

LEARNING MADE EASY

PTC Special Edition

# Product Sustainability

for  
**dummies**<sup>®</sup>  
A Wiley Brand



Design for  
lower footprints

—  
Manufacture  
efficiently

—  
Service and circulate  
profitably

Compliments  
of



ptc<sup>®</sup>

Dave Duncan

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From planes to medical devices to wind turbines to computers, PTC's unique portfolio of software solutions enables companies to transform how they design, make, and maintain their products.

As a global leader in product life cycle management, PTC's software supports the management of data throughout the entire product life cycle to help simplify product complexity and drive excellence in engineering and design, efficiency in manufacturing and supply chain, and optimization in operations and service.

Companies of all sizes rely on PTC because of its portfolio of digital technologies, extensive partner network, and industry expertise. Together, its software supports each stage of the product life cycle and includes market-leading product life cycle management (PLM), application life cycle management (ALM), computer-aided design (CAD), and service life cycle management (SLM).

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The purpose at PTC is to do more than just imagine a better world; it's to help create it. This purpose is reflected across its values, sustainability initiatives, social impact efforts, and software solutions.



# Product Sustainability

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**by Dave Duncan**

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A Wiley Brand

# Product Sustainability For Dummies®, PTC Special Edition

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# Introduction

**B**etter, cleaner, and more profitable products — it's time to progress product sustainability beyond lofty strategy messaging into the hands of leaders like you who design, manufacture, service, and retire products. Product footprints don't improve until you act, and with about 80 percent of a product's footprint determined by design decisions (including manufacturing and service planning), you're the eco and business heroes that profitably make it happen.

*Sustainability* is a new and fast-moving topic for most folks. So, don't worry if you lack veteran knowledge; if you read this book, you'll soon be able to collaborate with the best experts. Sustainability practitioners are a welcoming group.

Think of university and college intramural sports. If you want to pick up soccer, that may be tough because most players started when they were small children. But most everyone is new at ultimate frisbee, so you can quickly get on the field and contribute to the team.

Product sustainability is like ultimate frisbee. You just need to grasp the fundamentals to begin playing. Throughout this book, I emphasize three main points that I believe to be true:

- » **Product footprint reduction is sustainable when it's profitable.** You can likely reduce half or more of your product footprints in the next five to ten years with actions you should take anyway for financial benefit. Additional techniques and technologies are scaling for you to profitably tackle much of the rest in the 2030s.
- » **Leave politics out of the discussion.** Political sentiments come and go. Technology's march toward better products with less cost and less footprint is irreversible and universally praised for its durability, energy bill savings, and supply chain resiliency — no matter what side of the fence you're on or if you're in the middle.

» You don't need to overhaul how you work today. David Genter, retired systems design engineering director, notes that product life cycle practitioners are already balancing cost trade-offs across several dimensions of quality (performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality). You just need to add a ninth dimension: sustainability.

So, grab your secondhand, PFAS-free, 100-percent-recyclable polyethylene frisbee, and let's get started!

## About This Book

This book contains six chapters that explore the following:

- » Level setting product sustainability to frame the topic and where you should focus
- » The problems caused by our products and the legal landscape driving footprint reductions
- » The business case — aligning footprint reduction with financial priorities
- » Design for Sustainability (DfS) principles
- » Managing footprints with full life cycle thinking
- » Ten life cycle tips to profitably reduce product footprints

Each chapter is written to stand on its own. So, if you see a topic that excites you, feel free to jump ahead to that chapter. You can read this book in any order that suits you.

## Foolish Assumptions

Sustainability is a broad topic, but product sustainability is more focused. Therefore, I made some loose assumptions about you, the reader:

- » First, you want to understand sustainability for discretely manufactured products. These include equipment like planes, trains, automobiles, footwear, X-ray machines,

toaster ovens, smartphones, elevators, bulldozers, valves, and pretty much anything else solid that hurts if you dropped it on your foot. I don't cover process manufacturing in this book, which would include oils, gasses, chemicals, food, beer, material commodities, and other recipe-based products.

- » Second, you fit one of two backgrounds, *product life cycle practitioner* or *corporate sustainability* (or an executive over these functions). On the product life cycle side, you could generalize or specialize in a broad range of functions like engineering, manufacturing planning, service management, IT, product management, sourcing, compliance, or more.
- » If you're not in discrete manufacturing with product or sustainability roles, this book is still a good read to learn how this industry tackles reducing footprints.

## Icons Used in This Book

I occasionally use special icons to focus attention on important items throughout the book. Here's what you find:



REMEMBER

This icon reminds you about information that's worth recalling.



TIP

Expect to find something useful or helpful by way of suggestions, advice, or observations here that help you leverage experiences from other implementations.



WARNING

Warning icons are meant to get your attention to steer you clear of potholes, money pits, and other hazards. Paying extra attention to these parts in the book helps you avoid unnecessary roadblocks.



TECHNICAL  
STUFF

This icon may be taken in one of two ways: Techies will zero in on the juicy and significant details that follow; others will happily skip ahead to the next paragraph.

# Beyond the Book

This book is a good primer, but the depth for some topics is limited in these 64 pages. If you're wondering where you can learn more, check out [PTC.com/beyond-the-book](https://www.ptc.com/beyond-the-book). I also reference this link throughout the book, so you have one convenient link for all your resources.

## IN THIS CHAPTER

- » Understanding sustainability
- » Seeing the impact of our products
- » Working with compliance
- » Chasing profitability
- » Using life cycle thinking to reduce footprints

# Chapter **1**

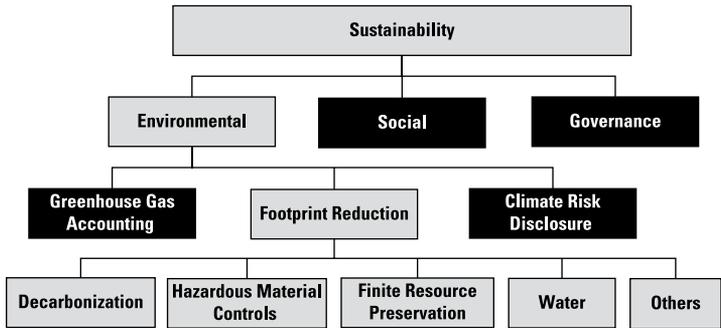
# Level Setting Product Sustainability

**S***ustainability* has many contexts (and many syllables!), so it can be confusing to figure out where you fit in the journey. This chapter explores the principles of product sustainability and where product life cycle practitioners make the most impact for discrete products. Subsequent chapters drill further into these topics.

## Defining Sustainability

In 1987, the United Nations (UN) Brundtland Commission defined sustainability, and that definition still stands up well today. *Sustainability* is meeting the needs of today without compromising future generations in meeting their own needs. We all enjoy conditioned homes, convenient transportation, adventurous vacations, and nourishing meals. You want your great-great-great-great-great-great-great grand descendants to have similar or better opportunities while enjoying thriving natural habitats. The spirit of sustainability balances good living with environmental preservation, and you need replenishing ways to enjoy your products and services.

Sustainability includes three branches: environmental, social, and governance. Each of these breaks down further, as shown in Figure 1-1. The lighter tiles in Figure 1-1 are your likely focus areas for the product life cycles you manage (although some products like fire alarms or weapons may add positive or negative social impacts).



**FIGURE 1-1:** The common sustainability focus for product life cycle practitioners in discrete manufacturing.

You may have heard the term *ESG* interchanged with the word *sustainability*. *ESG* stands for *environmental, social, and governance* and is anchored on the United Nations' 17 sustainable development goals (SDG). The 17 goals' premise is that even if we have the technological means to better preserve the environment (which we mostly do today), we'll never implement it with necessary speed and scale if citizens and nations are uncooperative. (Don't worry; I'm not getting political here. Keep reading — I explain how to keep your contributions politically neutral.)

Social goals like No Poverty (#1) and governance goals like Peace, Justice, and Strong Institutions (#16) are integral to driving the environmental E goals, which are the ones I focus on in this book. All product life cycle practitioners play in the E space, pursued with science-backed technology and business value. The two of the 17 goals I focus on are

- » **#9 — Industry, Innovation, and Infrastructure:** These are the design elements of the product life cycle.
- » **#12 — Responsible Consumption and Production:** These are the manufacturing, service, and circular execution elements of the product life cycle.



TECHNICAL  
STUFF

Some S goals around supply chain human rights are important compliance items for material and component selections in your designs. You don't directly judge your suppliers, though. Instead, your sourcing group will do this for you and present you with lists of approved vendors based on conflict minerals compliance and other factors.

## Making a Mess with Our Products

In the preceding section, I identify E as the main ESG focus for this book within the UN's SDG framework. In this section, I introduce the environmental issues within your businesses that must improve. Chapter 2 details it further.

Our products commonly have three significant negative impacts on our environment:

» **Hazardous materials:** Hazardous substances like mercury, lead, and cadmium harm humans and other organisms. Based on recent research, plastics can be gnarly, too. Metals like steel and aluminum are mostly inert in products, but their extraction leaves tailings that can pollute water and soil.

In mining, tailings are the materials left over after the separation process of ore.

» **Greenhouse gas emissions:** In product life cycles, greenhouse gas emissions can come from anything that burns fossil fuels to be produced or used. An example is cars that burn gas for driving. Other machines use electricity, and the upstream generation of this electricity may burn fossil fuels like coal or natural gas. Even non-powered products have embodied carbon used to create them. **Note:** Some products' activities may emit additional warming gasses like refrigerants.

Embodied carbon is the sum of greenhouse gas emissions used to create products with activities like mining, material processing, manufacturing, and transport.

» **Finite resource depletion:** Finite resource depletion considers how there's only so much of an extractable



TECHNICAL  
STUFF



TECHNICAL  
STUFF

resource like metals, minerals, and oil in Earth's geosphere. If we continue to consume in linear ways, such as trucks burning diesel or broken products trashed for incineration and landfill, at some point, future generations will no longer have these productive supply chains.

Environmental corporate responsibility mitigates these externalities — often voluntarily — to drive business value. Increasingly, regulations force corporations toward responsibility.

## Compliance — The Sticks

*Compliance* is obeying regulations, which I detail in Chapter 2. Hazardous material compliance has been scaled in our industries for about 20 years. You probably already have mature programs for hazardous material controls.

Unlike hazardous material controls, decarbonization and circularity are new compliance areas. There are many national level rules, but the driving global force is through the European Union's (EU) Corporate Sustainability Reporting Directive (CSRD). CSRD broadly spans ESG topics and also applies internationally for exporters to the EU. So, if you sell in the EU, or work with supply companies who do, you may have these compliance pressures.

For *product life cycle practitioners*, CSRD and its related rules compel manufacturers to

- » Measure product footprints
- » Commit to quantified footprint reductions
- » Circulate materials from end-of-life parts and products



REMEMBER

From an *economist's perspective*, global warming is a market failure in managing the externality of greenhouse gas emissions. Increasingly, regulatory “sticks” address this externality.

In pure *business terms*, the cost of noncompliance is severe. First, there are legal penalties, which differ per country and trading bloc. For business-to-business (B2B) manufacturers, these penalties may be small in comparison to the risks of lost business — customers may disqualify noncompliant suppliers.



TIP

Don't view this compliance as a drag. Instead, it raises the bar for product designs, competitively levels playing fields, and opens new lucrative business opportunities.

## Profitability — The Carrots

With compliance, your business case can simply be, “Boss, we gotta do this!” But that cost-of-doing-business approach won't invite differentiating investment, and the opportunity is fortunately much better than that.

At its core, product sustainability drives visibility to pinpoint value and efficiency priorities. It then pairs these priority opportunities with both proven and cutting-edge solutions. Even when discounting compliance value, the outcomes align with business priorities:

- » Lower material and component costs through recycling, lightweighting, scrap avoidance, and embedded software.
- » Lower production costs with energy efficiency, remanufacturing, and refurbishment.
- » Focus designs on customer value, elegantly avoiding over-engineering.
- » Increase initial sales revenue with durability, efficiency, and embedded software innovation.
- » Increase after-sales revenue with efficient service, upgrades, and secondary product markets.
- » Improve supply chain visibility and risk resilience.
- » Expand markets with brand reputation and green premiums.

It's a no-brainer! This list is good for business and good for the environment, and it keeps the boss out of courtrooms.



REMEMBER

Product footprint reductions are sustainable when they're profitable, and profitability is the carrot on the stick (see the preceding section) that you're chasing. Focus on the easier wins first and then push on the tougher increments. Some opportunities like renewable electrification, dematerialization, distributed manufacturing, and servitization are profitable in common contexts today. Other opportunities may be pre-scale but offer first-mover

advantage today or second-phase options tomorrow. You can dig into value details more in Chapter 3.

## Reducing Footprints with Life Cycle Thinking

Yesterday's sustainability programs focused on operational footprints — mainly in factory operations where footprints are visible in the corporation: reduce scrap, reduce energy used, and switch to renewable energy where possible. Also apply emissions capture devices where required or profitable.

However, in the new world of CSRD compliance plus investor and customer expectations, manufacturers have full life cycle responsibility for their products, not just within their factory walls. For the materials and components arriving at the factory receiving dock, manufacturers are now responsible for all the upstream impacts of this supply in mining, transport, material processing, and lower-tier manufacturing. Manufacturers also have responsibility for the downstream (after sales) impacts — operating energy, service, and waste footprints of their products.



REMEMBER

In discrete manufacturing, typically 1 to 10 percent of the footprint is operational. The other 90 to 99 percent is upstream and downstream. Focusing sustainability on factory operations won't cut it anymore — responsibility extends to the entire product life cycle. For this reason, product life cycle practitioners are central to the solution. Companies need robust processes and digital backbones to profitably iterate product footprint reductions.

Head to Chapter 4 for more coverage on sustainability design principles, and Chapter 5 details their life cycle implementations.

- » Exploring how products harm the environment
- » Understanding laws to reduce harm

# Chapter 2

## Solving Ecology and Compliance Problems

The topics in this chapter are essential for understanding the problems you need to solve in product sustainability. I don't want you to be too bummed out while reading this. Just know that you have to take the bad with the good.

In this chapter, you explore how products harm our environment and what activities contribute most to these negative impacts. You also see how I frame the regulations that drive manufacturers to mitigate these product externalities.

### Figuring Out the Problem

Manufactured products simply aren't sustainable today. They pollute and warm the planet and consume finite resources. When your marketing departments put out statements about your products, they should avoid phrases like *sustainable product* or *green product*. While you may iterate toward net-zero footprints, for now, it's better to stick to phrases like *more sustainable products*.



*Net zero* refers to reducing your company's greenhouse gas emissions significantly (generally over 90 percent from where you started because carbon removal has practical limits), and buying carbon removal for the remaining to net out as zero emissions.

## The nine planetary boundaries

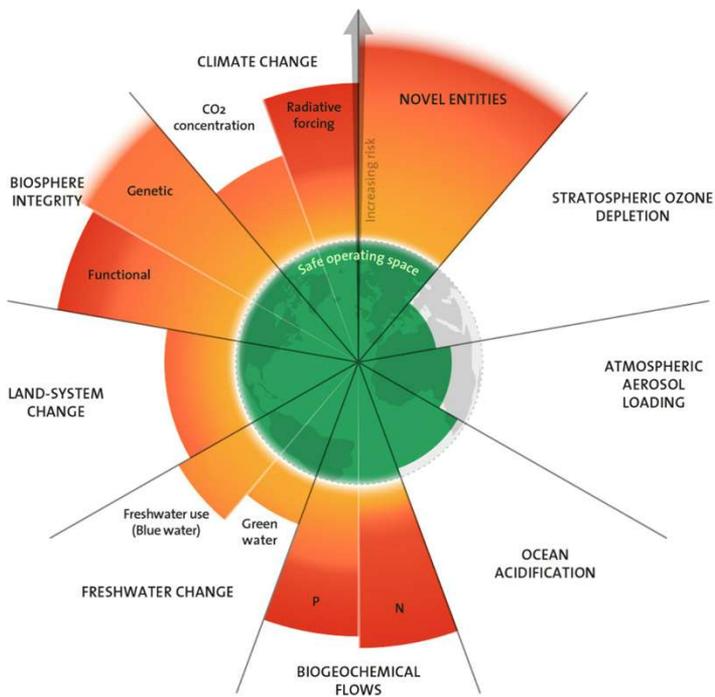
Earth keeps us alive with a thin atmosphere (air), thin biosphere (ground and soil), and thick geosphere (crust and mantle). With over 8 billion humans roaming about and seeking rich world living standards, humans add stress to these life support systems in new ways.

The Stockholm Resilience Centre uses the nine planetary boundaries to track these problems. This framework illustrates nine dimensions of badness, shown in Figure 2-1, where human activity damages the planet. Boundaries within the safe operating space are okay for the long term. The ones beyond it aren't. These boundaries need to be brought back into the safe operating space, and ideally gracefully before Mother Nature reacts with drastic balancing measures.

With many breached safe operating spaces shown in Figure 2-1, this picture may look like doom and gloom, but there are ways to improve each boundary. One success story is the stratospheric ozone depletion boundary, which was the most publicly recognized boundary failure in the late 1980s. Coolants and other chemicals were disintegrating the atmosphere's ozone layer, which could've led to excessive radiation on humans and other organisms. Fortunately, technology had a way (substitute chemicals at reasonable cost), and world leaders had a will (the Montreal Protocol). Now, this boundary is the best one, the ozone layer is healing, and you still have affordable air conditioning and cold drinks.

In discrete manufacturing, products may help with other boundaries. For example:

- » Precision farming avoids excessive fertilization and pesticides with advanced tractors, seeders, drones, and more. This improves biochemical flows.
- » Water treatment technology helps make freshwater cleaner and safer.



Source: Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009.

**FIGURE 2-1:** The nine planetary boundaries.

If you have these helping products, kudos to you! Markets will reward your healing powers.



A few of the nine boundaries endure damage from our products. One example is novel entities (hazardous materials like micro-plastics). The other two are climate change and ocean acidification (both caused by greenhouse gas emissions). Fortunately, like the stratospheric ozone depletion boundary, you increasingly have the technical ways and business-aligned means to improve these boundary conditions.

## Decarbonization

*Decarbonization* is the act of reducing greenhouse gas (GHG) emissions. GHG emissions are mostly carbon dioxide, but they include other warming gasses like methane.

Many consider climate change to be the most urgent boundary in the nine planetary boundaries. In discrete manufacturing, the contribution of GHG is mostly from burning fossil fuel across the value chain.



WARNING

Figure 2-2 illustrates that problem. Burning biosphere materials like a fallen tree in a forest can be cycled quickly back into new plant matter. However, fossil fuels have been locked in the deeper geosphere for millions of years. Burning them into Earth’s atmosphere creates carbon imbalance because they don’t cycle back into the geosphere on their own.

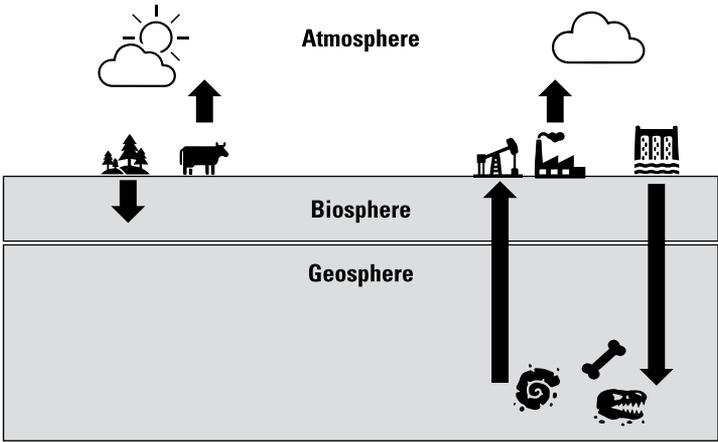


FIGURE 2-2: The carbon cycle.

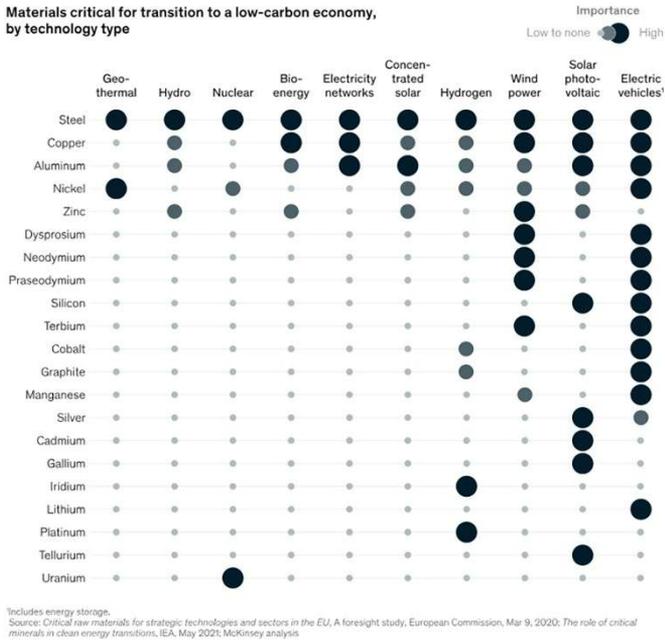
Carbon removal machines from providers like Climeworks and Charm Industrial can pump carbon back into the geosphere. Optimistically, through the 2030s and 2040s, carbon removal technologies like these can scale to affordably pump 10 percent of the current emissions rates back into the geosphere. To reach net zero with carbon removal, you don’t need to stop using fossil fuels entirely, but you do need to use much less of them and with cleaner blends (natural gas burns 50 percent cleaner than coal, and oil grades are in between).

## Finite resource preservation

Discrete manufacturing has responsibilities to use less fossil fuel and control hazardous materials. If we’re going to keep more of the coal, oil, and gas in the geosphere (for environmental and cost reasons), there’s a massive amount of metal and minerals we

need to dig out of the ground over the next few decades to replace our energy infrastructure with things like wind turbines, batteries, solar panels, nuclear plants, and smart grids.

The McKinsey chart, shown in Figure 2-3, shows the relative needs of raw materials for the energy transition. Other products like home electronics, cars, airplanes, home appliances, and medical devices need these same materials.



**FIGURE 2-3:** Economically critical finite materials.

For more on Figure 2-3, visit [PTC.com/beyond-the-book](https://www.ptc.com/beyond-the-book).

The problem in the United States, Europe, Japan, South Korea, and other industrial economies is that these materials aren't often available domestically in sufficient quantities. As a result, while circularity can have remarkable environmental benefits, it's now boosted by national security mandates to keep critical materials utilized within the economies.



**REMEMBER**

Circularity has staying power in advanced manufacturing countries because of its economic necessity. Production lines halt without sufficient materials.

# Regulating the Problems

To reduce discrete manufacturing’s mess, regulations force action on hazardous material controls, decarbonization, and circularity. *Regulations* are market conditions to incorporate in your product plans and designs.

The breadth of sustainability regulations and standards can be intimidating, though. Legal and Compliance manage these, and they guide you to where they need your participation. Fortunately, for life cycle practitioners, key regulations boil down to a short list of expected actions commonly referenced in product life cycle programs. Those are referenced in Table 2-1.

**TABLE 2-1** Regulations Driving Footprint Reduction

Regulation or Directive	Relevance with Product Life Cycle
Corporate Sustainability Reporting Directive (CSRD)	Requires in-scope companies to report their environmental impacts. EU manufacturers and their global supply chains may be in-scope (think of almost every medium and large discrete manufacturer in the world).
Corporate Sustainability Due Diligence Directive (CSDDD)	Related to the CSRD. Where CSRD requires <i>disclosures</i> , CSDDD requires <i>actions</i> . Obliges companies to reduce their environmental impacts in auditable ways. There’s special focus on decarbonization and circularity.
Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH)	Hazardous material control for any product with a broad list of substances (241 substances and counting).
Restriction of Hazardous Substances (RoHS)	Hazardous material control for electrical and electronic equipment. Only applies to 10 substances.
Waste from Electrical and Electronic Equipment (WEEE)	Circular designs plus a tax paid by manufacturers to fund the collection of e-waste at government recycling centers.



REMEMBER

Don’t worry about being a regulation expert. As life cycle practitioners, your compliance contribution generally boils down to measuring your product footprints and iterating footprint reductions.

## Environmental product declarations

One outcome of sustainability expectations is the environmental product declaration (EPD). An EPD is like a nutrition label for the product, indicating its environmental impact. Figure 2-4 shows a sample EPD, measuring the product's environmental impacts including energy used, carbon emitted, ocean acidification, water pollution, stratospheric ozone depletion, and ground-level ozone pollution.

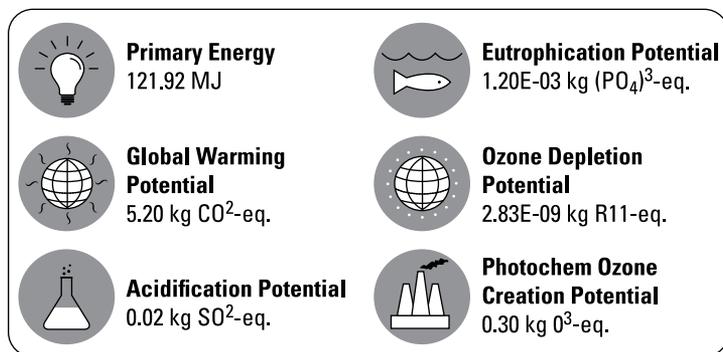


FIGURE 2-4: A sample EPD.

EPDs are summary outputs from more extensive life cycle assessments (LCAs). While savvy consumers may use EPDs to inform a buy decision, EPDs are more often used today in business-to-business (B2B) transactions. This may change over time if EPDs are presented in simplified consumer-facing formats.



TIP

Your bill of materials (BOM) programs can offer substantial automation to both LCAs and EPDs.

## Hazardous material regulations

When it comes to hazardous material regulations, for example, REACH and RoHS, their approaches are similar: Best case, don't use any of these hazardous materials beyond specified trace amounts. If you do, you must prove that it harms neither the human handlers nor the environment during manufacturing, use, and end-of-life.



PFAS (per- and polyfluoroalkyl substances) are expected to be the next category of hazardous materials that have similar controls, but they aren't consistently regulated as of the publication date of this book. If you have any products that resist heat, grease, or water, you may have PFAS issues to mitigate.

## Decarbonization regulation

CSRD mandates GHG measurement and CSDDD pushes science-based targets (SBTs) for reducing emissions toward net zero. Naturally, you must first measure what you plan to improve.

### The GHG Protocol

Much like financial accounting has rules (like the GAAP) about measuring transactions with a unit of measure like dollars, GHG accounting has its own rulebook called the GHG Protocol, which measures warming gas emissions (unit of measure is Metric Tons of Carbon Dioxide equivalent, or  $\text{MTCO}_2\text{e}$ ). GHG accounting has several categories called *scopes*, and each is intended to encourage certain corporate behaviors. The ones that are the most relevant to life cycle practitioners are

- » **Scope 1 — Direct emissions:** Fuel burned in owned and leased offices, factories, and vehicles (as opposed to fuel burned by your suppliers). Manufacturers are pushed to replace factory fossil fuel burning with electrical or other potentially renewable energy sources. This scope also pushes companies to reduce service truck emissions by avoiding dispatches and converting to electric trucks.
- » **Scope 2 — Indirect emissions (power generation):** This scope is made up of *brown electrical use*, which is generated from coal, gas, or oil. Technically, purchased steam energy counts here, too. Pushes companies to replace brown use with green use, which is renewable generated electricity. (**Note:** Nuclear is praised as low carbon but not considered renewable, but it's still an option to reduce Scope 2).
- » **Scope 3 — Indirect emissions (value chain):** This includes emissions produced in your value chain, including upstream (before your product is assembled) and downstream (after your product is sold) activities. Scope 3 has subcategories, the ones commonly significant for your products include the following:

- **3.1 — Purchased Goods and Services:** This includes the embodied carbon from the stuff that arrives at your factory's receiving dock. Embodied carbon accumulates from your supply's upstream emissions from mining, transport, material processing, and lower tier manufacturing. It pushes companies to choose less carbon-intensive suppliers and use less materials.
- **3.4 — Transportation and distribution:** This encompasses supply chain shipping emissions. It pushes companies toward lower footprint transport (ground versus air, and renewable versus fossil-powered). This scope subcategory also pushes distributed manufacturing to leverage local supply chains.
- **3.11 — Use of sold products:** This is fuel burn or non-renewably generated electricity used for customers to power your products. This category pushes companies to replace fossil fuel powered products with potentially renewable energy sources (mostly electrification).
- **3.12 — End-of-life disposition:** This covers carbon emitted during transport, incineration, or decomposition of the retired parts and products. It pushes companies toward circularity (which in turn helps Scope 3.1 with carbon-efficient supply).

Your company won't ask you to compute the overall corporate footprint because those emissions include office activities, business travel, and more. But they will ask you to calculate product carbon footprints (PCFs). A PCF in GHG accounting terms includes

- » Embodied carbon of the product's supplier material and parts, including transportation to your factories (Scopes 3.1 and 3.4)
- » Nonrenewable energy emissions in your own factories to build the product (Scope 1 and 2)
- » Expected operating nonrenewable energy emissions for the product's lifetime (Scope 3.11)
- » Expected end-of-life recovery or disposal emissions (Scope 3.12)

Service dispatches and service parts, operational transport, and upstream fuel are additional areas that may be in scope but are usually smaller footprint contributors.

Managing this may sound like a tough task, but your product life cycle management (PLM) system can help. A well-populated BOM can manage the data to calculate PCFs. This includes carbon and other attributes to roll up at the material, part, and configuration levels.

## Net-zero commitments

Another part of your decarbonization responsibility is driving PCFs toward net zero by using science-based methods. CSRD with CSDDD requires many companies to have net-zero commitments with audits of science-based reductions. This is to be done at the corporate level, but because most of a manufacturer's emissions are in its product offerings, your company relies on you to drive most reductions.

Figure 2-5 illustrates a science-based, net-zero pathway, which involves the following:

- » **A baseline measurement:** This is your company's starting footprint from which your subsequent reductions are committed.
- » **2030 near-term commitment:** On or before 2030, your baseline's Scope 1 + 2 must reduce by at least 42 percent. Also, your highest Scope 3 area, typically your supply chain Scope 3.1, must be reduced by at least 25 percent.
- » **2050 net-zero commitment:** On or before 2050, your net emissions must be reduced to less than 90 percent of your baseline. Any remaining emissions (up to 10 percent) require auditable carbon removal purchases to reach net zero.

Removals have real costs but aren't required until your declared net-zero date. For example, you may have a material supplier that still uses a fossil-fueled processing machine in 2051. If they emit 1 MTCO<sub>2</sub>e from this machine for material that you ordered, your Scope 3.1 is charged 1 MTCO<sub>2</sub>e. Your company can pay someone like Climeworks to permanently sequester 1 ton of CO<sub>2</sub> for a market price (for example, \$100). So, you preserve your net-zero commitment, but your material effectively costs an additional \$100.

For more on Figure 2-5, visit [PTC.com/beyond-the-book](https://www.ptc.com/beyond-the-book).

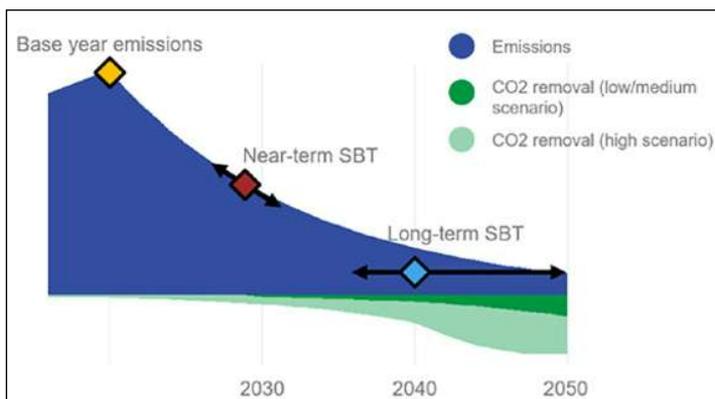


FIGURE 2-5: The decarbonization pathway.

## Circularity regulation

*Product circularity* involves reducing waste through repair, reuse, refurbishment, remanufacturing, and recycling. Today, WEEE drives basic recycling for electronics, which correlates well to the REACH and RoHS end-of-life controls for the hazardous substances that are common in electronics.

Starting this decade for battery manufacturers, digital product passports (DPPs) hold some manufacturers accountable for circular return of their products' materials. This includes end-of-life parts and products. Beyond batteries, other product areas will require these passports, but the dates aren't final at the time of this book's publication date.

In Figure 2-6, the passport tracks impact summaries and material flows for physical products. It summarizes the material content, hazardous materials, carbon footprint, water usage, and circular potential of the product. This data is known and posted pre-sale. Post-sale data includes service part transactions, service parts return proof, and any end-of-life transfer or return proof.

For these passports, there's still some "coming to a theater near you" anticipation about exactly how far which products need to go for both pre-sale and post-sale data tracking. Serialized expensive assets are more likely to require post-sale tracking than lot-based nondurable products in the early phases.

<p><b>Summary</b></p> <p>Product Serial#: 4040425A1</p> <p>Product Manufacturer: Universal Exports</p> <p>Product Model: Lightning-A.1</p> <p>Carbon footprint: 1.2 kg</p> <p>Water usage: 14.5 liters</p> <p><b>Material composition</b></p> <p>1.23 kg aluminum (%60 recycled)</p> <p>0.29 kg stainless steel (30% recycled)</p> <p>0.003 kg cobalt (0% recycled)</p> <p><b>Activity Ledger</b></p> <p>2024-11-18: Manufactured in Denver facility</p> <p>2024-11-19: Received by owner XYZ</p> <p>2025-01-23: Part 123 swapped with RMA 456</p>
--

**FIGURE 2-6:** A simplified DPP example.

DPPs require a strong engineering and service data backbone. Fortunately, beyond compliance, passports offer substantial upside revenue opportunities, and I cover value in Chapter 3.

- » Learning techniques to profitably reduce footprints
- » Focusing on decarbonization and circularity

# Chapter 3

## Aligning Sustainability and Business Value

**P**roduct footprint reduction is sustainable when it's profitable. Pitching "It's good for the planet" risks backlash unless paired with "and it's a business priority."

Fortunately, there's an impressive menu of profitable opportunities, and this menu grows with new technology and scale. A few examples of products that disrupt their dirtier predecessors while providing financial value include the following:

- » **Consumer:** For a similar price, LED lightbulbs have 30 times the durability and 7 times the energy cost savings over incandescent bulbs.
- » **Automotive:** Electric drivetrains have about 20 moving parts compared to about 2,000 in internal combustion engine (ICE) drivetrains. Charging is 50 to 90 percent cheaper than refueling. Electric vehicle (EV) acceleration is about 50 percent faster than comparably priced ICE cars.
- » **Industrial:** For utility-scale expansion, solar and wind farms are typically more economical than new fossil fuel plants. Even on a smaller scale, onsite solar usually breaks even within 5 to 7 years.

- » **High tech:** A pocket-sized smartphone can conveniently do much more for less expense than material-heavy combinations of flip phones, GPS units, digital cameras, MP3 players, calculators, and flashlights.
- » **Aerospace:** Advanced engine technology like geared turbofans, lighter composite materials, and improved aerodynamics have improved fuel efficiency by 15 to 20 percent. Adding 8 percent seat density and 10 percent schedule optimization yields efficiency improvements per passenger of 30 to 40 percent.

This chapter focuses on decarbonization and circularity opportunities. Compared to hazardous material controls (which I cover in Chapter 2), decarbonization and circularity offer flexible approaches to achieve regulatory outcomes. Often, these approaches yield profitability on top of compliance value.

## Decarbonization Value

It costs money to emit carbon, and avoiding unnecessary emitting activity can save you money. Figure 3-1 shows that McKinsey dug into this premise and noted that discrete manufacturers can profitably abate 20 to 60 percent of their carbon emissions by 2030. Many are in the 50 to 60 percent range.

### ANALYST PERSPECTIVE ON VALUE ALIGNMENT

In a 2024 report, Paul Miller from Forrester highlights the business opportunity in reducing footprints: “Industry was responsible for 31 percent of global energy consumption and 38 percent of reallocated CO<sub>2</sub> emissions in 2021 and is also a significant consumer of finite natural resources. The rising costs of energy and raw materials, combined with tightening environmental regulations, make cutting consumption and waste a sound business decision for even the most climate-skeptical executive.”



**FIGURE 3-1:** Cost efficiencies that also reduce emissions.

For more on Figure 3-1, visit [PTC.com/beyond-the-book](http://PTC.com/beyond-the-book).



TECHNICAL  
STUFF

Due to faster obsolescence, batteries and semiconductors have more difficulty reusing old components to save carbon in new products. However, a supporting indicator of value size and speed, Mark Reisig of CIMdata notes that high-tech companies investing in energy-efficient hardware, recycling materials, and optimizing supply chains for carbon reduction have reported return on investment (ROI) of 10 to 30 percent within the first 18 months.

This section gives you, as a product life cycle practitioner, actions for decarbonization opportunities.

## Reduce material in part designs

Computer aided design (CAD) software offers generative design capabilities iterated with performance simulations that optimize material usage within declared constraints (geometric, thermal, strength, manufacturing process, and so on). Figure 3-2 illustrates how generative design suggests three constraint-qualified options to reduce material in an eBike steering stem. The engineer selects an option balanced with other criteria like cost. Additive options typically have the lowest material usage, but they may have added cost or less throughput than subtractive options.

Veteran engineers championing these optimization approaches have shared with me that new-hire engineers design more efficient parts than they could ever dream up manually, even with decades of experience. CAD aides in reducing material and that proportionally saves both embodied carbon from material suppliers (Scope 3.1) and the cost of the material. An additional benefit is lightweighting, which can have significant energy efficiency benefits for mobile applications like cars (Scope 3.11). I cover scopes in Chapter 2.



**FIGURE 3-2:** Example of part material removed with generative design.

## Dematerialize with embedded software

Taking material reduction to the extreme, some mechanical parts can be replaced with software. A personal story of mine conveys this value well. I received a recall for my electric car. The window safety switch wasn't reliably retracting and could damage someone's fingers (like when a child is playing with the window). I thought, "Oh no. There are a couple hours gone sitting in a dealer's waiting room with blaring soap operas." Then I read further, and the car manufacturer noted my car's model year had replaced the physical window sensor with software. They would simply provide me with a remote software update to quickly and easily resolve the safety issue.

Replacing this window sensor with software saved the manufacturer the cost, weight, and embodied carbon of a physical part in their bill of materials (BOM). It also avoided any recall technician labor and replacement parts. Additionally, as an increasingly loyal customer, I was pleased with the proactive and simple "fixed in my sleep" outcome.



TIP

To do this well requires a systems approach to product design spanning application life cycle management (ALM) and product life cycle management (PLM) so modular embedded software can complement modular mechanical designs. These software and hardware blends also need requirements and test tracing for safety-critical functions like my example of power window raising.

## Improve supplier data and selection

For commodity materials and components, both cost and environmental footprints may vary significantly. Risks also have a lot of variability. Connecting your design engineers, specifically BOM managers, to material and supply chain databases facilitates improved initial selections. As supplier offers improve, they also pinpoint opportunities for inexpensive change orders to improve cost, footprint, and risk (changing a commodity supplier rarely affects performance or manufacturing process).

## Balance material selection criteria

Unlike commodity supplier selection that can be changed inexpensively at any time, changing a part's materials is a substantial effort that affects geometry, performance, tooling, and other aspects.

Materials have engineering properties. These don't change over time or among suppliers. Copper's coefficient of thermal expansion will always be .000017. If you only needed to manage a few materials and only cared about these static engineering attributes, you could work without a commercial material database integration.

However, with sustainability, there are three dynamic dimensions of material data that you need to manage.

## Footprint, cost, and risk attributes

Attributes like cost and carbon intensity change often and differ among suppliers. Material databases typically keep pace with global average costs and footprint attributes but won't be supplier specific. This global average is often sufficient precision to make informed material selections (like aluminum versus steel, or

steel grade A versus steel grade B) to balance cost, performance, and footprint criteria. Supplier selection is usually a subsequent design decision.

## New recycled blends

Common materials like steel have new blends of recycled content and processing methods (like 80 percent recycled steel). These blends and processing methods not only have different costs and footprints but also varying engineering properties. You can't simply one for one substitute virgin steel with recycled steel and achieve the same strength, stiffness, and other performance properties.

## New materials

Thanks to AI and a boost in core material science investment, new materials are available at a blistering pace. Integrating material databases with CAD and PLM decision makers is important to select the right material. Material selection is a high-stakes decision (for cost, performance, and footprint) with considerable expense to change it late in design or post-production. Furthermore, designers must trace where materials are used in their designs to detect and assess when material attribute updates warrant design changes.



TECHNICAL  
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To appreciate the pace of availability of new materials, you can read about the Google's 2023 GNoMe project that discovered 380,000 new stable materials. There were only 48,000 discovered by humans before this! Visit this book's resource page at [PTC.com/beyond-the-book](https://www.ptc.com/beyond-the-book) for a link to more details.

## Distribute manufacturing

Heavy and expensive products with global markets risk large transportation and customs expenses. An automobile manufacturer with one global assembly plant would centrally ship two tons of international supply into their plant and then ship a two-ton car to wherever their customer lives in the world. There may be sizeable customs fees added to the transportation fees. Much of today's transportation fees cover fossil fuel costs, adding embodied carbon on top of cost to your product offerings.

With distributed manufacturing, large automotives today typically distribute assembly plants near local markets (like the

United States, Germany, and China) with local supply chains. This saves cost and footprint. It can also hedge risks when supply chain shocks occur, like typhoons, tariffs, and conflicts.



TIP

Distributed manufacturing is an opportunity beyond automotive. Any manufacturer with heavy or expensive products on a global scale can benefit. But you need to manage added variation from different factory product lines and different supply chains. Modular design with manufacturing planning can help manage these complexities. Thinking ahead to circularity opportunities, remanufacturing has potential for even greater distribution when the rework is simpler than initial full manufacturing.

## Simulate manufacturability

For parts made in-house (also called *make parts*), cost optimization often correlates to footprint savings. Scrap reduction saves materials' embodied carbon and cost. Energy efficiency saves utility costs (and footprint when the energy source isn't 100 percent clean).

For a given manufacturing process, simulations can recommend geometry, control characteristics, treatment, and other adjustments to reduce scrap and energy. The simulation can go further to suggest material and manufacturing process alternatives to reduce cost and footprint.

Additionally, manufacturability simulations can predict the production's contribution to the product's footprint, which needs to be rolled up in environmental product declarations (EPDs). This saves manual analysis effort.

## Automate EPDs

EPDs with product carbon footprint (PCF) reports are expensive to produce manually. Estimates vary, but they're often in the \$10,000 to \$50,000+ range. Not only is this expensive for manufacturers offering many product variations, but also it's a staffing bottleneck with a limited number of environmental engineers to take on the wave of new PCF/EPD demands.



TECHNICAL  
STUFF

Fortunately, PCF data can largely be rolled up within high-quality PLM BOMs, and these same BOMs can feed life cycle assessment (LCA) tools to mostly automate EPDs. In sustainability-speak, the PLM BOM manages the life cycle inventory (LCI) data, from which LCA software calculates the life cycle impact

assessment (LCIA) that outputs on an EPD. The key to this automation is a strong PLM BOM, containing material, part, supplier, and configuration level attributes on embodied and activity footprint contributions. Next is an LCA tool that can receive this BOM payload, make the calculations, and return environmental impact results to PLM.

## Circularity Value

Circularity's focused outcome is to preserve finite resources. The most recognized global framework for circularity is the Ellen MacArthur Foundation's Butterfly Diagram, which is too detailed to reproduce in this book, but certainly worth a look online. Check out [PTC.com/beyond-the-book](http://PTC.com/beyond-the-book) for more information.

Circularity has organic material flows (with composting and regeneration) and finite material flows. In discrete manufacturing, we mostly play on the finite material side with our metals, minerals, ceramics, plastics, and so on. Over time, industry incorporates more biomaterials and helps with safe composting of renewable material, particularly for single-use or high-wear parts.



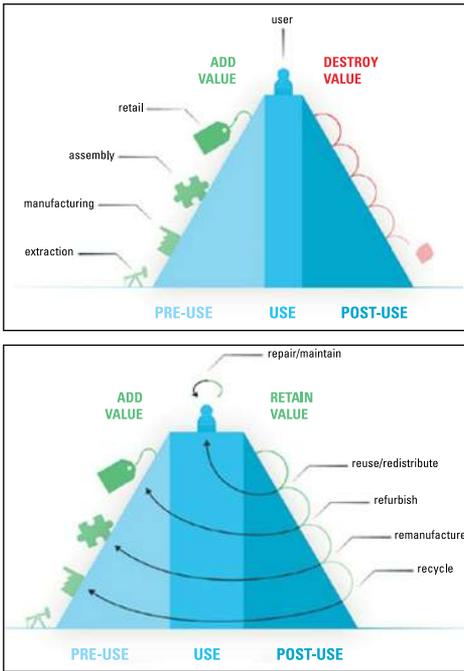
REMEMBER

A central point of finite material circularity is that recycling is far from the best outcome for us. Repair, reuse, refurbishment, and remanufacturing are all better outcomes to consider before recycling. To put it in economic terms, look at the Value Hill from Circle Economy in Figure 3-3. It demonstrates circularity's alignment with business value.

Linear life cycle products require mine extraction for raw materials, material processing and lower tier processing, final assembly, transport for retail, and transport to customer's location for every product. If the product breaks or the customer is otherwise done using the product, throwing it away destroys all five levels of value. It's better to recover and maintain product value at a higher tier level through repair, reuse, refurbishment, remanufacturing, and recycling (in that order of preference).

Sounds like common sense, but the trick is making it profitable, which only happens with proper design intent and service execution.

Visit [PTC.com/beyond-the-book](http://PTC.com/beyond-the-book) for more information on the Value Hill.



**FIGURE 3-3:** The Value Hill demonstrates circularity's alignment with business value.

## Design modularly



REMEMBER

Modularity creates both the supply and demand for part reuse, refurbishment, and remanufacturing. It also facilitates classic designs, where users desire to use products longer, maintain them, and circulate through multiple product generations.

Some recognizable toy brands have been market champions for decades because of their modular value. There are two toy platforms that I played with throughout my childhood that my children also enjoyed and asked us to hold onto for their children (hence our full attic): LEGO and Playmobil. Both are exceptional modular designs where components may be reconfigured into new products as the user's desires evolve. Done with the pirate phase? Rebuild the blocks into a space station. Consumers rarely throw away LEGOs or Playmobil.

Automotive was another early adopter of modular design. Go to any car website and you can configure a car to your liking — motor, color, wheel size, sunroof, fog lights, sports seats, ten speakers, and more. You not only get the variability you seek, but also the car manufacturers can manage an effective service parts network due to the limited variety of parts needed to serve all configurations. Modular cars capture a broader market of buyers and facilitate high margin spare parts businesses. Even retired cars have commercial value because they're designed for disassembly to repurpose salvageable parts and efficiently recycle much of the remaining separated materials.

Without modular design, circular value beyond basic recycling is tough to do profitably. As a life cycle practitioner, modular design spans software, hardware, and electronics with modular correlation among them. A modular battery needs accompanying modular software to work in its varying products. A unified engineering BOM in PLM helps to manage these modular systems, with modular ALM software objects contributing. Downstream derivatives requiring modular intelligence include manufacturing BOM, service BOM, disassembly BOM, and instructions for front-line workers.

## Dispatch technicians as a last resort

To stay at the top of the Value Hill (see the earlier section “Circularity Value”), products need to be designed for repair. Not only will the products last longer, but also your service business can contribute substantially to both growth and margin.

Today, all manufacturers have at least basic warranties, and many iterate levels of product service systems (service contracts, leasing, performance-based contracts, and so on). With service cost risk increasingly added on the manufacture, the profit-boosting objective is to serve customers with the least cost channel. Conveniently, the lower cost service delivery options, shown in Table 3-1, align directly with footprint reduction goals.



REMEMBER

For all levels, configuration-specific instructions are essential. Modular design otherwise makes frontline workers' jobs complex because they rarely see the same products in consecutive tasks. Filtering parts lists and operating and service procedures to the exact configuration saves time and parts. Critical for circularity, these service procedures need to extend to disassembly and part and material returns.

**TABLE 3-1 Service Delivery Options**

Service Channel	Manufacturer Cost	Footprint
Self Service	\$ None or Contact Center	Negligible
Fix Remotely	\$\$ Over-the-air software update	Negligible
First Visit Fix	\$\$\$ Technician dispatch, parts	Truck mileage, part embodied carbon
Repeat Visit(s)	\$\$\$\$\$ Added dispatches and parts	Multiplied truck mileage, part embodied carbon

Embedded software is a driver for self-service and technician service (precise alerts and notifications). It’s also the only way to do remote fixes because technicians can’t remotely change physical parts.

For field service, asset-centric approaches optimize far better than appointment-based dispatching. Asset-centric approaches use product smarts to first try avoiding the dispatch with self-service or remote service. If a dispatch is necessary, it remotely triages and coordinates van parts stocks to prepare the likely fixes (avoiding repeat visits). It also calculates when reactive visits may be combined with scheduled maintenance.

## Order service parts as a last resort



REMEMBER

Service parts networks deserve special attention due to the amount of money and embodied carbon locked in these parts. If you’re a billion-dollar manufacturer of durable goods, you likely carry tens or hundreds of millions of dollars of service parts inventory to meet your service level targets.

Deploying multi-echelon optimization (from central warehouses to truck stocks and areas in between) with forecasts from historical demand can reduce the part inventory costs significantly while improving service levels. But with PLM data and smart connected products, you can reap additional cost and footprint savings. The more your parts planners know about specific asset locations, contract levels, configurations, and conditions, the more they can reduce your inventory and expedited shipping costs.

Additionally, you can track the return loops of your circular modular parts. For example, if you have brake discs returning to remanufacturing with a restocking lead time of ten days, you can avoid buying new discs from your suppliers for forecasted needs beyond ten days. You can also measure the financial and footprint savings from these avoided buys in your reuse, refurbishment, and remanufacturing operations. It's financially auditable circularity value.

## Product differentiation on footprint

Some market segments will pay more for products with lower footprint. This revenue is called a *green premium*. Submarkets include eco-conscious consumers in business-to-consumer (B2C) and business-to-business (B2B) companies with net-zero commitments. Alex McQueen from ABI Research notes that “Today’s consumers continue to gravitate toward sustainable products, increasingly considering sustainable product attributes in purchasing decisions. LCAs have become a valuable tool for consumer companies as they look to respond to consumers’ sustainability expectations.”



TIP

Additionally, governments will occasionally subsidize greener approaches or products. Take advantage of green premiums and government subsidies, but manage them as dynamic contributors to your business case.

## IN THIS CHAPTER

- » Putting DfS value in the life cycle
- » Learning from DfS wisdom
- » Tailoring a DfS framework for life cycle practitioners
- » Looking at real-world sequencing

# Chapter 4

# Designing for Sustainability Principles

In this chapter, I brief you on the basics of Design for Sustainability (DfS), which is the practice of creating products with minimal impact on the environment and society. I also dig deeper into the discipline and give you a summarized DfS framework for discrete manufacturers.

## Seeing DfS Value in the Life Cycle

With about 80 percent of the product's footprint determined in its design phase, there's value in making the right decisions up front. Changing materials, fasteners, geometry, manufacturing processes, software, service plans, or business models gets more expensive over time.

Engineers with upfront DfS knowledge and requirements system references can make better decisions in the early design phases.

# Fishing for DfS Wisdom

Currently, there's not a consolidated playbook for more sustainably designing discrete products (which is one reason why this book was written). Fortunately, good information is available because DfS is an evolving and now well-funded topic. In this section, I share my secret fishing holes.

The ISO14000 family covers DfS topics but today mostly at higher levels. ISO14001 (Environmental Management Systems) is the one that offers scaled certifications with thousands of participating companies. It's excellent at a program level but doesn't offer detailed design guidance for discrete products.

For early product design guidance, the Life cycle Design Strategies (LiDS) Wheel can be an effective quick reference card. You dig into more detail on LiDS in Chapter 5.

The deeper structure of Internet-available design guidance is in the "Design for X" framework, which has many contributors of both public and purchasable content. The related disciplines include those shown in Table 4-1.

**TABLE 4-1 Sustainable Design Methods**

DfX Method	Sustainability-Related Objective
Assembly (DfA)	Ease manufacturing and repair.
Circularity (DfC)	Tune business models and human factors to support material recovery.
Disassembly (DfD)	Ease of repair and end-of-life return encourages product longevity.
Energy Efficiency (DfEE)	Reduce product operational energy and consumables.
Logistics (DfL)	Control service part purchases and shipping costs and footprint.
Longevity (DfLG)	Manage high- and low-wear parts for longer product life, reducing waste.
Manufacturing (DfM)	Reduce waste and energy.
Recycling (DfR)	Enable material separation and high-value secondary/recurring use.

DfX Method	Sustainability-Related Objective
Remanufacturing & Refurbishing (DfRM-DfRF)	Enable multiple product life cycles for durable modules and parts.
Repair & Maintenance (DfR-DfM)	Extend the serviceable life of the product.
Reuse and Repurpose (DfRR)	Plan for secondary use (example: worn tires as dock moorings).
Sustainable Behavior (DfSB)	Encourage end-users to responsibly operate, dispose, and return products.
Use (DfU)	Balance energy use and consumables with product lifespan.

In addition to these ISO14000 Series, LiDS Wheel, and DfX research areas, you can find other recommended books, blogs, groups, and resources at [PTC.com/beyond-the-book](http://PTC.com/beyond-the-book).

## DfS Framework for Discrete Manufacturers

This DfS framework boils much of the DfS research (see the preceding section) into a mid-level maturity matrix for product life cycle practitioners. This matrix consists of three levels. This section breaks down each of these levels.

Figure 4-1 gives a visual representation of the three levels and how they work together.

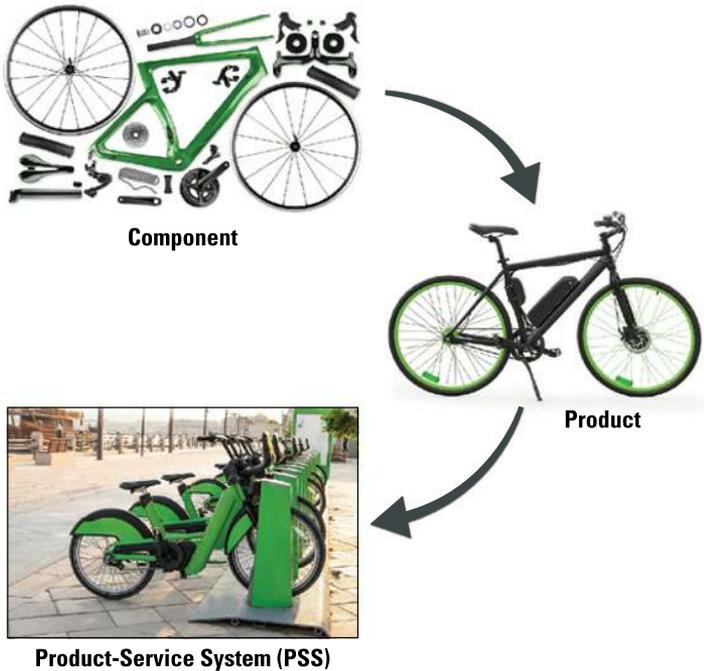
### Component level

For parts you design yourself, keep in mind the following considerations for reducing footprints:



REMEMBER

- » **Select the best material.** Beyond engineering attributes like strength, material properties to consider are carbon emissions intensity, water intensity, percent recycled content, percent recyclable content, toxicity, supplier compliance, and cost. Commercial material database integrations help with not only selection but also selection enforcement within company-approved materials. Too much material variety can complicate end-of-life separation for recycling streams but may be okay for remanufacturing cycles.



**FIGURE 4-1:** DfS maturity levels for discrete manufacturing.

- » **Use as little of the selected material as possible.** Within performance, geometric, and appearance constraints, cut the use of excess material. Generative design and additive manufacturing are two tools to help with this.
- » **Select the best manufacturing process.** This point sounds straightforward, but good assessments may loop back to reconsider material, geometry, and control characteristic selections. Manufacturability and costing simulation assists with these predictions and refinements.

At this level, computer aided design (CAD) is the home system for digital maturity optimization with callouts to supply chain data (material databases) and simulations (generative design, performance, and manufacturability).

## Product level

This level optimizes products, specifically focusing on the cradle to gate portion, which is the product life cycle from material extraction and acquisition through product assembly. Top considerations at this level include

- » **Hotspot analysis:** An environmental hotspot analysis identifies and measures where a product's life cycle activities generate the highest sustainability impacts (measured by carbon equivalents, water use, toxicity, and so on). An advantage of product-level analysis is the prioritization of which parts are worth footprint reduction efforts based on where you can have the largest savings potential.
- » **Low impact suppliers:** Choosing low impact material and part suppliers reduces Scope 3.1 emissions. For product life cycle management (PLM) users, this is mainly for buy parts because supplier selection for make part materials is typically done by sourcing. The footprint attributes to evaluate are the same as materials, but suppliers usually provide the values at a part level rather than material levels.
- » **Distributed manufacturing:** For heavy products with globally scaled customers, localizing production can save money and footprint. But localizing production can cause complex variability such as modular products and site-specific supply chains and production lines. To simplify for designers and workers, PLM engineering bill of materials (BOM) may derive site- and configuration-specific manufacturing BOMs, process plans, and work instructions.
- » **Efficient operation:** Lightweighting, electrification, and thermal tuning are methods to improve product energy efficiency. PLM BOMs identify lightweighting opportunities to accomplish in CAD's generative design capabilities. Other energy efficiency analysis is typically done with simulations integrated in PLM workflows.

PLM is the digital maturity home system for product-level DfS with integrations to life cycle assessment (LCA), supply chain databases, and loops to CAD for component-level improvements.

## Product service system level

Product service systems bundle products with services to fulfill customer needs. Product service systems span the full cradle-to-cradle life cycle. Including both the product and a risk-sharing business model, this level requires the following considerations:

- » **Extend initial product lifetime.** A product should last just long enough where users maximize value relative to the service costs and resell upsides of the asset. This requires service planning with failure modes and effects analysis (FMEAs), spare parts networks, parts catalogs, service procedures, and technician coverage.
- » **Optimize the end-of-life system.** Well planned end-of-life parts and products should retain value in the following order of priority: reuse, refurbish, remanufacture, and recycle.

Application life cycle management (ALM), service life cycle management (SLM), and Internet of Things (IoT) are important additions for companies that progress to product service systems levels. SLM drives the service processes and can be reasonably extended to facilitate material return loops. ALM drives service efficiencies and material recovery with IoT-enabled embedded software. IoT-connected products offer geo-tracking, over-the-air updates, remote triage, alerting, operator guidance, returns tracking, and more.

## Managing DfS Real-World Sequencing

While the framework maturity path is component, product, and then product service system levels, companies often implement DfS in different orders. Established companies prefer to start at the product level, with PLM BOMs. With new environmental regulations, companies need to first measure footprints for their numerous products, each containing hundreds or thousands of parts. Next, to drive reductions, they can prioritize the top X percent (choose the percentage for your needs) of parts for component-level loops to enable profitable footprint reductions.

Start-ups and new platforms in established manufacturing often begin at the product service system level. The barriers to starting here are small with a clean slate, and the outcomes offer differentiation against their incumbent competitors.

## IN THIS CHAPTER

- » Reviewing life cycle thinking guidance
- » Getting your priorities in order
- » Discovering the life cycle digital thread
- » Incorporating the PLM BOM and asset hub

# Chapter 5

# Managing Footprints with Full Life Cycle Thinking

Ultimately, circularity will save the day for discrete manufacturing. Our industries average below 10 percent circular today, so there's a lot of work to do.

Circularity directly solves for our finite resource problem by using the same materials repeatedly. It can also avoid unnecessary high-energy supply chain rework and keeps materials safely in use. Therefore, circularity can help solve for much of our other two common challenges: decarbonization and hazardous material controls.

Optimizing product footprints from material acquisition through product assembly (called *cradle-to-gate* in sustainability-speak) isn't sufficient anymore. Life cycle practitioners need to assess multi-generational value of their products and offerings, factoring in operation, service, reuse, and material recovery (called *cradle-to-cradle*).



REMEMBER

Offerings need to accompany products if we ever expect return loops with customers.

In this chapter, you explore process and digital frameworks for managing across the full life cycle. The good news is that it's not an overhaul; instead, it's an extension of how you digitally manage your products today. Sustainability is just an additional value dimension.

## Life Cycle Thinking Guidance

High-level sustainability intuition and guidance early in the design has remarkable value. The Life Cycle Design Strategies (LIDS) wheel, outlined in Figure 5-1, is an effective guide for life cycle thinking. The LIDS framework offers designers general rules for the clockwise life cycle, scoring design adoption for each of the eight areas (higher adoption further from the bull's-eye). Each recommendation is seemingly obvious, but it's important to holistically consider the system in early design decisions.

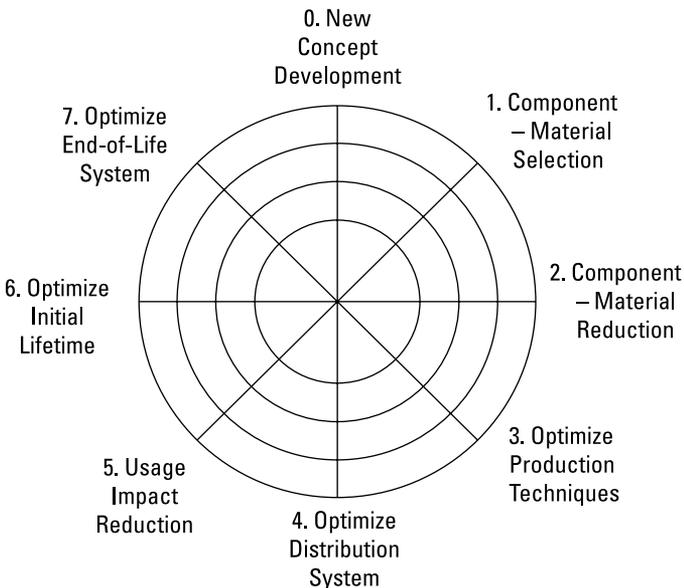


FIGURE 5-1: The LIDS wheel.

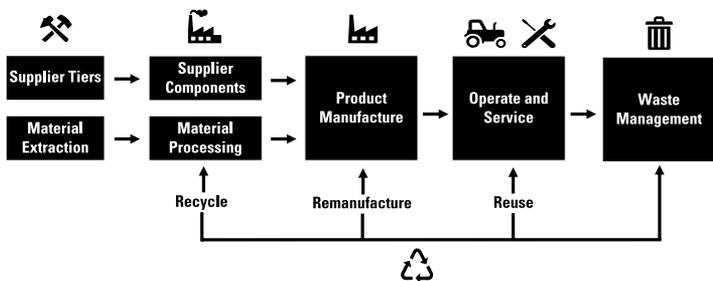
For more information on the LIDS wheel, visit [PTC.com/beyond-the-book](http://PTC.com/beyond-the-book).

To further institutionalize this life cycle thinking, you may add Design for Sustainability (DfS) guidance directly into your requirements management systems (“Do the right thing”). These requirement templates may be generalized and then derived for product-specific requirements. Tracing requirements with tests, designs, and system functions further validates that designers are incorporating DfS best practices into their product service systems (“Do the thing right!”).

For organizations using model-based systems engineering, (MBSE), quantifiable footprint targets like embodied carbon, water and energy usage, weight (for mobile products), and toxicity may be attributed to system models early in design. This sets subsystem targets for design teams to execute or renegotiate at the system level as needed. Later, product life cycle management (PLM), application life cycle management (ALM), electronic computer-aided design (ECAD) and other supporting systems can roll up values to verify that footprint goals are achieved across the system.

## Life Cycle Inventory Priorities

Figure 5-2 establishes a mutual understanding between product life cycle experts and sustainability experts.



**FIGURE 5-2:** The life cycle inventory.

Product life cycle experts recognize make parts and buy parts that flow into the factory to assemble the product configuration, after which it flows to aftermarket service and end-of-life stages.

Sustainability experts recognize a life cycle inventory (LCI) diagram of footprint-accumulating activities that would ultimately feed into a life cycle assessment (LCA) tool to calculate a product's life cycle impact assessment (LCIA).

This section details the four life cycle categories from Figure 5-2.

## Operational footprint

The first part of Figure 5-2 to analyze is manufacturing, as shown in Figure 5-3.



**FIGURE 5-3:** The operational life cycle stage: Manufacturing.

Consider operational footprint to be your factories. Intuitively, you may think the factory has the highest footprint and priority. It's belching exhaust, heat, scrap metal, and hazardous material waste, right? But in reality, the factory is surprisingly a smaller footprint contributor and is a lesser priority for our roles for two reasons.

- » It typically represents only 1 to 10 percent of a discrete product's footprint. Discrete manufacturing is mostly lower energy transformation and assembly compared to the mining, material processing, and other upstream and downstream activities.
- » One of the top actions a factory takes to decarbonize is electrifying production machines (capital purchases do this). Additionally, the factory can source the electricity cleanly (your treasury department does this through solar power, a VPPA, or another investment method). **Note:** For industrial heating, hydrogen in place of natural gas is also a common machinery pursuit because hydrogen may be generated renewably. Dual burner machines can use natural gas and then switch to hydrogen when available.

Product life cycle practitioners do focus on some factory footprint activities, though, mainly around designing for manufacturability to reduce scrap and energy use. This includes not only machining but also configuration-specific instructions for front-line workers. Distributed manufacturing can also be a design priority to reduce supply chain distances.

## Upstream footprint

The second part of Figure 5-2 to analyze is the upstream footprint stages, which are the first two sections of the figure and shown in Figure 5-4.

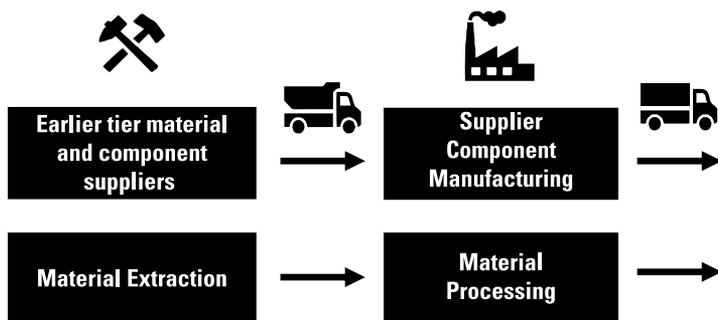


FIGURE 5-4: Upstream footprint stages.

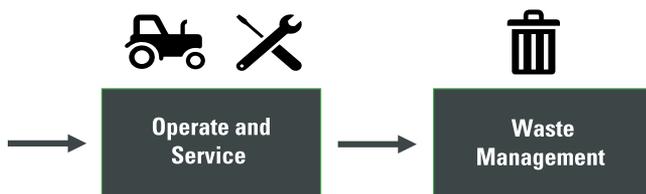
For most discrete manufacturers, the materials and parts arriving at your factory receiving dock represent 75 to 90 percent of your product footprint. Take a steel rod component as an example. Iron ore is mined in a remote location, the heavy rock is trucked long distances to the steel foundry where it's processed into steel rods, and then it's trucked farther to your factory. That's a lot of energy, and it's mostly fossil fuel in today's economy. What do you then do with that steel rod in your factory? Maybe you bend it and screw it into an assembly — that's relatively low energy.

And it's not just your heavy metals and components that cause upstream footprints. The lighter and innocent-looking electronics can be far worse. In a laptop, the processor may be more carbon and waste intensive than the bigger and heavier laptop casing or even the battery. Electronics contain rare earth metals whose concentrate is typically only 5 to 10 percent of the ore extracted by weight, which then needs additional processing to extract the 50 to 70 percent of rare earth metals within the concentrate.

Your sustainability leader calls your upstream Scope 3.1 Purchased Goods and Services. Not only is it a big footprint for your products, but also regulatory frameworks may require you to reduce this — common science-based methods expect a reduction of at least 25 percent by 2030. As a product life cycle practitioner, your top 1 or 2 footprint reduction effort(s) will be focused on the upstream. It's also the area your corporate sustainability leads often pressure you the most for fast action.

## Downstream footprint

The third part of Figure 5-2 to analyze is the downstream life cycle stages. These are a linear process and are the last two sections of the figure, as shown in Figure 5-5.



**FIGURE 5-5:** Downstream life cycle stages — a linear process.

Manufacturers also have responsibility for the downstream (aftersales) impacts — operating energy, service, and waste footprints of their products. If you make a product that requires a lot of power, you may have a large Scope 3.11 Customer Use of Sold Products footprint. It may even be higher than your upstream (it's usually more than 95 percent total footprint contribution for automotives and machine builders today). Depending on your fuel source, you may have to act on this aggressively.

If your product's fuel source is electricity or another increasingly renewable source, you're in better shape. While your Scope 3.11 footprint may be high today due to your customers plugging into coal and gas generated electrical grids, these grids should clean up well by 2050. So, you can ride the coattails of grid cleaning to decrease your Scope 3.11 emissions.



**WARNING**

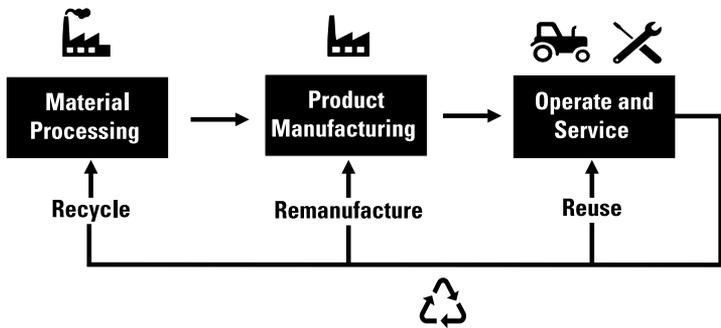
However, if your product is fossil-fueled, you won't make a net-zero commitment without switching to a renewable source. There's limited fossil fuel efficiency improvement opportunity. Your objective is to electrify or move toward another renewable

power source like hydrogen gas technology. A few sectors like long-haul aerospace don't have scaling tech yet to replace fossil fuels, but most do.

If you have a service intensive product, additional significant footprint contributors include truck dispatches, service parts, consumables, and parts shipping (particularly expedited air versus standard ground methods). However, the overall footprint proportion here is still much less than your upstream. *Note:* Your upstream includes the embodied carbon of your service parts inventory, so reduce this massive carrying cost where possible.

## Circularity

The last part of Figure 5-2 to analyze is the circular downstream life cycle stages, which are a combined section of Figure 5-2, as shown in Figure 5-6.



**FIGURE 5-6:** Downstream life cycle stages (circular process).



REMEMBER

While upstream footprint is likely your reduction focus, the only way you'll profitably achieve your goals is by ramping up circularity. Use a laptop as an example. A remanufactured laptop, with like-new capabilities and a like-new warranty, can be 90 percent more carbon efficient than a virgin-sourced laptop for the following reasons:

- » **Reuse:** The laptop's aluminum casing took high energy to produce the first time. But it's durable and has a classic design. You may not notice the difference between a new and a 5-year-old laptop case. As a result, the casing can be reused as is. No need to redo mining bauxite, reprocessing it into aluminum, or retransforming the aluminum into a laptop case.

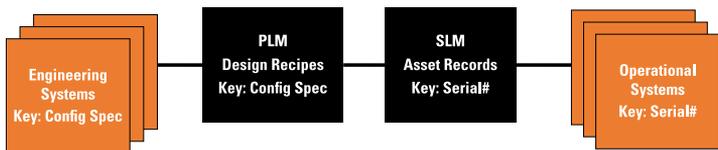
- » **Remanufacture:** The laptop's keyboard is mostly okay for another 5-year period. The Q key wasn't used much, but the vowels are worn and require some remanufacturing and maybe new springs. The plastic doesn't need to go back through mining, material processing, or molding. The keyboard only needs a few minor tweaks to be fixed and running in like-new condition.
- » **Recycle:** The motherboard is no longer a competitive speed. The best we can do with it is shred it, separate the materials, and build a new motherboard. With this, we avoid the high footprint cost of redoing rare earth metal mining.

Add these three reuse, remanufacturing, and recycling streams together, and this yields the 90 percent carbon efficiency for the remanufactured laptop, not to mention the benefits of rare earth metal preservation and avoided hazardous e-waste risks. The remanufacturing footprint advantage is also large for other verticals too — amounting to a 60 to 95 percent range, based on manufacturers I've worked with.

## Life Cycle Digital Thread

It's one thing to learn the principles of life cycle thinking, but it's another to do it for real and at scale. To pull this off well, it requires a strong digital backbone. There are two connected hubs for your product digital thread, and each aligns to a new regulatory mandate (which can help your funding to achieve these hubs).

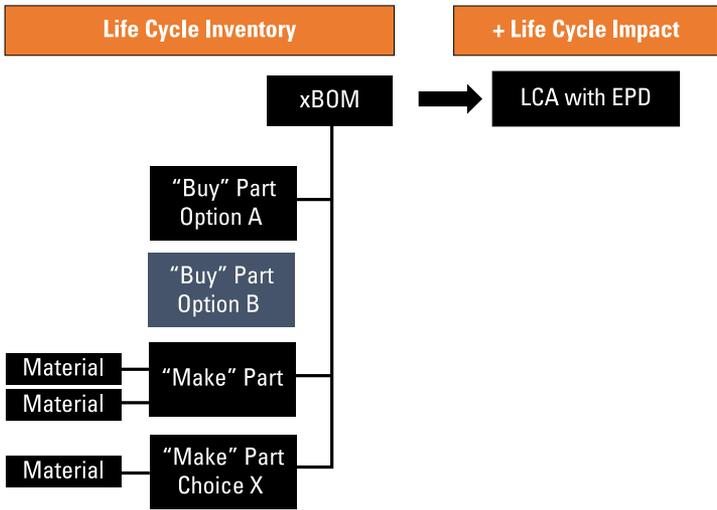
Figure 5-7 shows how product data in engineering systems are related on design recipes (also called *configuration specifications*). Product data in operational systems are related on the asset's serial number.



**FIGURE 5-7:** The life cycle digital thread.

# Engineering hub

The first hub is the modular BOM in a PLM system. Figure 5-8 shows how your footprint data (or life cycle inventory) hangs on this structure. Material databases link through CAD to PLM at the material level, rolling up production activity footprints at the “make part” level. Supplier component databases link at the “buy part” level. At the configuration level, your PLM BOM subroutines to LCA tools to simulate environmental impact during design, then output EPD’s at the end of design.



**FIGURE 5-8:** The modular BOM rolls up a product’s life cycle inventory.



TIP

For engineering data, sustainability emphasizes three areas: modularity, supply chain integrations, and new simulations. LCA is an “environmental simulation” from an engineering perspective.

In addition to the modular BOM’s footprint roll ups, ALM integrates in two ways to the BOM. Figure 5-9 illustrates the integrations. First, modular software parts are linked with the unified BOM to complement the physical parts. Second, ALM’s managed requirements trace to both ALM tests and PLM design objects to ensure sustainability requirements are met and have test coverage.

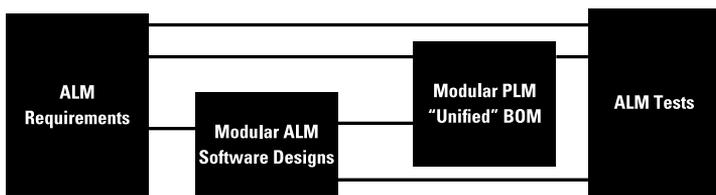


FIGURE 5-9: Detailing ALM integrations.

## Asset hub

The second hub is a physical asset system of record, mapped in Figure 5-10. At the asset's birth, it starts with a copy of its BOM recipe from PLM (and can be complemented with production order specifics if available).

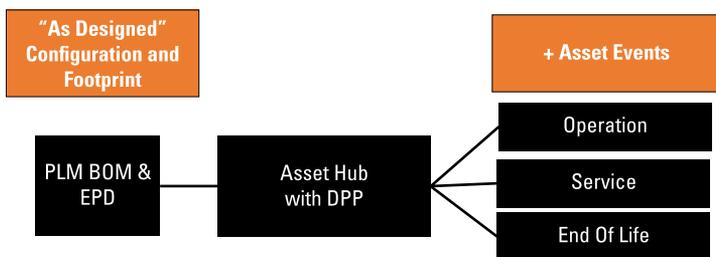


FIGURE 5-10: The digital product passport (DPP) is a subset of the asset hub.

Next, this asset hub manages a ledger of interesting activities that can be leveraged by owners, service providers, designers, warranty adjudicators, and more roles. For digital product passport (DPP) workflows, part of this ledger includes location, ownership, and return information to prove circular return of used materials and parts (and ultimately the retired product).



TECHNICAL  
STUFF

Sustainability has a lot more supply chain and aftersales integration requirements on asset data. Fortunately, there are some smart and cooperative industry leaders developing exchange standards. The Industrial Digital Twin Association (IDTA) has developed an Asset Administration Shell (AAS) set of services to use for inter- and intra-company asset data exchange. Meik Billmann, Managing Director of IDTA, says the AAS makes standardized asset information available throughout an asset's entire life cycle.

This alignment makes the AAS the ideal basis for circular business models.

## Integrating the PLM BOM and Asset Hub

Sustainability regulations, especially those supporting DPPs, are forcing functions for the full life cycle data backbone. These are four perhaps less obvious yet substantial profit-boosting, footprint-reducing areas that you can leverage with this backbone.

### Configuration-specific work instructions

Frontline workers in product assembly lines, inspection bays, operations sites, maintenance facilities, field service trucks, and remanufacturing centers require updated and configuration-specific instructions. With modular designs (which profitable circularity demands), every product they see is likely different than the previous one.

Fortunately, an asset hub stores the configuration parameters for the equipment they are working on, which PLM can use to filter instructions and parts lists. Your digital thread can remove variability complexity for frontline workers.

## CIRCULARITY NEEDS DIGITAL MATURITY

According to Bjoern Stengel, Global Sustainability Research and Practice Lead at IDC, "Sustainability practitioners view the lack of software that can help manage circularity in their operations and supply chains as the biggest operational challenge around implementing circularity into their business. Working with a provider that understands the industry- and business-specific needs is critical for an IT-enabled approach to sustainability and business models that follow circular economy principles."

## Equipment-based forecasting

If your company sells service parts, two numbers may shock you. First is the profitability of service parts — often it's four or five times the initial product sales' margins. Second is the size of the inventory you carry. For a billion-dollar manufacturer, it's often tens or hundreds of millions of dollars of parts stocked on shelves and trucks across the world (with a lot of embodied carbon in those parts).

As a result, service parts optimization software helps manufacturers stock the right part-location quantities to meet service level targets. This software at least uses historical data to predict future needs. But if it also understands part attributes like durability, product configurations, asset locations, and asset conditions, it can further remove millions of dollars in inventory, saving embodied carbon too.

## Data-driven design and service

Engineering leaders and analysts have talked about data-driven design for decades. In a perfect world, design engineers continuously receive robust data from fielded assets. With this data, they can quickly react to over-engineering and under-engineering issues. Service can scale tailored offerings.

Sounds great? Yes, but typically only on a university chalkboard because manufacturers struggle to capture robust field data. However, with passport adoption, there's a fast opportunity for your asset hub to gather product life cycle data that your company can leverage.

## Boosted AI value

AI's a new buzz. How does it relate to sustainability? The answer is concise and powerful. Sustainability is a catalyst for achieving the rich product data that AI needs to generate insights. EPDs and DPPs demand structured and thorough data linked across the life cycle. What could AI do over this data? A lot, and not just for footprint reduction!

## IN THIS CHAPTER

- » Pursuing circularity
- » Taking DPP into consideration
- » Making your CFO happy
- » Establishing your digital thread

# Chapter 6

## Ten Life Cycle Tips for Profitable Footprint Reduction

**P**roduct sustainability is a deep topic, and it's getting deeper with increased mindshare and investment. Whether you've jumped to this chapter first for a quick rundown of the highlights or you're reading this chapter last for some emphasized pointers, this chapter gives you ten tips for profitable footprint reduction.

### Think Full Life Cycle

In discrete manufacturing, your factory operations likely contribute only 1 to 10 percent to your product footprints. The other 90 to 99 percent is in the upstream and downstream life cycle stages:

- » *Upstream* requires more attention on material selection and usage and supplier component selection. Better data and decision tools yield improved supply chain costs, resiliency, and footprint.

» *Downstream* requires circular programs for material and energy, such as modular systems, part recovery, electrification, and software-enabled service. Downstream circularity is ironically a top lever for upstream value because it provides efficient part reuse, remanufacturing, and recycling.

See Chapter 5 for more about this life cycle thinking.

## Pursue Circularity with Modular Hardware and Software

Profitable circularity demands modularity — it's the only way to have both demand and supply for remanufactured parts. Modern products require both software and hardware to be modular. For example, a control unit remanufactured from Product A couldn't be redeployed to Product B without aligned software updates. Software also assists sustainable user behavior, equipment servicing, and returns tracking.

## Don't Forget the Frontline Workers

Circular products require modularity, but modularity also offers high variability. Variability helps sales by offering more options for buyers, but it can add complexity to frontline workers if you don't properly manage it. Don't forget to include these workers with your modular designs.

Each modular product that a frontline worker sees on the assembly line, inspection bay, or customer site is different than the one they saw before it. Therefore, be sure to digitally eliminate variation complexity for these workers.



TIP

To help with the task, leverage product life cycle management (PLM) configuration logic to filter workers' instructions to the exact products they're building or servicing.

# Approach Your EPD as a Function of a Well-Populated BOM

Environmental product declarations (EPD) look like frighteningly complex product eco labels. How are you ever going to find and fund environmental experts to manually calculate an EPD for every product you sell?

With strong bill of materials (BOM) management, you should be able to automate most or all the EPD. In sustainability terms, your BOM can roll up the product's life cycle inventory (LCI) from attributes like carbon intensity, water intensity, hazmat compliance flags, percent recycled content, and recyclability. From the LCI, you can feed a life cycle assessment (LCA) tool to calculate the EPD's life cycle impact assessment (LCIA), which will calculate specific environmental impacts of the product such as CO<sub>2</sub> emissions.



REMEMBER

If that alphabet soup was tough to digest, here's the fortune cookie version: "A nourished BOM seeds an automated EPD." Check out Chapter 2 for more on EPDs.

## Consider the Upsides of the DPP

To a pessimist, the digital product passport (DPP) expands the liabilities for extended producer responsibility to ensure material returns. To an optimist, the DPP prints money. For your downstream service programs, DPPs solidify after-sales relationships with your customers. This facilitates high margin services, new business models, circular take-back value, and loyalty for follow-on sales. For your upstream engineering programs, your suppliers' DPPs offer a wealth of linked component and material data to guide selections and populate your BOMs.



REMEMBER

For your product data backbone, these passports offer the forcing function to scale your asset systems of record. Connecting service life cycle management (SLM) and PLM facilitates data-driven design and configuration-aware frontline decision support. Find details on these data linkages in Chapter 5.

# Act Now on Footprint Reductions That Make Your CFO Happy

Win early street cred where footprint reductions drive profits. You should do these activities for reasons independent of sustainability goals. It's good for business *and* good for the environment. The straightforward chief financial officer (CFO) lever is cost reduction. Eliminating unnecessary material and energy from your products and services usually saves cost. Additional business value levers with footprint reductions include customer segmentation on green premiums, compliance and supply chain risk mitigation, and leveraging regional subsidies.



Analysts and advisories agree that today you can cut half or more of your footprints with financially beneficial techniques. Your 2020s can get you high fives on profitable sustainability projects, and new approaches will scale through the 2030s for your next wins. I detail this more in Chapter 3.

## Consider Leading on Brand-Critical Topics

In sustainability, being the first mover may cost more than waiting to adopt commercially scaled approaches. But being the first mover can also yield advantages where it aligns strongly with your brand.

Be bold where you should, but do your homework on these sustainability measures. Many public benchmark details exist from which you can take inspiration. The *Beyond Zero* documentary, for example, is about Interface's modular carpeting and is an excellent case study (find out more here: [beyondzerofilm.com](http://beyondzerofilm.com)). Read sustainability reports to learn business alignment of other brand leaders like Patagonia, Schneider Electric, IKEA, and Vestas.

Innovation areas are broad but may include

- » Cutting-edge material and energy sourcing for "green premium" customer segments

- » Using additive manufacturing to achieve more lightweighting and/or service parts resilience
- » Multi-generational circular platforms with leasing/upgradable commercial programs

## Gain Carbon Value Intuition

To decarbonize, get a feel for your best opportunities. At their core, humans need to keep geosphere carbon in the deep geosphere (and when we take some out, push the same amount back). In discrete manufacturing, this means lowering fossil-sourced energy across your full life cycle value chain.

What if you still need some fossil fuel burn in the long term (beyond 2050)? You can burn it, but model your future costs to inject a comparable carbon quantity back into the geosphere through direct air capture (DAC) or other means (see Chapter 2 for details on carbon cycles).

Table 6-1 is an easy chart to help you grasp the current and future values of fossil fuel reduction (and keep in mind your company is valued on future earnings potential). Table 6-1 compares driving a fossil fueled car, an EV charged with fossil-generated electricity, and an EV charged with solar.

**TABLE 6-1 Comparison Driving 4,000km (~2,500 miles) in the United States**

Car Option	Energy Cost	Kg CO <sub>2</sub> e	DAC Cost
Gas vehicle	\$300	1,000	\$100
EV charged on grid	\$140	500	\$50
EV charged with home solar	Near \$0	Near 0	Near \$0

This table shows the present-day energy costs for the driver and the car's emissions and also the future net-zero liabilities to recapture that CO<sub>2</sub> back into the geosphere via direct air capture

with 2050's expected \$100 per Metric Tons of Carbon Dioxide Equivalent (MTCO<sub>2e</sub>) cost. You can use this understanding more broadly in your life cycle intuition of mining, material processing, transport, manufacturing, operation, service, power generation, and other potential fossil-burning activities.

## Gain Circularity Intuition



WARNING

Avoid repeating energy-intensive activities to deliver products wherever possible by applying circularity principals:

- » **Good:** Recycling avoids mining.
- » **Better:** Remanufacturing avoids material processing and mining.
- » **Best:** Reuse or repair avoids it all.

But remember that the footprint reduction is only half the need. The other half is to make circularity profitable:

- » **Good:** Material selection and design-for-disassembly foresight scales recycling.
- » **Better:** Modularity offers both the supply and demand for remanufactured parts.
- » **Best:** Product service systems lead to utilization, service, and recovery efficiencies with direct profit contributions.

Circularity is the focused business outcome. Not only can it offer best-in-class profitability, but it can also address all three footprint areas for product sustainability:

- » Finite material preservation (low or no waste)
- » Decarbonization (remanufactured products can be 60 to 95 percent more carbon efficient than linear products)
- » Hazardous material controls (avoids incineration, water pollution, and landfill leaching)

# Use the Sustainability Mandate to Establish Your Digital Thread

In a perfect world, a modular PLM BOM is your configuration system of record, connected with an asset hub as your physical equipment system of record. Participating systems thread to these two hubs. See Chapter 5 for more on the life cycle digital thread.

With regulations scaling adoption of EPDs and passports, you need to quickly establish these centerpieces. PLM BOMs feed EPD automation. Asset hubs serve as passports. This robust product data backbone drives a ton of other value beyond sustainability, including AI. But that deserves a separate book. I hope you enjoy this one!



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# Drive profits with better, cleaner products

Unlock the secrets to reducing product footprints while boosting profits. Dive into the world of product sustainability with practical tips and expert insights for discrete manufacturers. Whether you're a seasoned pro or new to the field, this book offers a fresh, approachable guide to making a positive impact. Learn the breadth of product sustainability, key focus areas, and priority actions to take across the product life cycle. Get ready to transform your products and lead the way to a greener future!

## Inside...

- Define product sustainability
- Understand compliance needs
- Profitably reduce product footprints
- Explore Design for Sustainability
- Adopt full life cycle thinking
- Transition to circular economy
- Differentiate product offerings



**Dave Duncan** is Head of Sustainability at PTC. He develops sustainability capabilities in PTC's product portfolio to help customers design, make, and maintain products more sustainably. Dave also leads PTC's corporate environmental and social impact programs.

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