sustainable Materials & Circular Economy For Engineers

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Module 1: Introduction to Sustainable Engineering Materials

Engineering materials shape the built environment in ways that extend far beyond the structural or mechanical performance they are specified to deliver. Every ton of concrete poured, every steel section fabricated, and every molded polymer has an environmental footprint. Their extraction, energy use, processing, and eventual disposal, all contributed to a material's true cost as much as its compressive strength or yield point (see Figure 1). Global material extraction reached approximately 100 billion tons per year in 2020, and only around 8.6% of those materials were returned to the economy through recycling (Circle Economy, 2021). The gap between what is extracted and what is recirculated is, in engineering terms, an efficiency problem of considerable magnitude.



Figure 1. The major stages in a material's lifecycle. Source: EPA, 2025

Engineers specify materials, design systems, and set performance thresholds. They also shape supply chains, influence procurement decisions, and, through code compliance and project documentation, define what acceptable practice looks like. Professional bodies, including the American Society of Civil Engineers (ASCE) and the American Institute of Chemical Engineers (AIChE), have embedded sustainability into their codes of ethics, reflecting a broader shift in what the profession considers within its scope (ASCE, 2017).

1.1 Sustainability, Circularity, Resilience, and Decarbonization

Sustainability in engineering refers to the design systems, products, and infrastructure that meet present needs without compromising the ability of future generations to meet theirs. In practice, this means that when evaluating materials, engineers need to balance immediate technical performance and cost with environmental stewardship, resource efficiency, and long-term social impact.

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Circularity extends sustainability to actively designing waste. A circular approach aims to keep materials in active use for as long as possible, through reuse, remanufacturing, and recycling, before they are either safely returned to the environment, or are reprocessed into new raw materials. The Ellen MacArthur Foundation (2021) distinguishes the circularity concept into two material pathways:

- **Technical cycles**: materials circulate continuously through industrial processes.
- **Biological cycles**: materials are designed to safely biodegrade without ecological harm.

For engineers, this distinction matters at the specification stage. A material's circularity depends not just on its intrinsic material properties, but also on the availability of collection, recovery, and the reprocessing infrastructure required to support these cycles at scale.

Resilience refers to the capacity of materials and engineered systems to maintain acceptable performance under stress, whether from mechanical loading, environmental exposure, or climate-driven events. In the sustainability context, resilience also encompasses the ability of a material system to withstand supply chain disruptions, shifts in regulatory requirements, or changes in end-of-life infrastructure availability.

Decarbonization involves the reduction of carbon emissions associated with a material's production, use, and disposal. It is typically achieved through material selection, e.g. selection of lower-carbon materials, adoption of clean energy in manufacturing, and design strategies that minimize overall material demand. Cement production alone is responsible for approximately 7% of global CO_2 emissions (IEA, 2023), highlighting that material related emissions are a central concern in modern engineering.

1.2 Material Impacts Across Engineering Disciplines

The environmental footprint of materials is not uniform across engineering disciplines. In civil and structural engineering, concrete and steel dominate both by volume and by embodied impact. The production of Portland cement clinker is inherently one of the most carbon-dense industrial processes due to the need to sustain kiln temperatures exceeding 1,450°C. Similarly, asphalt carries a significant carbon footprint at its extraction and refining stages, before construction activities such as transportation and compaction are factored in.

Mechanical engineers typically encounter metals, polymers, and composites in applications where dimensional tolerance and fatigue life govern specification. The environmental consequences appear at both ends of the lifecycle; upstream, in the energy-intensive smelting and forming processes required to produce them, and downstream, in the complex disassembly and contamination risks that multi-material components present. Chemical engineers face a different profile, working with process materials whose environmental profiles are defined less by volume than by toxicity, reactivity, and the complexity of managing the waste streams that they generate.

What connects these disciplines is the recognition that lifecycle impacts cannot be fully evaluated at the point of specification. A material that performs well under a single metric, for example compressive strength or

thermal resistance, may perform poorly when its extraction burden, maintenance frequency, and end-of-life options are included in the assessment.

1.3 Engineers and the Sustainable Development Goals

The United Nations Sustainable Development Goals most directly relevant to engineering material decisions are SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production; UN, 2015). Together, they ask engineers to design infrastructure that is inclusive, resilient, and resource-efficient, and to decouple economic development from environmental degradation.

US federal and state agencies are increasingly tying infrastructure funding to environmental performance criteria, including embodied carbon thresholds for publicly procured construction materials. California's Buy Clean California Act requires disclosure of global warming potential for structural steel, flat glass, mineral wool board insulation, and carbon steel rebar used in public projects. This effectively mandates lifecycle thinking at the procurement stage. The same expectations have since been more broadly extended by federal executive orders to publicly funded infrastructure. This shows that lifecycle-informed material specification is no longer confined to voluntary rating systems; it is becoming a condition of engineering practice.

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Module 2: Life Cycle Assessment and Environmental Metrics

A **Life Cycle Assessment (LCA)** is the quantitative method engineers use to evaluate the environmental performance of a material, product, or system across its full lifespan (see Figure 2). The methodology is governed by ISO 14040 and ISO 14044, which together define a four-phase process:

1. Goal and scope definition
2. Life cycle inventory analysis
3. Life cycle impact assessment
4. Interpretation

Each phase involves decisions about system boundaries, functional units, allocation methods, and impact categories that can meaningfully alter the conclusions drawn.

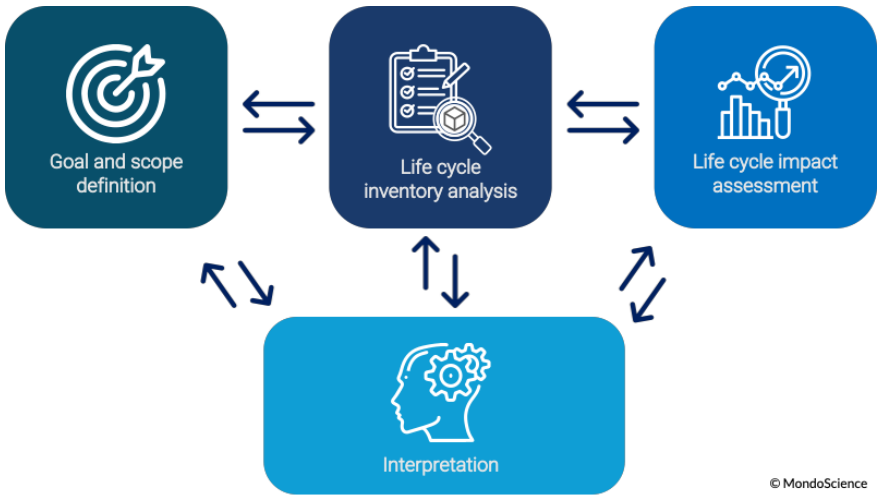


Figure 2. Overview of the Life Cycle Assessment (LCA) framework based on ISO 14040

LCA is a structured way of asking the right questions. Two engineers conducting an LCA on the same material under different assumptions may reach different numerical results, though a well-executed study will make those assumptions visible and therefore open to scrutiny. This transparency is part of its value.

2.1 Cradle-to-Cradle and Cradle-to-Grave Models

The scope of an LCA is defined by its system boundary, and in engineering practice this most commonly takes one of two main forms: the cradle-to-grave and cradle-to cradle models (see Figure 3).

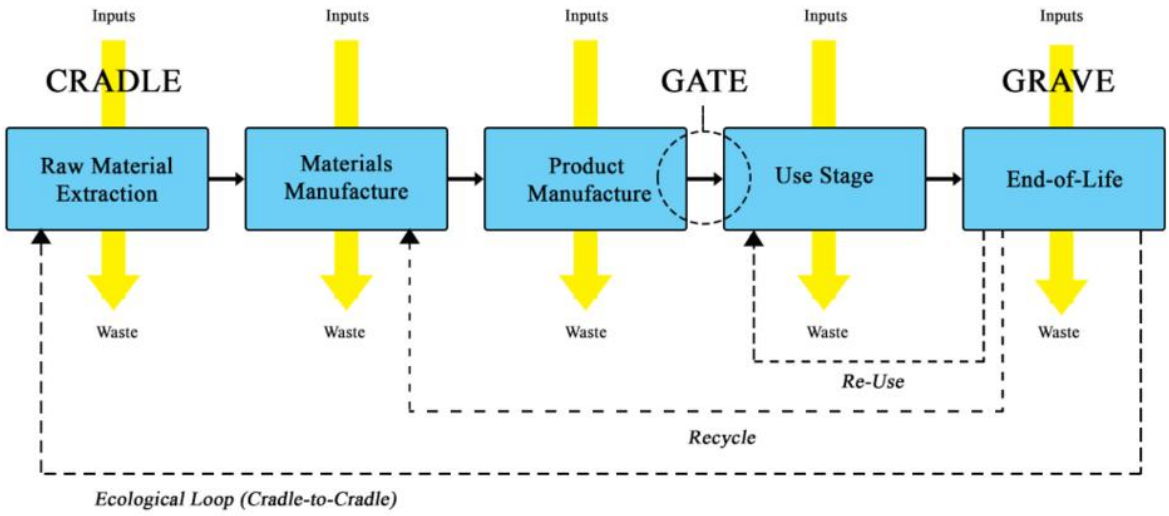


Figure 3. Life Cycle Assessment methodologies cradle-to-gate, cradle-to-grave, and cradle-to-cradle. Source: MtW17 via Wikimedia Commons

The **cradle-to-grave model** traces a material from raw material extraction through to final disposal, treating the end of the material's useful life as a waste event. This model reflects the linear logic of most industrial systems and is the basis for most conventional embodied carbon calculations.

The **cradle-to-cradle model**, developed by McDonough and Braungart (2002), challenges that terminal assumption. In a cradle-to-cradle system, materials are designed for perpetual recirculation (see Figure 4). This can be done either through technical cycles, meaning continuous industrial reuse with no loss of quality, or biological cycles, meaning safe biodegradation and return to natural systems. This model has influenced green building certification systems and modular construction practice. However, it requires supply chain infrastructure, particularly collection, sorting, and reprocessing capacity, that does not yet exist at scale for many material streams.

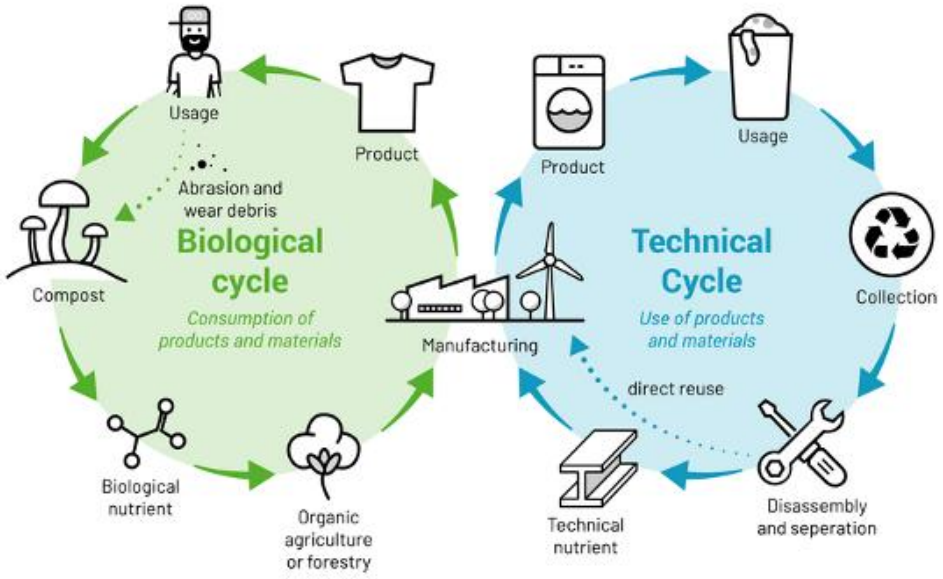


Figure 4. Cradle-to-cradle model. Source: Felix Joerg Mueller via Wikimedia Commons

For engineers working within existing industry systems, the most practically useful LCA boundary is often cradle-to-gate (extraction and manufacturing) or cradle-to-practical completion (including transport, installation, and use-phase energy). End-of-life treatment is often appended as a separate module, with credits assigned for materials that have established recycling pathways.

2.2 Embodied Energy and Carbon Accounting

Embodied energy is the total energy consumed across a material's lifecycle stages, typically expressed in megajoules per kilogram (MJ/kg). Embodied carbon, expressed in kilograms of CO_2-equivalent per kilogram (kgCO2e/kg) of material, captures the associated greenhouse gas emissions. Both metrics are essential in evaluating materials beyond their operational performance.

In buildings and civil infrastructure, embodied emissions typically account for 20 to 50% of total lifecycle emissions (Pomponi & Moncaster, 2017). This proportion tends to increase in more energy-efficient buildings as operational energy efficiency improves through better insulation, glazing, and building services. For a net-zero building where operational emissions have been substantially eliminated, the embodied impact of its structure and envelope at the point of construction becomes the dominant share of the building's total lifetime impact. Because of this, embodied carbon has moved from a niche academic metric to a required submission item in several US green building certification programs.

The calculation for the total embodied energy for an assembly is the sum of the quantity of each material multiplied by its embodied energy intensity:

$$E_{total} = \Sigma (Q_i \times EI_i)$$

Where:

Q_i = the quantity in kilograms or cubic meters

EI_i = the published intensity factor for material i.

Intensity values for common materials are available from the Inventory of Carbon and Energy (ICE) database, the US Life Cycle Inventory (USLCI) database, and the Ecoinvent database. Each applies slightly different methodological conventions, therefore consistency within a single project is important. Refer to Appendix A for a worked example using this formula for a simple concrete and steel foundation.

Table 1 below illustrates the range of embodied carbon and energy intensity values for common structural materials. The difference between virgin and recycled steel reflects the energy saved by melting scrap in an electric arc furnace rather than reducing iron ore in a blast furnace: roughly a 60% reduction in energy and over 50% reduction in emissions (World Steel Association, 2020).

Table 1. Embodied carbon and energy intensity of common structural materials

Material	**Embodied Carbon (kg CO_2-e/kg)**	**Embodied Energy (MJ/kg)**
Virgin steel	2.89	35.40
Recycled steel	0.47	9.40
Portland cement	0.95	5.50
Virgin aluminum	12.79	218
Recycled aluminum	1.81	29.0

Note: Values are indicative and vary with regional energy mix and specific product. Sources: ICE database v2.0.

2.3 LCA Tools: GaBi, SimaPro, openLCA, and One Click LCA

There are several software platforms that support LCA practice in engineering:

- **GaBi**, developed by Sphera, is widely used in industrial and academic settings for complex, multi-stage product systems.
- **SimaPro**, from **PRé** Sustainability, offers a range of impact assessment methods, including TRACI (the US EPA's preferred method for North American projects)
- **ReCiPe** available in **openLCA** is an open-source alternative. It provides full methodological transparency and compatibility with the Ecoinvent and USLCI databases, making it suitable for projects requiring peer review or public disclosure.

One Click LCA has gained significant traction in construction practice, particularly for LEED projects, due to its integration with BIM software and its extensive library of verified Environmental Product Declarations. It offers a faster path to whole-building LCA result than traditional research-grade tools, but with less scope to customize system boundaries, allocation methods, or impact categories that suit unusual project conditions. Table 2 summarizes the key characteristics of each platform.

Table 2. LCA software tool comparison

Tool	Developer	Cost model	Key databases	Best-fit application
GaBi	Sphera	Commercial	Ecoinvent, GaBi	Complex industrial product systems
SimaPro	PRé Sustainability	Commercial	Ecoinvent, USLCI	Academic research; TRACI and ReCiPe methods
openLCA	GreenDelta	Free/open source	Ecoinvent, USLCI, ELCD	Peer-reviewed studies, public disclosure
One Click LCA	One Click LCA Ltd	Subscription	EPD databases, regional data	BIM-integrated workflows, LEED submissions

2.4 Hypothetical Case Study: Recycled vs. Virgin Steel in a Mid-Rise Structural Frame

This hypothetical example illustrates how embodied carbon analysis can drive specification decisions.

A lifecycle comparison was conducted for a mid-rise commercial building in the US Pacific Northwest. The structural frame required approximately 500 tons of steel. The design team evaluated two options:

- Virgin steel produced via basic oxygen furnace (BOF) imported from an overseas mill.
- Recycled steel from a regional electric arc furnace (EAF) producer located within 300 miles of the site.

Using SimaPro with the Ecoinvent 3.6 database, the team calculated lifecycle greenhouse gas emissions for both options across all stages of the build, from raw material extraction through fabrication and transportation to projected end-of-life.

The LCA confirmed that specifying EAF recycled steel from the regional supplier reduced total lifecycle greenhouse gas emissions by approximately 56% compared to the imported BOF virgin steel option, a finding consistent with the broader literature on steelmaking carbon intensity (World Steel Association, 2020). The production stage drove most of the saving, as scrap melting in an electric arc furnace avoids the energy-intensive ore reduction process of the blast furnace route. Transportation emissions were broadly comparable across both options. Based on this, the recycled steel specification was adopted, and the project team revised

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its standard material guidelines to permit EAF-sourced steel where the supplier can demonstrate chemical composition compliance with ASTM A992.

A material with higher embodied energy but significantly longer service life may outperform a lower-carbon alternative in total lifecycle terms, particularly when replacement and maintenance emissions are included. Stainless steel in marine infrastructure is a routine example. Its higher production energy is often justified by corrosion resistance that extends service life by several decades compared to carbon steel with protective coatings requiring periodic renewal. The most defensible specifications integrate both embodied metrics and service life projections, rather than treating embodied carbon as the sole optimization criterion.

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Module 3: Recycling Science and Engineering Applications



Recycling an engineered material is not simply a matter of collecting it and returning it to circulation. The material carries its processing history with it, including thermal exposures, mechanical loading, contamination events, and chemical degradation, that may alter its properties in ways that are invisible to casual inspection but are consequential in service. Understanding these changes and knowing which materials are more or less tolerant of multiple processing cycles, is a prerequisite for specifying recycled materials responsibly.

3.1 Thermomechanical Behavior of Recycled Materials

Metals generally retain their crystalline structures when remelted. The atom-by-atom reorganization that occurs during solidification effectively resets the material's microstructure. This is why steel and aluminum can in principle be recycled indefinitely without intrinsic property loss. The practical constraints are external and are due contamination by tramp elements, alloy mixing, and oxidation during melting. In aluminum recycling, sorting scrap by alloy series is essential because mixing 2xxx-series (copper-bearing) and 6xxx-series (magnesium-silicon) alloys produces a product that satisfies neither specification. Scrap processors use X-ray fluorescence (XRF) sorting and spectrometric analysis to manage this. Engineers specifying recycled aluminum should always ask about the scrap sourcing and alloy verification procedures used by the producer.

Polymer recycling is more challenging. Thermoplastics soften and flow when heated, which allows mechanical reprocessing. However, each thermal cycle induces chain scission, which is the breaking of long polymer molecules into shorter segments. Shorter chains mean lower molecular weight, which translates directly to reduced tensile strength, lower impact resistance, and increased brittleness (Hopewell et al., 2009). Recycled polyethylene terephthalate (PET) from bottle streams, for example, typically shows a reduction in intrinsic viscosity after the first reprocessing cycle, limiting its use in applications requiring high molecular integrity. Stabilizers, chain extenders, and compatibilizers are routinely added during reprocessing to partially offset these effects, but they add process complexity and cost.

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3.2 Limitations: Fatigue, Creep, and Corrosion

Recycled metals used in structural applications must be evaluated for fatigue performance, particularly when the scrap source includes components that have already experienced significant cyclic loading. Inclusions and micro-cracks introduced during remelting or casting can serve as fatigue initiation sites, and their distribution is less predictable than in virgin material produced under tightly controlled conditions. Engineers specifying recycled steel for fatigue-critical applications, such as bridge girders or crane rails, should require supplemental testing, including ultrasonic inspection and Charpy impact testing, beyond the standard mill certificate.

Creep, the time-dependent deformation of a material under sustained load, is a particular concern for recycled thermoplastics. Recycled high-density polyethylene (HDPE), widely used in drainage pipes, decking, and marine fender systems, shows measurably higher creep rates than virgin material due to shorter chain lengths and reduced crystallinity (Vilaplana & Karlsson, 2008). For long-term structural applications, creep compliance data for the specific recycled product should be obtained from the manufacturer.

Corrosion in recycled steel can be exacerbated by residual slag inclusions or inconsistent alloy composition arising from mixed scrap inputs. This is less of a concern for EAF producers operating on well-sorted scrap streams, however, it can be significant for smaller-scale recyclers. Specifying recycled steel to applicable ASTM standards, rather than by recycled content alone, addresses this risk by establishing a performance baseline independent of input stream variability.

3.3 Engineering Polymers: PET, HDPE, and ABS

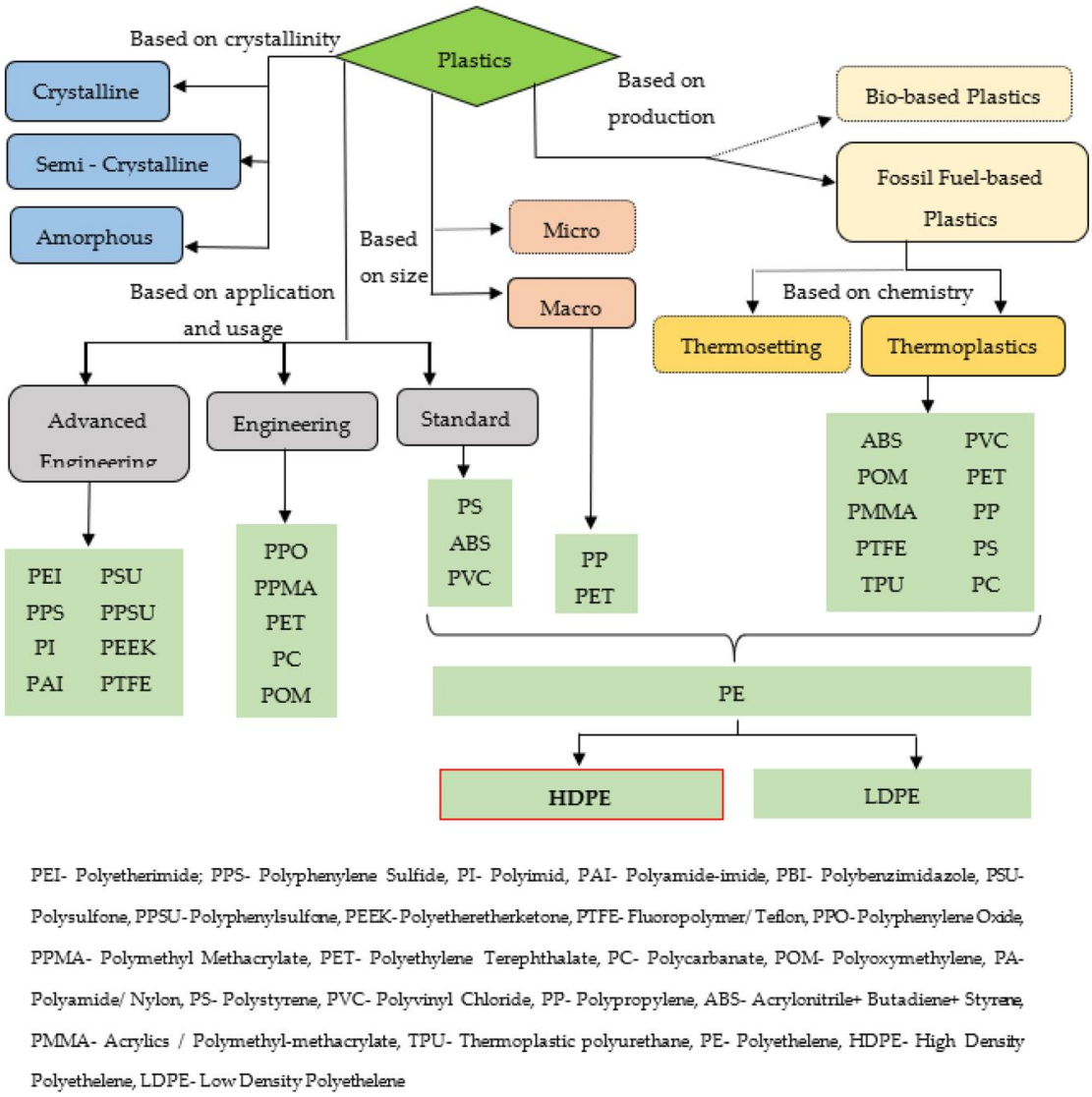
Among thermoplastic engineering polymers (plastics), polyethylene terephthalate (PET), high-density polyethylene (HDPE), and acrylonitrile butadiene styrene (ABS) represent the largest-volume recyclable streams relevant to civil and mechanical engineering applications. Different plastics have characteristics and can be categorized based on their various properties (see Figure 5 below).

PET is the most widely collected post-consumer plastic in the US. Recycled PET is used in geotextile fibers, drainage composites, and insulation materials. The main degradation mechanism is hydrolytic chain scission during processing, which is mitigated by drying the resin to very low moisture content, typically below 50 ppm by mass, before extrusion.

HDPE has robust recyclability, with extensive use of its post-consumer recycled form in piping, lumber alternatives, and containment systems. Its mechanical degradation over multiple cycles is moderate, and blending with virgin resin at controlled ratios is common practice where consistent mechanical properties are required.

ABS is more technically challenging to recycle. The butadiene rubber phase that gives ABS its impact resistance is susceptible to oxidative degradation during thermal reprocessing, leading to phase separation and embrittlement. For applications where impact resistance is critical, the provenance and reprocessing history of recycled ABS should be documented.

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PEI- Polyetherimide; PPS- Polyphenylene Sulfide, PI- Polyimid, PAI- Polyamide-imide, PBI- Polybenzimidazole, PSU- Polysulfone, PPSU- Polyphenylsulfone, PEEK- Polyetheretherketone, PTFE- Fluoropolymer/ Teflon, PPO- Polyphenylene Oxide, PPMA- Polymethyl Methacrylate, PET- Polyethylene Terephthalate, PC- Polycarbanate, POM- Polyoxymethylene, PA- Polyamide/ Nylon, PS- Polystyrene, PVC- Polyvinyl Chloride, PP- Polypropylene, ABS- Acrylonitrile+ Butadiene+ Styrene, PMMA- Acrylics / Polymethyl-methacrylate, TPU- Thermoplastic polyurethane, PE- Polyethelene, HDPE- High Density Polyethelene, LDPE- Low Density Polyethelene

Figure 5. Categorization of recycled plastics. Source: Abeysinghe et al., 2021

3.4 Industrial Metal Recycling: Steel, Aluminum, and Copper

Steel is the most recycled material globally, with an average recycled content in US structural steel of approximately 93% (AISC, 2021). EAF steelmaking, which processes scrap directly, accounts for around 70% of US steel production and uses roughly 60% less energy than BOF production using virgin ore. The challenge of unintended residual elements (known as the tramp element challenge), particularly copper contamination that reduces hot workability, is managed through scrap segregation and, in some cases, dilution with direct reduced iron.

Aluminum recycling is energetically stark. Secondary aluminum production requires only about 5% of the energy needed to produce primary aluminum from bauxite (Al-Almi et al., 2024). The automotive industry

operates near-closed-loop recycling for many aluminum alloys, with careful alloy segregation enabling high-quality recovery. In construction, aluminum curtain wall and window systems are high-value recycling candidates, provided they are separated from composite materials and gasket assemblies before smelting.

Copper's high intrinsic value incentivizes recovery throughout the supply chain. Recycling rates for electrical and plumbing copper are among the highest of any engineering metal. Contamination by aluminum or iron significantly impairs conductivity in recovered copper, which limits its use in high-specification wiring applications unless the scrap stream is tightly controlled.

3.5 Closed-Loop and Open-Loop Recycling in Civil Infrastructure



Figure 6. Closed-loop vs open-loop recycling

In civil engineering, two recycling models govern most material recovery decisions (Figure 6). **Closed-loop recycling** returns a material to the same application or equivalent performance level. This includes structural steel scrap remelted into new structural sections, or asphalt reclaimed and reincorporated into hot-mix at similar performance grades. **Open-loop recycling**, sometimes called downcycling, transforms a material into a product of lower performance or value. Examples include crushed concrete used as granular sub-base, or mixed plastic lumber used in non-structural landscape applications.

The appropriate choice of model depends on the material condition, contamination level, and available secondary markets. Waste concrete from a demolition project will rarely meet the contamination and gradation requirements for structural concrete aggregate at high replacement fractions. It is, however, entirely suitable as road sub-base where compressive strength thresholds are lower and gradation requirements more flexible. The task of the engineer is to match material quality to application requirements, and to preserve high-quality streams for high-value applications where they are genuinely needed. Table 3 illustrates this distinction with material examples and their use in civil infrastructure.

Table 3. Examples and typical quality outcomes of closed-loop and open-loop recycling models in civil infrastructure

Recycling model	Material example	Typical civil application	Quality outcome
Closed-loop	Structural steel scrap (EAF)	New structural sections (ASTM A992)	Full property retention with proper sorting
Closed-loop	Reclaimed asphalt pavement (RAP)	New hot-mix asphalt at equivalent performance grade	Near-equivalent performance; tested per AASHTO
Open-loop	Crushed concrete (RCA)	Road sub-base, lean fill, pervious pavement	Reduced strength requirements; variability managed by grading
Open-loop	Mixed demolition rubble	Bulk earthworks fill	Minimal structural requirements; contamination limits apply

Module 4: Upcycling Techniques and Value Retention Strategies

Where recycling typically returns a material to an equivalent or lower-grade state, upcycling aims to transform a waste material or recovered component into a product of higher quality, greater functionality, or increased value than the input stream. This distinction changes the economics of material recovery, the engineering analysis required, and the design decisions that make recovery viable in the first place.

4.1 Principles of Material Revalorization

The concept of revalorization, restoring or enhancing the inherent value of a material through processing, design, or recontextualization, drives the most productive developments in sustainable materials engineering. It shifts the question from "how do we dispose of this waste?" to "what is this material actually capable of, and what design would unlock that capability?"

Revalorization is most tractable when the material in question has a well-characterized composition, stable properties, and a known processing history. Reclaimed structural steel from a documented building is more amenable to upcycling than mixed demolition scrap of unknown provenance, because the design engineer can work from a defined starting point. This places a premium on material tracking and documentation during the construction and operation phases of a building's life, which is one reason material passports, discussed in a later module, are gaining traction in practice.

4.2 Upcycled Composites: Structural and Performance Analysis

Combining recovered material streams with binders, fibers, or matrices can produce composite materials that outperform either component in isolation. Wood-plastic composites (WPCs), produced by combining reclaimed wood flour or fibers with recycled polyethylene (Figure 7), offer improved moisture resistance and dimensional stability compared to untreated timber in exposed applications such as decking and cladding (Najafi, 2013). The wood fiber reinforces the polymer matrix, while the polymer protects the wood from moisture absorption that would otherwise cause swelling and biological attack.

Glass fiber reinforced polymer (GFRP) waste, previously difficult to recycle due to its thermoset matrix, has been reprocessed into particulate fillers for polymer concrete. Silane coupling agents improve matrix adhesion, enabling use in non-primary-load-bearing architectural elements. It also keeps high-value glass fiber in the material economy rather than consigning it to landfill. Performance testing for upcycled composites must be conducted on the recovered material itself, not on the virgin equivalent. ASTM D790 covers flexural properties, and ISO 178 addresses the same properties in metric format. Creep behavior under sustained load, long-term moisture exposure, and freeze-thaw durability should all be evaluated for applications where those service conditions apply.

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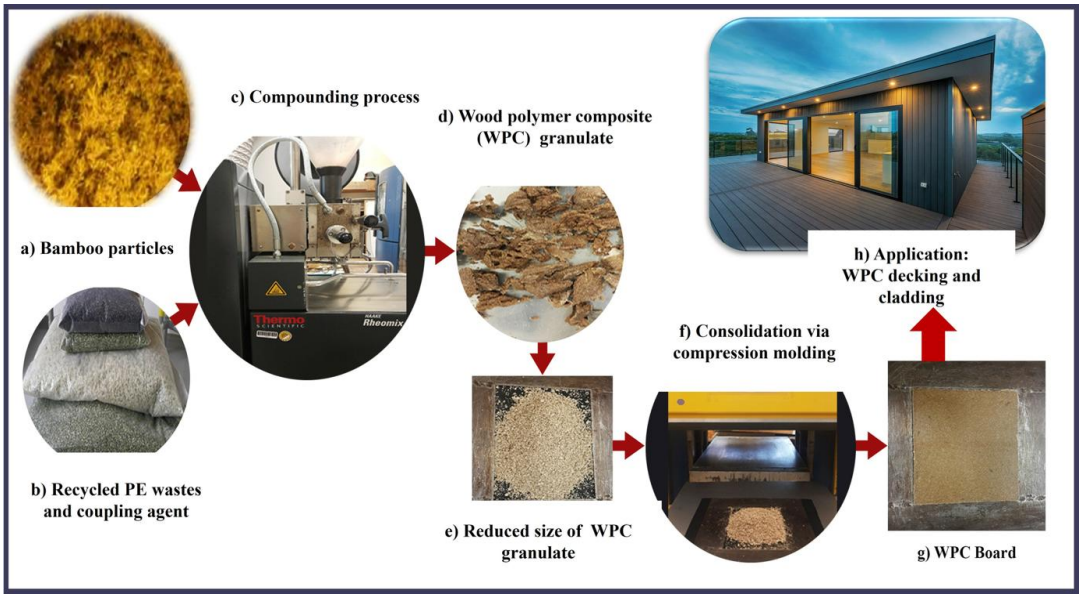


Figure 7. Upcycling of wood particles and recycled polyethylene (PE) waste for manufacturing of wood polymer composites (WPC) used in decking and cladding. Source: Ayana et al. (2024)

4.3 Additive Manufacturing with Waste Feedstocks

Fused filament fabrication (FFF, commonly called 3D printing) creates a direct route from plastic waste to value-added product, bypassing some of the performance losses associated with conventional melt-extrusion recycling. Plastics such as PLA, PETG, and ABS can be ground and extruded into printable filament. Because the printing process allows for infill density, orientation, and geometry to be adjusted at the design stage, minor variations in the mechanical properties of the recovered material can be accommodated without compromising the performance of the finished component.

In construction, practical applications include custom formwork for complex concrete geometries, architectural panels, and replacement components for mechanical systems. Limitations of melt flow index variation in recycled resin can cause inconsistent layer adhesion, and residual moisture causes steam voids during extrusion. Quality control procedures, including resin drying and MFI testing before printing, are essential if the printed component is to meet any structural or fit-for-purpose standard.

4.4 Electronic Waste and Rare Earth Recovery

Electronic waste (e-waste) is one of the fastest-growing and least-recovered waste streams in the United States, with a global recycling rate estimated at approximately 17% (Forti et al., 2020). From an engineering standpoint, e-waste is interesting because a single circuit board contains gold, silver, copper, palladium, and a range of rare earth elements in concentrations far exceeding those of natural ore deposits.

Advanced recovery techniques go beyond conventional smelting. Bioleaching, using bacteria such as *Chromobacterium violaceum* to solubilize metals from circuit board substrates, and offers a lower-energy and lower-toxicity alternative to hydrometallurgical acid leaching (Bose & Bhattacharyya, 2021). Mechanochemical processing, using high-energy ball milling to break down composite materials without solvents, enables recovery of neodymium from rare earth permanent magnets in hard disk drives. These recovered elements are returned to the production of wind turbine generators and EV motors, effectively closing a loop between the e-waste stream and the clean energy supply chain.

4.5 Architectural and Structural Reuse: Testing and Limitations

The most direct form of upcycling in construction is the reuse of structural or architectural components without reprocessing. This can include reclaimed timber beams, salvaged brick, precast concrete panels, and steel sections removed from deconstructed buildings and reinstated into new ones. The challenge is to demonstrate that the component meets current code requirements for its new application, without the benefit of mill certificates or load history records that would accompany new material.

Nondestructive testing (NDT) methods play a central role. For example, ultrasonic pulse velocity (UPV) testing can assess concrete integrity and estimate compressive strength in recovered precast panels. For reclaimed steel, tensile coupon testing to ASTM A370 establishes yield and tensile strength, while portable XRF identifies alloy chemistry and flags problematic elements. Reclaimed timber requires visual grading to the applicable Machine Stress Rated (MSR) or visual stress-grading standard, with additional attention to splits, checks, and biological degradation.

Upcycling is most effective when it is designed from the outset. A building with reuse in mind, using bolted rather than welded connections, standardized section sizes, and accessible joint details, makes material recovery at the end of life a realistic engineering proposition rather than an afterthought. This is the logic behind the circular design approach Design for Disassembly (DID).

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Module 5: Circular Economy Frameworks and Systems Thinking

The circular economy is a systemic response to the failure of linear material models. Conventional engineering practice accepts that materials flow from extraction to use to disposal. Circular economy, on the other hand, asks what would be required for materials to flow in closed loops instead, where materials retain value, remain accessible, and generate minimal waste. This would not just require better materials or better recycling, but also different ways of designing systems and different ways of organizing the industries that produce, use, and recover them.

5.1 Material Flow Analysis and Urban Metabolism

Material Flow Analysis (MFA) is the quantitative backbone of circular economy planning. It maps the flows and stocks of materials within a defined system, typically a building, city, region, or industrial sector. It accounts for inputs, transformations, outputs, and losses at each stage. The output is often rendered as a Sankey diagram, in which the width of each flow line is proportional to the mass or volume of material it represents. These visualizations make the scale of material losses immediately apparent in ways that tables of numbers often do not. Figure 8 is an example of a Sankey diagram, drawn from a MFA of global plastic production and waste management (Filiciotto & Rothenberg, 2021). The width of each flow line is proportional to the mass of material it represents, making the gap between what is recovered and what is lost to landfill, mismanagement, or the environmental immediately apparent.

Urban metabolism extends MFA to the city scale, treating a city as an organism that consumes, transforms, and excretes materials and energy. Kennedy et al. (2007) applied this framework to nine major global cities. They found that material throughput and waste generation are closely correlated with GDP per capita, but that the relationship varies significantly with urban form, infrastructure age, and policy environment. For engineers, the urban metabolism perspective reframes questions of infrastructure design. A city's stock of concrete, steel, timber, and polymer in roads, buildings, and utilities is treated as a material bank and not a sunk cost, and its eventual recovery and reuse should be designed for now.

In practice, MFA is used to identify the highest-impact intervention points in a material system. A city-level MFA of construction and demolition waste might reveal that concrete demolition waste accounts for 40% of total landfill mass, that clean concrete sub-base material is being imported at significant cost, and that the gap between supply and demand could be closed by establishing a regional construction and demolition waste processing facility. These findings have direct design and policy implications.

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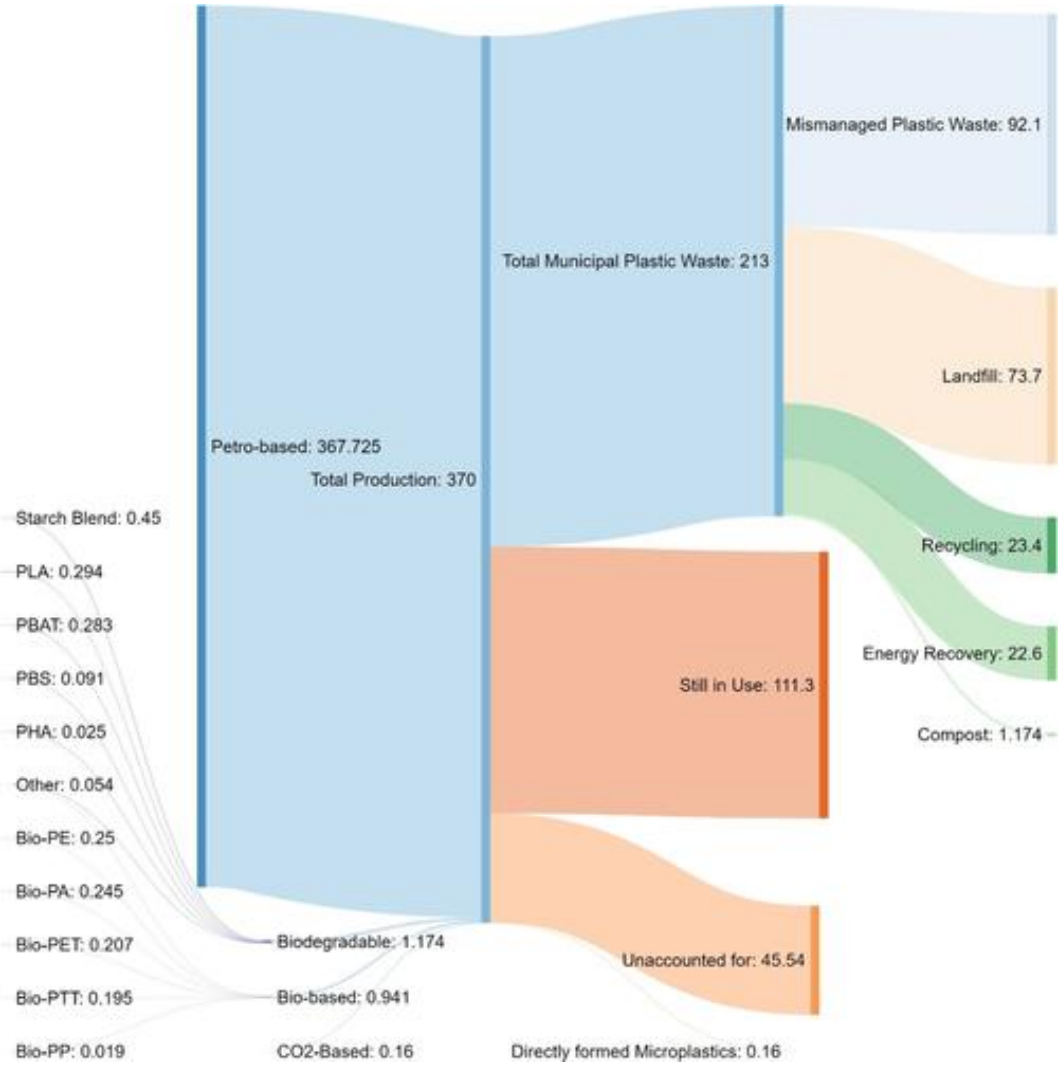


Figure 8. Sankey diagram showing the MFA for fossil-carbon-based, bio-degradable, bio-based, and CO2-based plastics in 2019. Values are in millions of tons. Source: Filiciotto & Rothenberg, 2021

5.2 Design for Disassembly and Modular Construction

Design for Disassembly (DfD) is the deliberate design of built assets so that their components can be removed, separated, and recovered at end of life without damaging either the component or the surrounding structure. In contrast to demolition, which recovers materials primarily as bulk rubble, DfD deconstruction can recover components for direct reuse, thus preserving the embodied energy and economic value that went into their original fabrication.

DfD principles affect decisions at every level of building design:

- **Connection level**: bolted joints are preferred over welded ones because they can be undone without cutting or grinding.
- **Structural system level**: column-beam frames offer more flexibility for sequential disassembly than monolithic concrete shear walls.
- **Building envelope level**: mechanically fixed cladding panels are easier to remove intact than adhesive-bonded systems.

These preferences are not absolute, they must be weighed against structural performance, cost, and durability requirements, however, they should be explicit considerations in the design process.

Modular construction amplifies these benefits. Prefabricated modules, manufactured offsite to standardized dimensions and transported to site for assembly, can be disconnected, transported, and reassembled at a new location if the original use becomes redundant. Case studies from the Netherlands and Scandinavia document schools and office buildings that have been successfully relocated, with the modular structure extended to a new function rather than demolished (Durmisevic et al., 2020). The enabling condition is the building passport, a digital record embedded in the BIM model, captures dimensions, material specifications, joint details, and structural assessments for every component.

5.3 The Pre-Demolition Audit and Deconstruction Planning

Before any structure is demolished or deconstructed, a pre-demolition audit (PDA) helps an engineer to identify what is recoverable, what is hazardous, and what the likely secondary market value of recovered materials might be. A PDA catalogues salvageable elements by material type, quantity, condition, and code-compliance status, producing an inventory that can be matched against demand in secondary materials markets.

Recovery rate targets for common materials in a typical commercial building are roughly 90 to 95% for structural steel by mass, 70 to 80% for dimensional timber where connections are bolted, 40 to 60% for precast concrete panels, and 30 to 50% for masonry depending on the mortar type and condition of the units (Durmisevic et al., 2020). Cast-in-place reinforced concrete offers limited recovery potential for structural reuse but high potential for recycled aggregate production, as discussed in Module 3.

Deconstruction logistics are operationally more complex than demolition. Disassembly must follow the reverse of the construction order to maintain structural stability, and components must be handled carefully to avoid damage during removal. Storage and protection from weathering between removal and reinstallation is a routine practical challenge that adds to the cost. These factors mean that the economic case for deconstruction over demolition is often marginal in current market conditions, which is why DfD thinking at the design stage matters as a building that is easy to take apart will cost less to deconstruct.

5.4 Reverse Logistics and Distributed Material Systems

Reverse logistics, as applied to construction materials, encompasses the network of processes that return recovered materials from the point of generation back into productive use. This includes collection, sorting, transport, storage, assessment, reprocessing, and redistribution. Designing these networks is an engineering problem with characteristics analogous to supply chain optimization, with the added complication that the quality and availability of recovered material is inherently variable.

An emerging approach to this is the distributed materials system. This is where small-scale processing facilities are located close to demolition and construction activity, reducing transportation distances and enabling faster matching of recovered supply to local demand. In urban contexts, building-scale or block-scale recovery operations, supported by automated sorting technology and AI-assisted material identification, can process construction and demolition waste at or near the point of generation. Additive manufacturing of custom formwork or repair components using locally recovered plastic waste is one application that the distributed model makes economically viable. Table 4 maps an example of a circular engineering workflow for a prefabricated building structure, from design intent through to end-of-life recovery.

Table 4. Circular engineering workflow for a prefabricated structure

Phase	Engineering action	Circular objective
Design	Modular dimensions; bolted connections; disassembly strategy documented in BIM	Maximize component reuse potential
Fabrication	Offsite prefabrication; minimal site waste	Reduce waste generation; increase precision
Use phase	Performance monitoring; material passport updates	Enable adaptability and future reconfiguration
Deconstruction	Systematic disassembly in reverse construction order; damage minimization	Facilitate high-quality component recovery
Redistribution	Assessment, transport, reinstallation; secondary market matching	Close the material loop; retain embodied value

The MFA, DfD, deconstruction planning, and reverse logistics frameworks are operational tools. They are increasingly referenced in infrastructure sustainability standards, including the Envision rating system, and are becoming baseline expectations in publicly funded projects. Module 6 applies this systems-level thinking to the specific materials that dominate civil and structural engineering practice.

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Module 6: Sustainable Materials for Civil, Structural, and Mechanical Applications

The materials that define civil and structural engineering practice, concrete, steel, and timber, are also the largest contributors to embodied carbon in the built environment. All three perform reliably and their supply chains are well-established. Their environmental footprint reflects the energy intensity of high-volume, high-performance production. Replacing these materials wholesale would neither be technically feasible nor economically realistic in most project contexts. The engineering challenge is to reduce their carbon intensity, extend their effective service life, and specify them in ways that keep them recoverable at end of life.

6.1 Low-Carbon Concrete

Portland cement clinker is responsible for the majority of concrete's embodied carbon. Clinker is the intermediate nodular product formed by heating limestone and clay in a kiln at temperatures above 1,450°C. It is then ground with gypsum to produce the finished cement powder. This process is thermodynamically demanding due to the fossil fuels required to heat the kiln to temperature, and releases CO_2 both from fuel combustion and from the decomposition of the limestone itself. Reducing clinker content is, therefore, the most direct path to lower-carbon concrete.

Supplementary cementitious materials (SCMs) are industrial byproducts that partially replace clinker in concrete mixes while contributing cementitious activity. Fly ash, a byproduct of coal combustion, is pozzolanic. It reacts with the calcium hydroxide released during cement hydration to form additional calcium silicate hydrate, the binding gel that gives concrete its strength. Class F fly ash, produced from anthracite or bituminous coal, is preferred for structural applications due to its low calcium content and consistent reactivity. Typical replacement levels range from 15 to 35% of cementitious content by mass, with higher fractions used in mass concrete where heat of hydration (thermal energy released) management is a primary design criterion.

Ground granulated blast furnace slag (GGBFS) is a byproduct of iron production with latent hydraulic activity, meaning it hydrates directly when combined with water, though at a slower rate than Portland cement. GGBFS replacement levels of 40 to 70% are common in applications requiring enhanced sulfate resistance or reduced permeability, such as in marine structures and underground infrastructure. Both fly ash and GGBFS are specified and tested under ASTM C618 and ASTM C989, respectively.

Geopolymers, or alkali-activated binders, eliminate clinker entirely. An aluminosilicate source material, typically fly ash or metakaolin, is mixed with an alkaline activator, such as sodium silicate or sodium hydroxide, to form a three-dimensional aluminosilicate gel with compressive strengths comparable to conventional concrete (Davidovits, 2015). Geopolymers offer excellent chemical resistance and fire performance, and their global warming potential can be 40 to 80% lower than ordinary Portland cement concrete, depending on the activator and energy source. Commercial adoption in the US has been slow, primarily because mix designs are sensitive to source material variability, durability data over decades of service are still accumulating, and there is no current US standard specifically governing geopolymer concrete, though some state DOTs have issued project-specific approvals.

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6.2 Recycled Aggregate Concrete

Recycled concrete aggregate (RCA) is produced by crushing waste concrete from demolition, then removing the rebar and other contaminants, and grading the resulting material by particle size. The engineering performance of RCA concrete is characterized by two persistent issues:

- Higher water absorption due to residual mortar adhered to aggregate particles.
- Greater variability in mechanical properties compared to natural aggregate concrete of equivalent design.

At replacement fractions up to 30% by mass of coarse aggregate, the performance penalty in compressive strength is modest, typically less than 10%, and can be compensated for by adjusting the water-cement ratio or using a superplasticizer to maintain workability (Kou & Poon, 2012). At replacement fractions above 50%, reductions in modulus of elasticity and tensile splitting strength become more significant, and RCA concrete is generally redirected to non-structural applications such as sub-base, pervious pavement, lean concrete fill, and mass fill. Mix design must account for the aggregate's absorption characteristics through saturated surface dry (SSD) condition testing per ASTM C127 on each RCA source batch, with mix water calculations adjusted accordingly.

6.3 Cross-Laminated Timber, Glulam, and Engineered Wood Products

Engineered timber systems offer one of the most favorable embodied carbon profiles of any structural material. This is because timber is a biogenic material that sequesters atmospheric carbon during the tree's growth. When that carbon is locked into a long-lived structural element, it represents a genuine offset against the production energy of the timber product itself. LCA of mass timber buildings consistently show net negative embodied carbon values for the structural system before any operational performance is considered (Pasanen et al., 2021).

Cross-laminated timber (CLT) is manufactured by bonding successive layers of dimension lumber in alternating grain directions under high pressure. This results in panels that are dimensionally stable, strong in both tension and compression, and capable of spanning in two directions. Glued laminated timber (glulam) bonds laminations in parallel grain orientation, producing beams and columns that can span longer distances than sawn timber of equivalent cross-section. Both products are governed by ANSI/APA standards and, since the 2021 International Building Code expanded its tall wood provisions, are permitted in US buildings up to 18 stories with appropriate fire protection.

Moisture management during construction and in service is critical, as moisture cycling causes dimensional change and can affect connection performance. In addition, fire resistance must be demonstrated through charring calculations or tested assembly ratings rather than assumed. In high-seismic zones, connection design for CLT requires careful attention to energy dissipation, as the panels themselves are stiff and brittle in the cross-grain direction. The US mass timber industry has accumulated significant project experience 2015, and the practical responses to moisture management, fire resistance, and seismic connection design are well

documented. Engineers moving to mass timber from steel and concrete framing will find that the detailing demands are less familiar than the structural concepts, therefore, early engagement with a specialist timber engineer on connection design is advisable on their first projects.

6.4 Steel Reuse: Structural Integrity, Fatigue Reanalysis, and Weldability

Reusing structural steel from deconstructed buildings avoids the energy of remelting while recovering a material whose properties, when properly documented and tested, are well-defined and reliable. The practical obstacles are mainly logistical, establishing structural identity, demonstrating current code compliance, and integrating reclaimed sections into new structural geometry.

The first step is establishing the material's grade and properties. Where mill certificates survive from the original construction, these provide a starting point, but they should be corroborated with physical testing. Coupon testing to ASTM A370 provides tensile and yield strength, while portable XRF identifies alloy chemistry. For sections fabricated before ASTM A992 was introduced in 1997, the standard that limits carbon equivalence and yield-to-tensile ratio for wide-flange shapes, weldability should be evaluated by calculating the carbon equivalent from the XRF analysis, with preheating applied if the value exceeds the threshold in AWS D1.1.

Fatigue history will require engineering judgment. Visual inspection, magnetic particle testing, and ultrasonic testing can identify existing cracks and near-surface discontinuities. For sections recovered from buildings without significant dynamic loading history, and where the new application does not involve fatigue-critical details, conservative design factors applied to the tested properties typically provide an adequate safety margin. BIM-based material passports that recorded load history, connection details, and inspection results for each recoverable member, provide the documentary foundation that makes structural steel reuse a defensible proposition. Several European circular construction projects have demonstrated that this level of traceability is practically achievable when documentation discipline is maintained from the original construction phase (Durmisevic et al., 2020).

6.5 Phase-Change Materials and Building-Integrated Photovoltaics

Two energy-related material technologies warrant specific attention in civil and structural engineering applications. They are phase-change materials for passive thermal regulation, and photovoltaic systems integrated into the building envelope.

Phase-change materials (PCMs) absorb or release latent heat during solid-liquid transitions, making them effective as passive thermal buffers in building envelopes. Common PCMs include paraffin waxes and hydrated salts, often microencapsulated and incorporated into wallboard, concrete, or insulation panels. By absorbing heat during peak temperature periods and releasing it as temperatures fall, PCM-integrated assemblies reduce the magnitude of diurnal temperature swings, lowering peak HVAC load without mechanical intervention. A simulation study by Zhang et al. (2019) found cooling load reductions of 20 to 30% in hot climates for PCM-integrated external wall assemblies. Selection criteria include melting point

matched to the desired indoor temperature range, latent heat capacity, and long-term cycling stability. It should be noted that some hydrated salt PCMs suffer from phase segregation after repeated melt-freeze cycles that reduces their effective storage capacity over time.

Building-integrated photovoltaics (BIPV) incorporate PV cells directly into the building envelope as roof shingles, facade cladding, glazed canopies, or spandrel panels. The structural and materials engineering considerations include:

- The loads imposed by panel weight and wind on the supporting framing.
- The thermal performance of the assembly (PV cells lose efficiency at elevated temperatures, making ventilated cavity designs preferable)
- The fire resistance classification of the composite assembly.

Crystalline silicon remains the dominant technology for BIPV due to its efficiency and established performance record. Thin-film cadmium telluride (CdTe) is used in some commercial facade applications at lower manufacturing energy per watt. Material compatibility between the PV laminate, structural sealants, and supporting framing requires verification over the expected service life, as differential thermal expansion can cause seal failure in poorly detailed systems. Table 5 provides a comparative overview of the sustainable material options discussed in this module.

This field is evolving rapidly, driven by changes in code requirements, improvements in manufacturing, and the commercial maturation of technologies. What remains constant is the analytical framework used, including embodied carbon, durability, recyclability, and code compliance as co-equal design criteria. The next module examines the certification systems and regulatory frameworks that formalize this multi-criteria approach in professional practice.

Table 5. Comparison of sustainable civil and structural materials by relative embodied carbon, applicable US standard, primary application, and recyclability

Material	**Embodied Carbon (kg CO_2-e/kg)**	**Key US standard**	**Primary application**	**Recyclability**
OPC concrete (50 MPa)	High	ACI 318	Structural frames, foundations	Low (aggregate recovery only)
SCM concrete (30% fly ash)	Medium	ACI 318, ASTM C618	General structural concrete	Medium
RCA concrete (<30% replacement)	Medium	ASTM C33, C39	Non-critical structural, sub-base	Medium
Geopolymer concrete	Low	No current US standard	Industrial flooring, repair mortars	Varies by activator
Cross-laminated timber (CLT)	Negative (biogenic sequestration)	ANSI/APA PRG 320	Mid-rise floors, walls, roofs	High (biogenic carbon stored)
Glulam	Negative (biogenic sequestration)	ANSI A190.1	Long-span beams, columns, arches	High (biogenic carbon stored)
Virgin structural steel	High	ASTM A992	Frames, columns, beams	90–95%
EAF recycled structural steel	Low – Medium	ASTM A992	Frames, columns, beams	100%

Note: Embodied carbon ratings are qualitative and reflect general industry consensus. Project-specific values should be obtained from verified Environmental Product Declarations for the relevant product and region; the EC# tool maintained by the Carbon Leadership Forum and the Inventory of Carbon and Energy (ICE) database are recommended starting points.

Module 7: Codes, Certification Systems, and Integration into Practice

The certification systems and regulatory frameworks that govern sustainable material practice in the United States are primarily tools for making environmental performance legible, comparable, and actionable. Without a consistent framework for reporting embodied carbon, an engineer specifying a low-carbon concrete cannot demonstrate its value to a client, a certifier, or a regulator. In addition, a standard definition of recycled content, claims about material circularity aids in verification and converting engineering decisions into documented, auditable performance.

7.1 LEED v4.1, Envision, and the WELL Building Standard

The Leadership in Energy and Environmental Design (LEED) rating system, maintained by the US Green Building Council, is the most widely adopted building sustainability certification in the United States. Version 4.1, the current applicable edition, includes a Materials and Resources (MR) category that rewards material transparency, lifecycle optimization, and responsible sourcing. Credits are available for products with third party-verified Environmental Product Declarations, for materials with disclosed ingredient lists, for bio-based and recycled content, and for building reuse and deconstruction practices. The awarded credits correspond to the level of LEED certification (Figure 9).



Figure 9. LEED certifications and their corresponding credit points (LEED)

LEED v4.1 represents a significant shift from earlier versions in that it moves away from prescriptive criteria toward performance-based disclosure. Rather than awarding credits for a specified percentage of recycled content, it awards credits for Environmental Product Declarations (EPDs) that quantify lifecycle impacts regardless of whether those impacts are low or high in absolute terms. The logic is that disclosure precedes improvement (you cannot reduce what you have not measured). This approach places a premium on supplier engagement. Engineers specifying materials for LEED projects need EPDs that comply with applicable product category rules.

Envision, developed by the Institute for Sustainable Infrastructure, applies a comparable framework to infrastructure projects covering roads, bridges, water systems, and energy networks that fall outside the scope of LEED. Its Resource Allocation category includes credits for material reuse, lifecycle costing, and reduced-impact materials. For engineers working on public infrastructure projects, Envision provides a structured basis for evaluating material sustainability that LEED does not cover.

The **WELL Building Standard**, developed by the International WELL Building Institute, focuses on occupant health rather than environmental impact, but it intersects with material sustainability through its air

quality requirements. WELL limits volatile organic compounds (VOC) emissions from adhesives, sealants, flooring, and paints, which effectively constrains the use of high-emission materials regardless of their embodied carbon profile. For engineers working on interiors-heavy projects, WELL compliance may influence material selection more directly than LEED.

7.2 ISO, ASTM, and EN Standards for Sustainable Materials

The technical standards that underpin the certification systems define the methodologies for data collection, impact assessment, and product disclosure:

- ISO 14040 and ISO 14044 establish the principles and framework for LCA.
- ISO 21930 provides the product category rules for environmental declarations of construction products, ensuring that EPDs from different manufacturers are methodologically comparable.
- ASTM E2129 covers data collection for sustainability assessment of building products.
- ASTM D6866 establishes the method for determining bio-based content by radiocarbon analysis.

In the European context, EN 15804 serves the same function as ISO 21930 for EPDs, and many US manufacturers of internationally traded products now issue EPDs that comply with both standards to serve both markets. Engineers working on projects with international supply chains should verify which standard a given EPD was prepared under, as the two are broadly compatible, but differ in certain impact category definitions and system boundary conventions.

7.3 Environmental Product Declarations and Material Passports

An EPD is a third party-verified, ISO-compliant document that quantifies the environmental impacts of a product across its lifecycle. It is expressed in standard impact categories including global warming potential, ozone depletion, eutrophication, acidification. EPDs allow engineers to compare the environmental performance of competing products, provided those products share a common product category rule (PCR). For example, an EPD for ordinary Portland cement cannot be directly compared to one for a blended SCM cement unless both were prepared under the same PCR.

EPDs in the US construction industry has expanded considerably since LEED v4 made EPDs a credit criterion. The Carbon Leadership Forum maintains a database of building material EPDs, and the Transparency Catalog aggregates EPDs across product categories. For engineers, the practical question is which EPD to request from a supplier, and whether the declared values reflect the product that will actually be delivered to the project site. Batch-to-batch variation in SCM content, aggregate source, or admixture formulation can affect embodied carbon values by 10 to 20%, and an EPD based on an industry average may not accurately represent a specific regional product.

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Material passports extend this logic from individual products to entire buildings. A material passport is a digital record capturing the physical, chemical, and structural characteristics of every material and component in a building, including manufacturer specifications, EPD references, connection details, and maintenance history. Enabled by BIM platforms, material passports serve a dual purpose:

- They support maintenance and renovation decisions during the building's life.
- They enable confident recovery and reuse decisions at end of life.

The Buildings as Material Banks initiative, a European research and pilot program, has demonstrated the concept at building scale and produced open tools for its implementation.

7.4 Procurement, Regulatory Compliance, and Material Foresight

US procurement policy for sustainable materials is evolving from voluntary guidance to enforceable requirements. California's Buy Clean California Act (AB 262) requires state-funded projects to report and, in some categories, comply with embodied carbon thresholds for structural steel, flat glass, mineral wool insulation, and carbon steel rebar. Federal executive orders have directed agencies to prefer lower embodied carbon construction materials in federally funded projects. In addition, several state transportation departments have introduced EPD submission requirements for bridge and highway construction materials, and this trend appears likely to continue.

Beyond current requirements, engineers practicing in this space benefit from what might be called material foresight. This is the systematic monitoring of emerging regulatory requirements, supply chain risks, and technological developments that could affect material availability or compliance status. Per- and polyfluoroalkyl substances (PFAS) in construction coatings and firefighting foams represent one example where regulatory restrictions are tightening across multiple US states. Engineers who have begun substituting PFAS-containing products are better positioned than those waiting for federal requirements to be finalized before acting. Critical mineral supply chain risks, particularly for materials used in building management systems and on-site renewable energy equipment, represent another area where early-stage awareness translates into more resilient project specifications.

Table 6 maps the interaction between engineering design activities, supporting standards and tools, and formal certification and regulatory outcomes, illustrating how each technical decision connects to a compliance pathway.

The certification systems, standards, and procurement policies examined in this module provide the formal structure within which sustainable material decisions are made and documented. They are not a substitute for engineering judgment, which requires balancing structural performance, lifecycle impact, cost, supply chain reliability, and code compliance within the constraints of each specific project. The aim of this course is to equip that judgment with the analytical tools, materials science understanding, and systems-level thinking that is required for responsible practice.

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Table 6. Integration of certification and regulatory systems in sustainable materials engineering workflow

Engineering activity	**Supporting tool / Standard**	**Certification or compliance pathway**
Material specification	EPD, ISO 21930, ASTM E2129	LEED MR credits; Buy Clean California compliance
Life cycle Assessment	ISO 14040/44, EN 15804, TRACI	LEED, Envision; federal/state regulatory disclosure
Design for Disassembly	BIM material passport; Envision guidance	Envision RE credits; circular procurement criteria
Embodied carbon reporting	EC3 tool, One Click LCA	LEED v4.1; federal executive order requirements
Procurement	Green Public Procurement guides; AB 262	Regulatory compliance; embodied carbon thresholds

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Appendix A

This appendix provides two worked numerical examples corresponding to material covered in Modules 2 and 6. They are intended as practical reference calculations, not as design templates. Values used are illustrative; engineers should substitute project-specific quantities and current published intensity factors.

A1. Embodied Energy Calculation

Formula: $E_{total} = \Sigma (Q_i \times EI_i)$

Where:

E_{total} = Total embodied energy (MJ)

Q_i = Quantity of material i (kg or m^3)

EI_i = Embodied energy intensity of material i (MJ/kg or MJ/m^3)

Scenario: A reinforced concrete foundation consists of 10,000 kg of concrete with an embodied energy intensity of 1.5 MJ/kg, and 1,000 kg of reinforcing steel with an embodied energy intensity of 35 MJ/kg (EAF recycled content). The engineer might perform this calculation to evaluate whether the foundation design meets an embodies energy target set by a green building certification program, to compare alternative material specifications, or to establish a baseline figure for a whole-building LCA.

Calculation:

Concrete contribution: 10,000 kg × 1.5 MJ/kg = 15,000 MJ

Steel contribution: 1,000 kg × 35 MJ/kg = 35,000 MJ

E_{total} = 15,000 + 35,000 = 50,000 MJ

Interpretation: The reinforcing steel accounts for approximately 70% of the total embodied energy despite representing only 9% of the total mass. This illustrates why material substitution strategies that target high-intensity materials, even at relatively low quantities, typically offer greater embodied energy savings than replacing larger volumes of lower-intensity materials such as aggregate or fill concrete.

A2. Embodied Energy Calculation

Scenario: A structural concrete mix is designed at 40 MPa compressive strength. Two options are compared:

- 100% OPC at an embodied carbon intensity of 0.83 kg CO_2-eq/kg cement.
- 30% Class F fly ash replacing OPC, with fly ash at 0.027 kg CO_2-eq/kg.

The binder content per cubic meter of concrete is 380 kg.

An engineer might perform this calculation to justify a material substitution decision to a client or certifier, to demonstrate compliance with an embodied carbon threshold on a publicly funded project, or to quantify the environmental benefit of specifying an SCM concrete mix over a standard OPC mix.

***Option A (100% OPC)**:*

Binder carbon = 380 kg × 0.83 kg CO_2-eq/kg = 315.4 kg CO_2-eq/m^3

***Option B (30% fly ash replacement)**:*

OPC content = 380 × 0.70 = 266 kg; fly ash content = 380 × 0.30 = 114 kg

OPC carbon = 266 kg × 0.83 = 220.8 kg CO_2-eq

Fly ash carbon = 114 kg × 0.027 = 3.1 kg CO_2-eq

Total binder carbon = 220.8 + 3.1 = 223.9 kg CO_2-eq/m^3

Carbon reduction = (315.4 − 223.9) / 315.4 = 29%

Interpretation: A 30% fly ash replacement yields approximately 29% reduction in binder-related embodied carbon. For a 500 m^3 pour, this represents a saving of approximately 45.7 tons of CO_2-equivalent, without modification to the structural design. Engineers should confirm that the fly ash source meets ASTM C618 Class F requirements and that the mix is tested for compliance with the strength and durability criteria of the project specification before proceeding.

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