WHITE PAPER

A Manufacturer's Guide to Reducing Product Carbon Emissions

HOW TO UNCOVER 'HIDDEN' CO_2E DURING PRODUCT DESIGN TO REACH YOUR NET-ZERO MANUFACTURING GOALS

Introduction

Manufacturers face increasing scrutiny regarding their progress toward reaching their net-zero goals. In addition to calls from customers and investors to reduce their carbon footprint, regulatory mandates can also have a significant financial impact on manufacturers that aren't embracing sustainable operations or a green supply chain.

Fortunately, manufacturers can still recover lost ground quickly and use their sustainability for a competitive advantage.

The shifting market landscape requires manufacturers to fundamentally rethink their entire product development lifecycle. By embedding sustainability into their operations, manufacturing teams can evaluate cost, carbon, and manufacturability simultaneously to make informed decisions quickly and confidently.

This enhanced visibility can be instrumental in boosting profit margins, mitigating risk, and making a significant shift towards responsible manufacturing.

What's Inside

This guide addresses **key considerations and best practices to reduce your environmental impact** during the product sourcing, design, and manufacturing "cradle-to-gate" portion of the full product development lifecycle.

Table of Contents

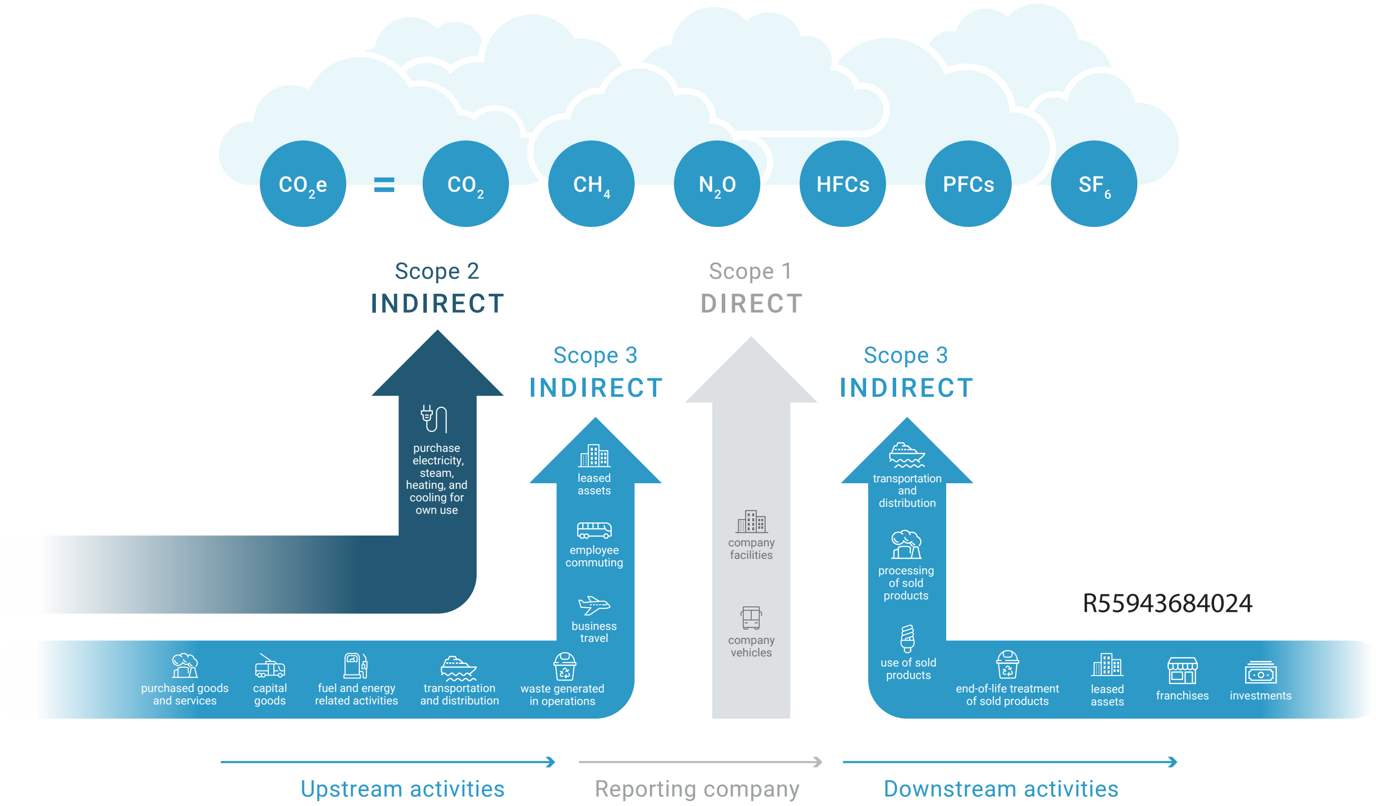
Breaking Down Emissions Categories

The Greenhouse Gas Protocol (GHG Protocol) provides a uniform method to gauge the entire "cradle to grave" impact of a product's carbon footprint using carbon dioxide equivalent (CO_2e) measurements. According to the European Environmental Agency, CO_2e "is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential."

The GHG Protocol categorizes the source of emissions in three levels/scopes for manufacturers to track across their entire operations beyond just product manufacturing:

- **Scope 1** addresses direct emissions from owned or controlled sources
- **Scope 2** includes indirect emissions from purchased energy generated
- **Scope 3** covers indirect emissions from assets and services that aren't owned or controlled by the reporting organization but that affect its value chain. This includes all upstream and downstream emissions

All GHGs are converted to CO_2e to create a standard measurement for emissions



Source: Adapted from the GHG Protocol

What are Upstream and Downstream Emissions?

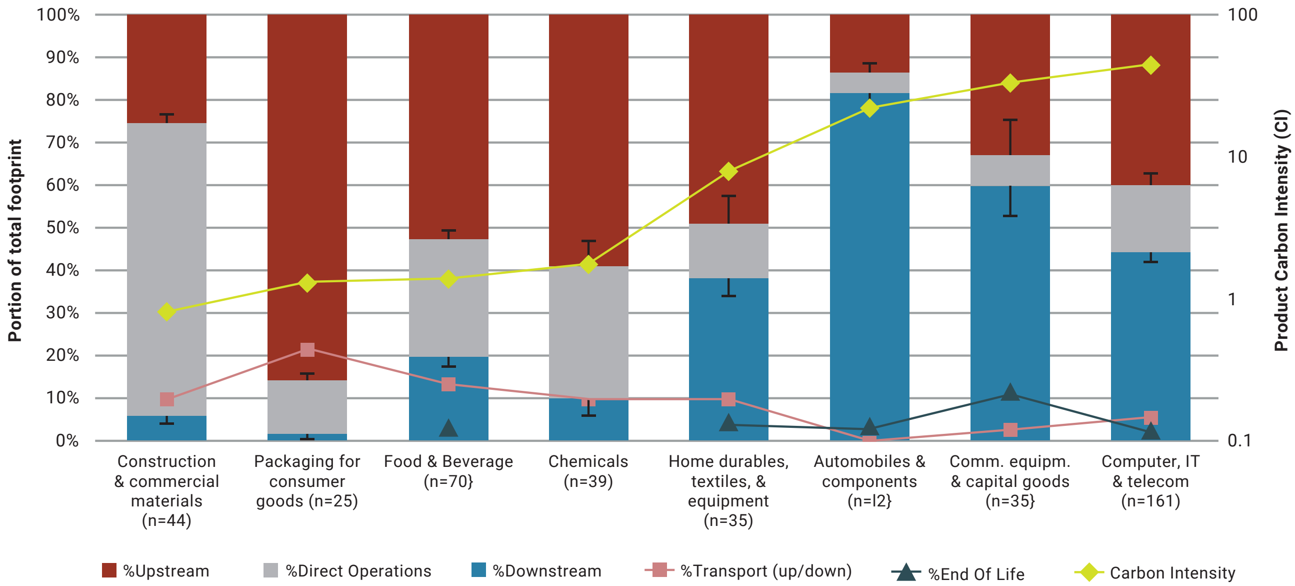
Scope 3 emissions are difficult to track and manage because this process typically requires extensive data collection from suppliers (and sometimes their suppliers) and other vendors across the supply chain. To help companies better understand the source of their CO_2e, the GHG Protocol categorizes value chain (Scope 3) emissions into up- and downstream emissions. Definitions and examples follow:

Upstream emissions are associated with products and services used to support a manufacturer or other organization directly. A company or its employees generally pay for upstream goods and services. Examples:

- Purchased goods and services: upstream CO_2e from the production of all products and services (purchased or acquired)
- Capital goods and leased assets: addresses manufacturing equipment purchased or acquired – and emissions from leased assets
- Fuel and energy: captures relevant emissions not covered in Scopes 1-2
- Transportation and distribution: emissions from third-party transportation and distribution services
- Waste: includes the treatment and disposal of waste and/or wastewater from the reporting company
- Business travel and employee commuting: covers vehicles owned or operated by third parties and emissions from commuting

Downstream emissions refer to indirect emissions related to customers. Typically, if a customer pays for this category of goods or service, the associated emissions are downstream. Examples:

- Transportation and distribution: includes vehicles that aren't owned or controlled by the reporting organization
- Processing of sold products: emissions created when third-parties process sold intermediate products
- Use of sold products: emissions from the use of sold services and goods
- End-of-life treatment: includes waste treatment and the disposal of sold products
- Leased assets: addresses areas not included in Scopes 1-2
- Franchises and investments: includes Scope 1-2 emissions from franchisees, and emissions associated with investments (primarily for financial institutions)



Research published in Nature shows that for the 866 products, on average 45% of total value chain emissions arise upstream in the supply chain, 23% during the company's direct operations, and 32% downstream.

The columns show each sector's emissions breakdown for a typical sector (industry) product value chain. Industries are sorted left to right to show the lowest average product carbon intensity (CI) to the highest. The sample size is listed at the bottom of the sector label. The end-of-life portion could not be separately quantified in three sectors because they don't include products with the respective breakdown for end-of-life emissions.

Source: Scientific Reports

Where You Have the Most Control Over Carbon

Manufacturers are increasingly focused on the “cradle-to-gate” portion of the entire “cradle-to-grave” product life cycle. Cradle-to-gate emissions – also known as embodied emissions – cover CO_2e emitted during product production, including raw material extraction and refinement, manufacturing, and assembly. To a lesser extent, embodied carbon also includes the environmental impact of shipping finished goods to the “gate” of a store or customer.

Operational (in-use) carbon measures the amount of carbon during a product’s life (use). Many of the downstream emissions factors occur during the operational phase (e.g., the use and disposal of a product, additional third-party transportation of products, etc.). Manufacturers have the least amount of control over in-use carbon, and projected carbon emissions are simply assumptions.

Why Manufacturing Contributes to a Growing Share of Carbon Emissions

A greener energy grid, coupled with advances in electrification (e.g., electric vehicles replacing gas-powered cars) is reducing operational carbon. Because cuts to embodied carbon have been slower, they account for a larger portion of overall emissions.

Carbon Brief reports that the renewable energy capacity added during the past five years can power the equivalent of the entire EU. And additional solar, wind, and other renewables projected to be online by 2030 will power the equivalent of the U.S. and Canada. Despite these gains, the International Energy Agency projects that renewable energy will fall short of COP28 goals.

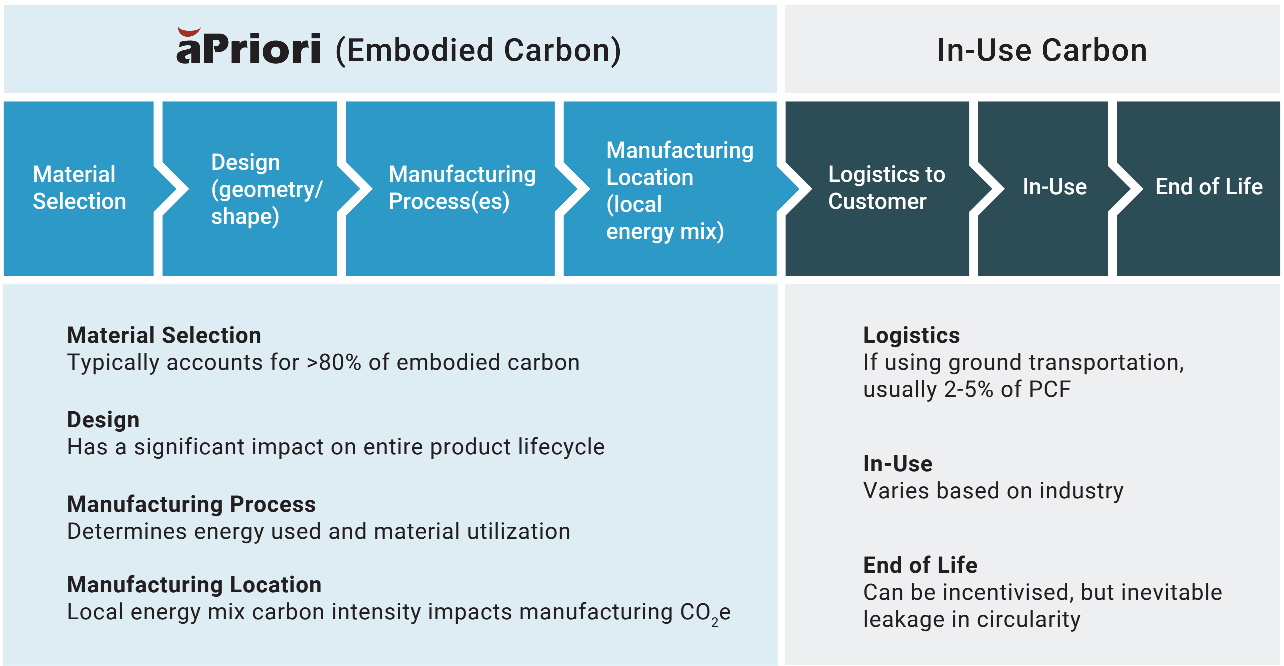
of the global carbon footprint is embodied in traded goods

As such, embodied carbon becomes a higher percentage of overall GHG emissions and is increasingly important to address. One-quarter of the global carbon footprint is embodied in traded goods, according to the U.S. Department of Energy Office of Science and Technical Information.

And this varies by industry. In building and construction, embodied carbon will account for 49% of the total carbon emissions between 2020 and 2050, according to a United Nations (UN) report. To put this in perspective, nearly half of all CO_2e for a building project is already released before its first tenants move in.

Companies with the visibility to assess the carbon impact during product design and manufacturing gain the ability to identify opportunities to reduce carbon that are often hidden due to the complexity of this process.

Focus Resources Where it Counts



How to Separate Validated CO_2e Data from Assumptions

Manufacturers use multiple tools to establish precise manufacturing data – including 3D CAD, computer-aided engineering/simulation (CAE), and product lifecycle management (PLM). And Industry 4.0 sensors track real-world performance on the machine shop floor.

- Detailed **calculations for the life** of a machine
- Material waste generated based on a **specific product design**
- Energy used to **complete a variety** of production runs

Although manufacturers have accurate, validated data for embodied emissions, that's not the case for the in-use phase, which relies heavily on assumptions. An automotive brand, for example, can manage the emissions during production, but doesn't have control over a specific car's lifespan due to variables including accidents, maintenance, etc.

Select the Right Tools for the Job

Insights and data used to usher in new levels of lean manufacturing and operational excellence can also be applied to address carbon emissions. **Forward-thinking manufacturers are unlocking design and manufacturing data – and applying it to help reach their net-zero targets.** And they are making significant gains in their sustainability initiatives by using manufacturing insights to generate accurate, validated data to optimize a product for cost, sustainability, and DFM simultaneously. Importantly, they gain this insight in real time earlier during the product design process.

In this scenario, product design teams can also apply manufacturing insights to evaluate complex scenarios and determine the most appropriate result. With manufacturing insights, product development teams can simulate how changes to a 3D CAD design, manufacturing process, factory selected, or production region can affect the KPIs for a new product.

Why LCA's Aren't a One-Size-Fits All Solution (And Here's How to Harness Their Data for Product Design)

Scope 1-3 illustrates the breadth and complexity associated with estimating CO_2e throughout a product's lifecycle. That's why a product's carbon footprint is usually calculated once it's already been manufactured based on life cycle inventory (LCI) data for life cycle assessment (LCA) tools. LCAs provide broad CO_2e averages across multiple industries and include generalized emissions estimates for outputs ranging from energy consumption to waste.

And due to its depth and complexity, LCI data is traditionally only used by experts such as LCA research scientists/analysts and sustainability managers. Without access to LCA tools (and the ability to test multiple design scenarios in real time), product design teams traditionally haven't had the fact-based insights to reduce a product's environmental impact. Until now.

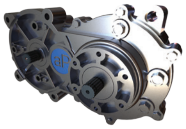
aPriori Sustainability Insights

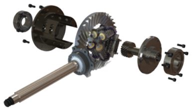
To gain accurate, immediate access to carbon data, leading manufacturers are using data-driven manufacturing solutions such as aPriori that integrate LCI data.

Uniquely, aPriori provides precise analysis of designs, coupled with modeling of digital factories and processes, to automatically align accurate CO_2e data with a specific product design and manufacturing facility. Companies that harness their design and manufacturing data can gain precise carbon emissions data based on factors ranging from materials to production specifications down to the machine level.

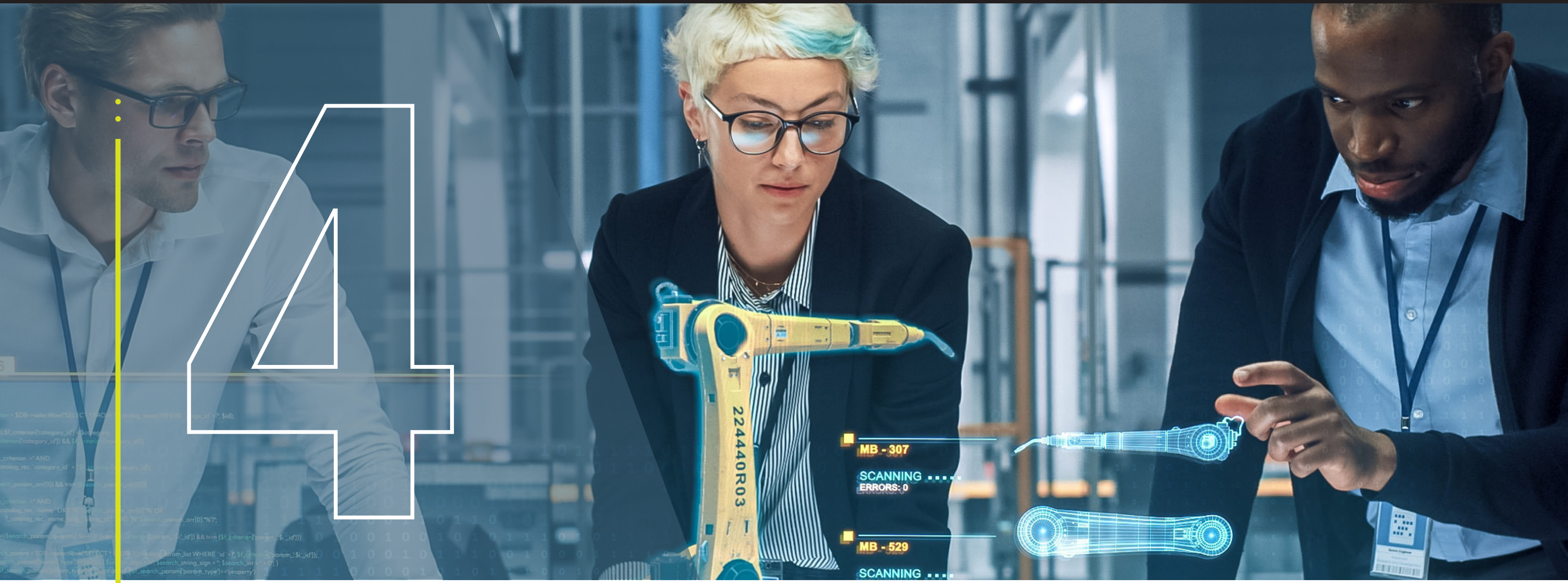
And this visibility enables product development teams to evaluate cost and carbon emissions simultaneously while ensuring manufacturability. This includes the ability to simulate how changes in designs, materials, manufacturing processes, and specific factories can balance cost and carbon reductions.

Comparing CO_2e Insights During Product Design

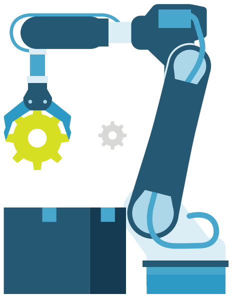




Variable	Life Cycle Analysis (LCA)	aPriori Analysis	aPriori Advantage
Cost	N/A	Included	Evaluate cost, carbon, and DFM simultaneously, in minutes for data-driven decisions
Design/Shape	N/A	3D geometry-based analysis	Precision for weight, wall thickness, and other product parameters
Material	Final product/ component mass	Calculate amount required for production	Capture waste based on specific design and manufacturing processes
Energy Mix	Country average– manual override available	Country average– and configurable to individual factories	Fossil fuel in energy mix can vary by 60% or more by region
Manufacturing Process(es)	General estimates based on mass, each one specified manually	Track down to individual machine and process/ secondary process levels	Use your/supplier manufacturing data for precise evaluations



Sustainability at What Cost?



The design phase locks in about 80% of a product's environmental impact and cost

Product design and manufacturing are the linchpins of successful sustainability efforts. Companies determine more than 80% of a product's environmental impact during the design phase, according to the EU Science Hub. Similarly, up to 80% of product cost is also defined during this early phase.

The design phase is the critical point to address cost, carbon, and DFM simultaneously. Manufacturers that misfire on one or more of these attributes risk launching a product that's either too expensive, is too carbon-intensive, or may suffer from performance or reliability issues. Manufacturers need to balance each of these product requirements for a competitive advantage.

Evaluate Cost, Carbon, and DFM Simultaneously

With aPriori Sustainability Insights, manufacturing teams can simultaneously evaluate how early design and production alterations influence real-time product cost and carbon while ensuring real-time manufacturability. Further, aPriori delivers the transparency and actionable guidance teams need to reduce costly GHG emissions throughout the supply chain (Scope 3).

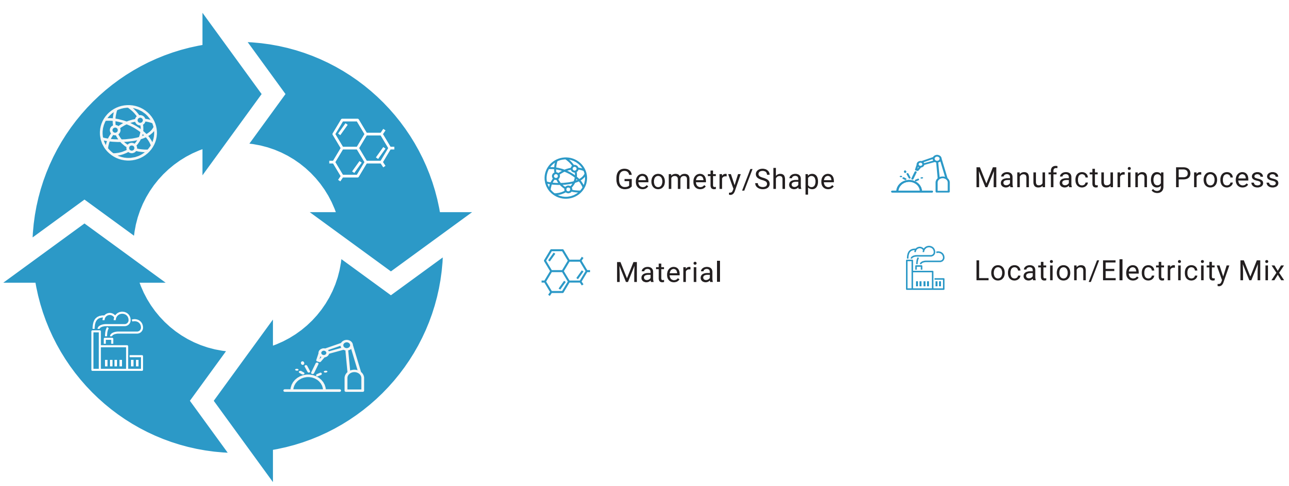
aPriori incorporates the following capabilities within its automated solution to generate rapid, cradle-to-gate CO_2e estimates and improve product development team decision-making:

- **End-to-End Digital Twins:** aPriori automatically extracts geometric data from 3D CAD files in real time or once the designs are checked into a PLM system. The solution leverages the 3D data and connects three digital twins—product, process, and factory—to generate precise carbon, cost, and manufacturability breakdowns. aPriori digital factories are fully configurable and can simulate production based on a product's design (geometry), raw materials, energy consumed, machines available and manufacturing processes, overhead rates, and more. aPriori delivers these insights using real-world production process groups and economic conditions for 87 global regions.

- **Rough Mass and Energy Consumption Analysis:** LCA tools calculate carbon based on finished mass, which misses most material CO_2e created for a product. aPriori provides more precise CO_2e calculations based on the rough mass, 3D design-specific cycle time, and energy consumption used to create parts or assemblies. Additionally, aPriori enables product development teams to calculate costs and carbon simultaneously to evaluate real-time trade-offs.

- **Centralized CO_2e Data and Automated Alerts:** aPriori centralizes and standardizes product, material, and manufacturing process data in a single platform. This enables internal project stakeholders to evaluate and make data-driven decisions regarding low-carbon design, manufacturability, and sourcing options. Additionally, aPriori delivers automated alerts with actionable manufacturing guidance to help product teams eliminate early carbon issues in new or updated designs.

Targeting 4 Areas to Reduce Embodied Carbon



3 Case Studies, 3 Paths to Product Sustainability

The following three case study examples showcase the interplay between costs and carbon emissions in the discrete manufacturing industry. Can you select the optimal option based on the background provided?

Without fact-based insights, you're at a disadvantage – especially because some data-driven recommendations may seem counterintuitive if detailed information isn't available to inform decision-making.

01 Does Factory Location Affect Your Cost and Carbon Footprint?

In the first example, an interior car panel is manufactured in Eastern Europe. The sourcing team is evaluating alternative locations to reduce manufacturing costs and/or carbon: China, Eastern Europe, Western Europe, and the United States.

To evaluate its options, the sourcing team uploads the 3D CAD model of the side door panel into uploads the 3D CAD model of the side door panel into aPriori, selects the appropriate digital factory, and enters the following specifications:

- **Material:** ABS
- **Production process:** Plastic molding
- **Annual volume:** 5,000
- **Production duration:** Five years

The current baseline cost from Eastern Europe is $16.85 per unit and 8.3 kilograms of carbon emissions, which is split evenly between material and process CO_2e. Now, the sourcing team compares GHG emissions across various regions. Learn more about aPriori's Regional Data Libraries.

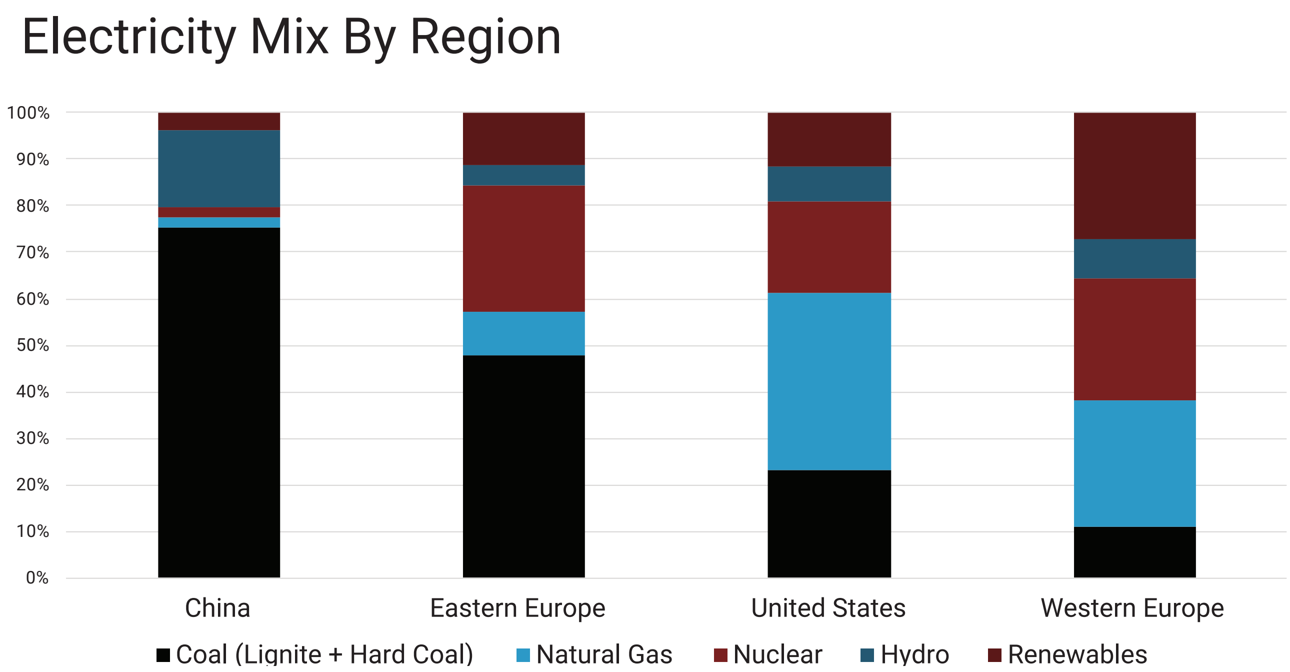


Figure 1: Energy Mix Comparisons by Region

Figure 1 shows the mix of energy sources, including coal, natural gas, nuclear energy, hydropower, and renewable energy in each region's energy use. China, producing about 75% of its electricity from coal, has the highest CO_2e emissions per kilowatt-hour. By contrast, Western Europe has the lowest emissions because it has a higher percentage of low-carbon energy sources (renewables and nuclear).

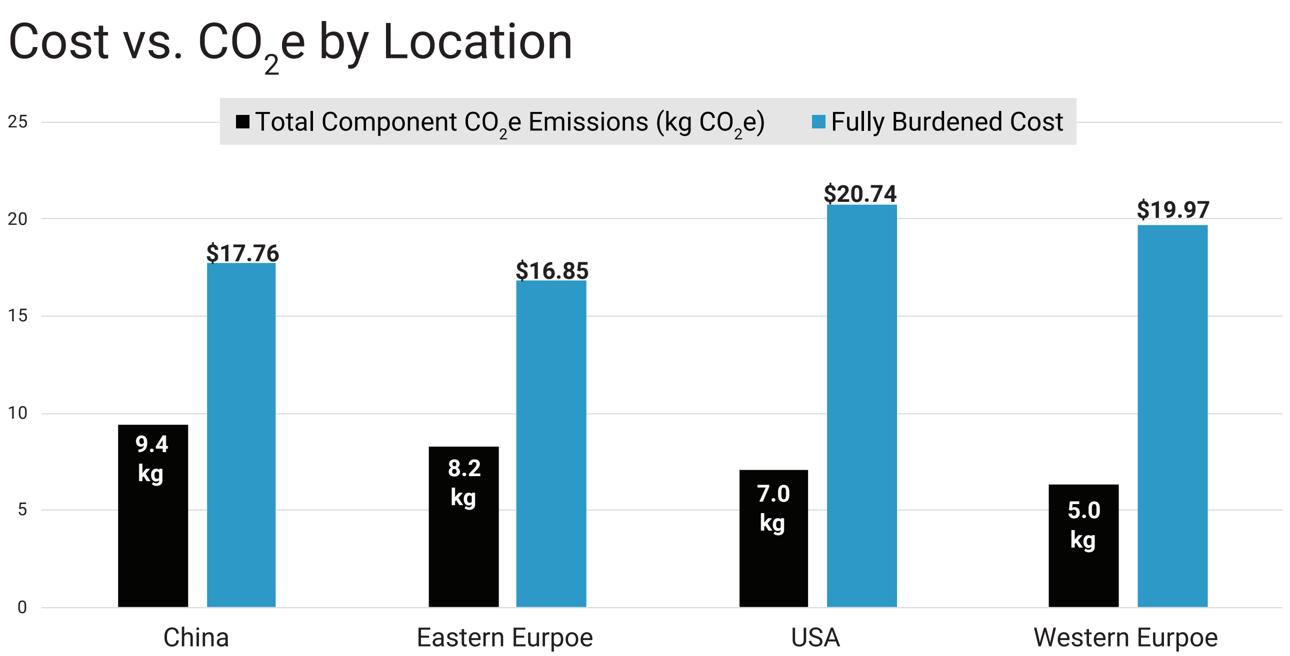


Figure 2: Comparing Cost and CO_2e Emissions by Region

Applying your Insights

The carbon impact for each location varies significantly. Companies can evaluate trade-offs and better understand the strategic value of saving 1.3 kg of CO_2e by moving production to the United States and increasing the production cost by nearly $4 per unit. The company can determine the best path forward based on its profitability and sustainability targets.

When considering cost and carbon using aPriori analysis, Eastern Europe is preferable to China because both the environmental impact and cost are lower. But depending on the company's priorities, Western Europe may be the preferred production region based on its mix of cost and carbon.

02

The Impact of Material Choices on Carbon Emissions

For an electric vehicle control unit connector, the difference in material selection can be significant. For the plastic housing of this assembly, the manufacturer is comparing Nylon 6 and Nylon 6 with a 30% glass fill to look at the differences between the two materials. The component assumptions and specifications are the same for each material:

- **Component/CAD model:** Electric vehicle control unit (EVCU) connector
- **Production process:** Plastic molding
- **Factory location:** United States
- **Annual volume:** 5,000
- **Production duration:** Five years

First, let's establish a baseline to base our assumptions using data from ecoinvent, aPriori's LCI/LCA partner. LCI data shows that Nylon 6 has 9.27 CO_2e per kg, while its glass-filled counterpart has 7.43 CO_2e per kg – 20% less than Nylon 6, which is a much lower carbon intensity.

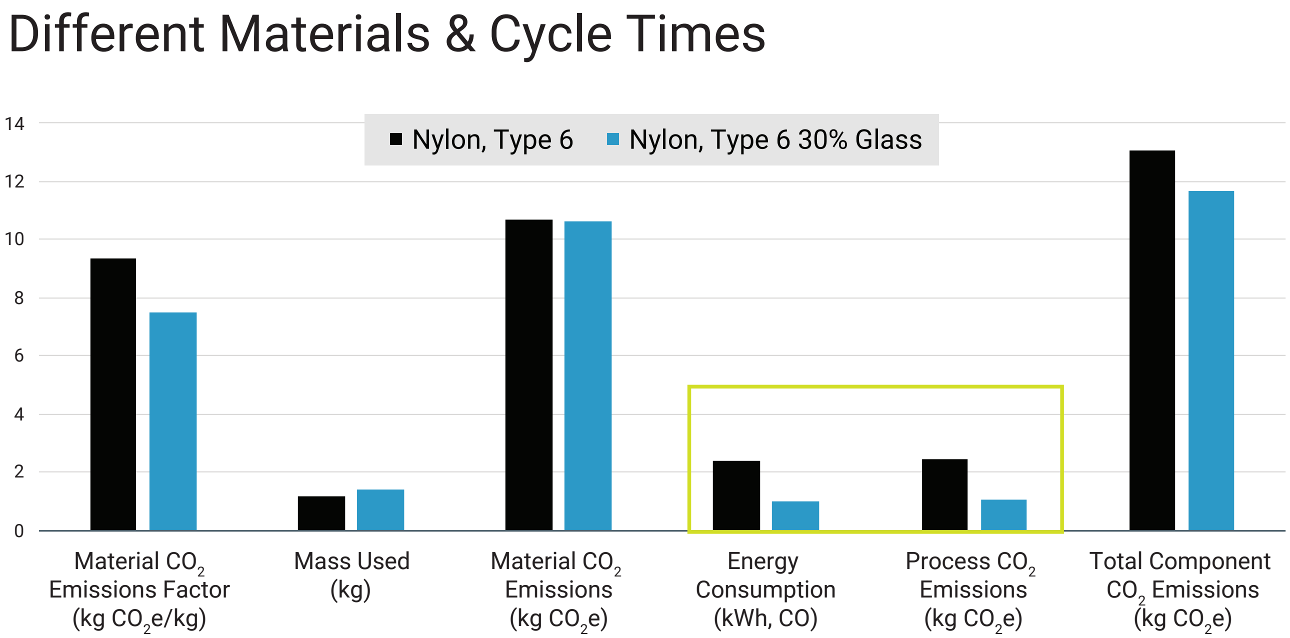


Figure 3: How Manufacturing Cycle Time Can Impact CO_2e

Result

The product design team assumed that glass-filled Nylon 6 would offer a reduction because glass-fill usually leads to faster cooling times, which reduces energy used during production. When you look at the data in isolation, the glass-filled nylon appears to have lower CO_2e per kg.

However, because the material is also denser, the same design (i.e., the same volume of material) will be heavier. CO_2e by volume of material is similar for both options. aPriori proved the design team's assumption: the reduced cooling time cut the process carbon but had virtually no impact on the material carbon.

Financially, this also translates to a cost reduction of about 10%, from $16.40 to $14.48. The glass-filled Nylon's stiffer properties also allow potential design modifications, such as reducing the sidewall thickness. This could lead to less material required (less volume), and thinner walls could mean even faster injection and cooling times.

This points to the importance of iterative design processes in manufacturing. Manufacturers can make more informed and sustainable decisions by considering a material's impact on carbon emissions and costs.

Material Cost Breakdown

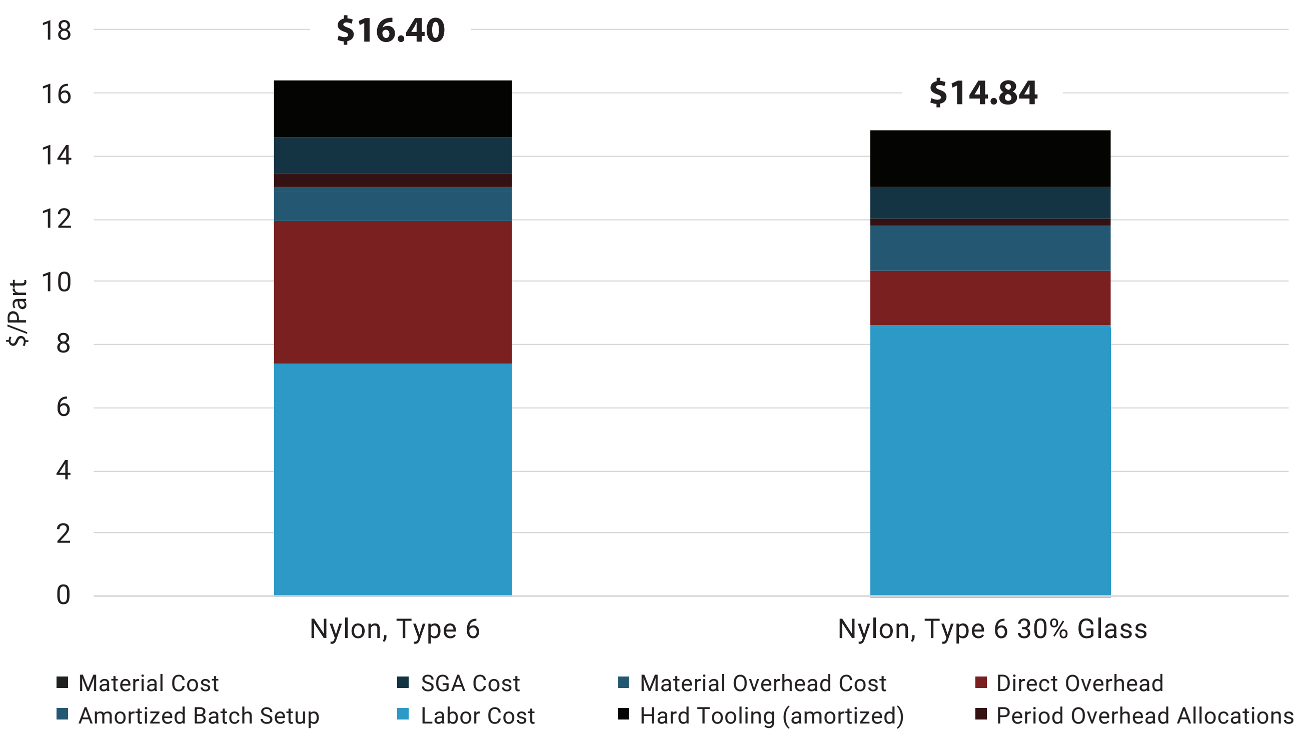


Figure 4: Comparing Costs for Nylon 6 vs. Nylon 6 – 30% Glass

03

The Manufacturing Process and Carbon Implications

Here we examine the carbon emissions difference between die casting and machining. We're using the same part in the previous example to evaluate the part's metal component (produce 5,000 components annually during a five-year period).

Die casting for this component provides a significantly lower cost and carbon footprint. Production volume is a central factor here: it's typically cost-prohibitive to die-cast low-volume parts. Due to the type of part and volume, it's approximately nine times more to machine it.

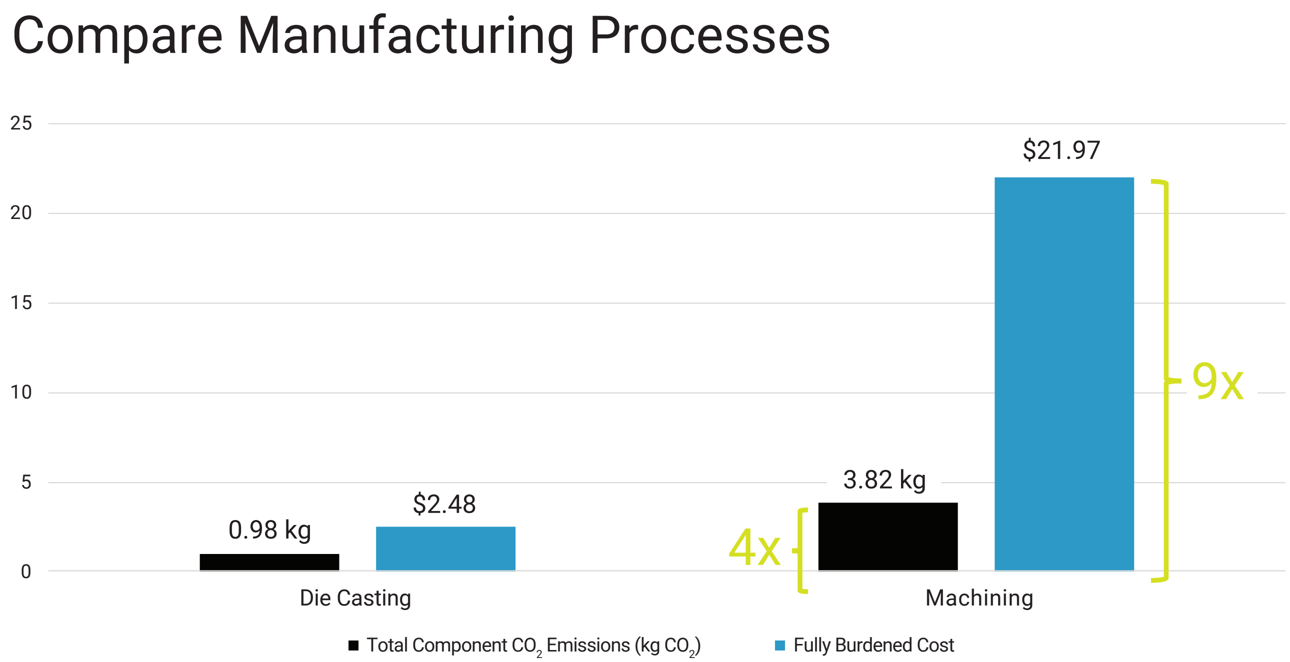


Figure 5: Die Casting vs. Machining (Cost and Carbon)

The machining process also has a significantly higher CO_2e component than die casting. Because die casting uses material more efficiently. Only the material lost in the sprues and runners is wasted. And that's despite requiring more energy to melt and pour the metal compared to machining, which starts with a billet, rather than ingots, and requires more energy to process it into that form. Additional machine waste includes all the material removed to create the final form.

Result

The biggest CO_2e driver for this part stemmed from its material carbon. The process uses aluminum billet, which requires more processing than aluminum ingots. The biggest factor, however, is the amount of waste associated with machining, which wasted about 68% of the original aluminum stock. Although this waste could be recycled or reused, we cannot claim credit for it at this stage without double counting.

With this understanding, manufacturers can consider ways to modify the product design or use less material during production to reduce waste and increase material utilization.

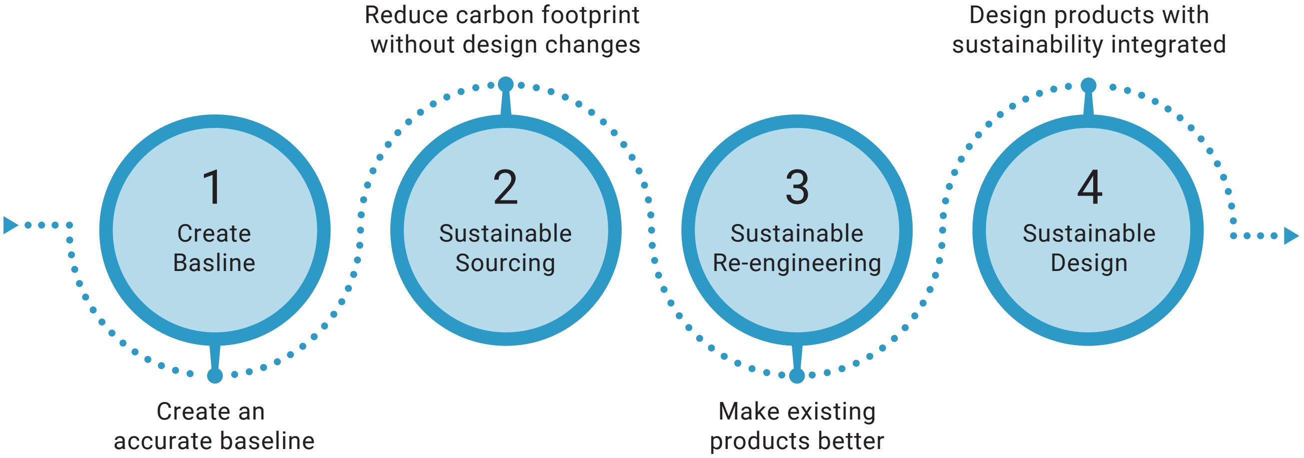
How to Apply aPriori's Sustainability Maturity Model

aPriori has established a sustainability maturity model as a strategic roadmap for manufacturers to assess their current capabilities and the effectiveness of their green supply chain management initiatives. By monitoring their sustainability maturity performance, manufacturers can implement strategies to advance their carbon reduction capabilities.

The following figure illustrates how product development teams can assess and pinpoint their position across the four stages of sustainability maturity.

Manufacturers that don't advance their sustainability maturity to the fourth and final stage risk falling behind their competitors and being saddled with additional operational costs due to incurred carbon taxes and other regulatory policies enacted to spur the reduction of GHGs.

Targeting 4 Areas to Reduce CO_2e



STAGE 1

Create Precise, Auditable CO_2e Emissions Baselines

Creating a precise carbon emissions baseline is the first step in achieving a sustainable and green supply chain. This baseline empowers sustainable manufacturers to measure and quantify the carbon footprint of their existing supply chain operations, enabling them to:

- Use their current "state of sustainability" as the starting point to plan and track their progress
- Identify and focus on the areas with the highest cost and carbon reduction potential
- Set realistic cost targets that guide and influence product teams' supply chain decisions
- Adhere to environmental, social, and governance (ESG) standards and regulations
- Benchmark and compare their sustainability performance against industry competitors

While companies recognize the importance of accurate baselines, they struggle to create them without a tool that provides early visibility into Scope 3 emissions. As an example, LCA tools don't provide access to real-time sustainability data for teams to make early and influential design-stage decisions.

aPriori's automated sustainability insights solution closes the gap by integrating data from ecoinvent, a leading third-party LCA and inventory database tool. aPriori utilizes ecoinvent's database to quickly establish environmental baselines and GHG emissions at the product level. With automated and more precise baselining, teams can quickly move to the second phase of sustainability maturity: evaluating and selecting sustainable suppliers.

STAGE 2

Select Sustainable and Responsible Global Suppliers

Next, evaluate and select suppliers based on their local electricity mix, material supply, and processes (Scope 3). Product teams aim to enhance the sustainability of existing innovations through informed supplier selections instead of resorting to costly design or material changes.

Sustainable sourcing offers the most straightforward approach to reducing CO_2e by minimizing the need for extensive design changes, and therefore can be implemented at any time. However, it is difficult for product teams to capitalize on this opportunity without a dedicated and standardized tool such as aPriori.

aPriori provides manufacturers with complete visibility into the sustainability of their supply chain, empowering them to make data-driven sourcing decisions. By utilizing aPriori for sustainable sourcing, companies can:

- Explore various "what-if" scenarios (regions, routings, materials, volumes/batches, suppliers, make vs. buy)
- Reduce iterations and negotiation by digitally connecting buyers and suppliers
- Fill skills gaps by providing design teams with exposure to granular, real-world sourcing data
- Identify sustainable procurement strategies to support internal ESG goals and initiatives

STAGE 3

Optimize Existing Products for Cost and Carbon

The path toward greener products involves optimizing existing product innovations. In stage three, product teams can consider alternative materials with lower carbon and higher recycled content. And they can also make processes more efficient and utilize renewable energy sources to improve cost and environmental sustainability.

The objective is to minimize cost overruns and release products at target costs to maintain profitability and competitive advantage. However, this is difficult to achieve when cost engineering teams are limited to conventional, labor-intensive costing tools like manual spreadsheets. And the complexity of this challenge heightens when the situation extends to CO_2e emissions. This is because spreadsheet-based solutions cannot:

- Evaluate the complex interrelationships between direct and secondary cost & carbon drivers in real time
- Accurately manage cost & carbon variables in an ever-changing global supply chain
- Identify and capitalize on cost & CO_2e reduction opportunities during early product design phases

aPriori provides a precise, real-world product cost optimization solution to make highly informed and effective manufacturing decisions. aPriori's automation-driven platform can simulate production based on product design (geometry), manufacturing overhead costs, direct labor hours, machine hours, and more.

Additionally, aPriori enables companies to navigate and manage rising material costs, inflationary pressures, and other external risks to build cost-effective products. aPriori also automatically notifies and provides actionable feedback to design, manufacturing, and sourcing teams when products exceed cost thresholds. This facilitates seamless collaboration among product development teams, enabling them to eliminate cost drivers early and maintain corporate profit margins proactively.

STAGE 4

Remove Embodied CO_2e Through Superior Product Design

The final stage of sustainability maturity represents the most challenging path and the greatest opportunity for reducing GHG emissions. Product engineers can typically compare multiple product designs and select the most cost-effective option for both cost and DFM. But when you add carbon to the mix, the answer usually far from intuitive today.

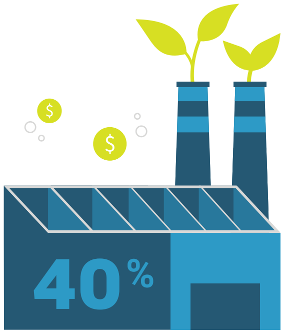
But by using real-time CO_2e feedback from the 3D CAD model, teams can proactively modify the product's design to reduce its embodied carbon. Or ensure that a product meets its targets for cost and sustainability, along with manufacturability.

Accelerate Your Path Toward Net Zero

A clear sustainability strategy and plan to reach its goals provide a foundation to stay competitive. And digitalization is central to reducing carbon emissions rapidly and effectively across an organization.

By embedding sustainability into the core of business operations and strategic planning, manufacturers can create a culture of environmental responsibility and drive meaningful change. To underline this point, BCG reports that companies with a leading position on sustainability calculate emissions at the product level and use digital capabilities for emissions management.

Net-zero initiatives are achievable. But this requires a clear vision and collaboration to unite all corporate manufacturing departments and the associated value chain. By embracing innovative technologies, collaborating with partners, and taking advantage of available incentives, manufacturers can navigate the complexities of embodied carbon and pave the way for a more sustainable future.



"40% of senior executives estimate an annual financial benefit of at least $100 million for meeting emissions reduction targets"

Source: Boston Consulting Group

Why aPriori?

aPriori provides a unique, end-to-end digital twin solution that empowers manufacturers to unlock and identify new opportunities rapidly for innovation, growth, cost savings, and sustainability. With aPriori, customers achieve a ~600% ROI within three years and payback within six months of adopting our software platform.

And companies use our automated manufacturing insights to reduce product cost, improve productivity, and reduce their products' carbon footprint. aPriori also boosts manufacturers' digital thread investments to deliver business value at scale, increase agility, and minimize risk. To learn more about aPriori's cloud and on-premise solutions, visit www.apriori.com.

Corporate Headquarters USA
Concord, MA | hello@apriori.com

EMEA
Belfast, Northern Ireland | emea@apriori.com

APAC
Tokyo, Japan | apac@apriori.com

DACH
Munich, Germany | dach@apriori.com