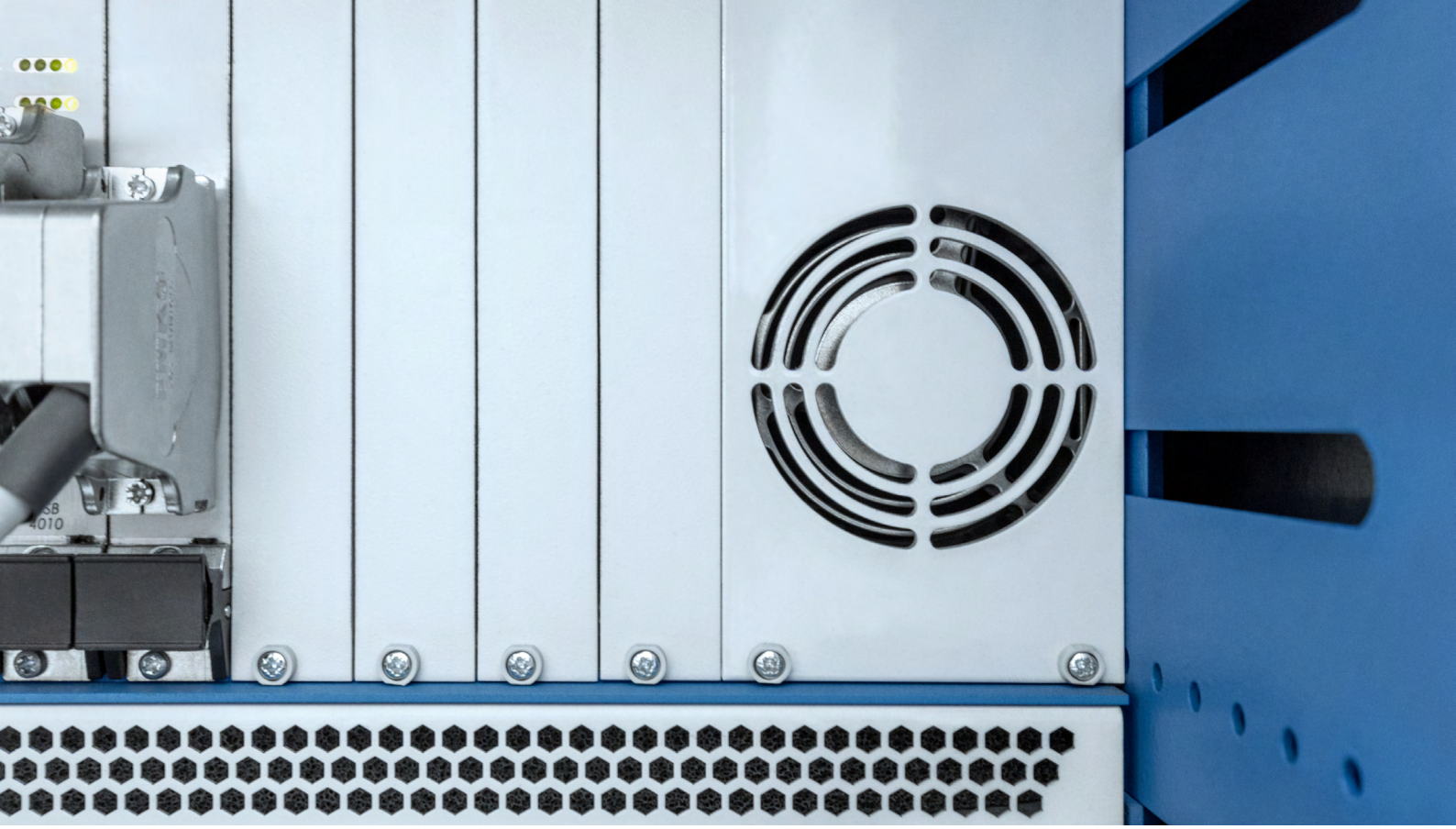
How to achieve circularity with a digital-first approach

SIEMENS



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Introduction

Each year, 9.2 billion tons of industrial waste are generated worldwide. For industry, this trajectory is both environmentally destructive and economically unsustainable. Volatile material prices, regulatory demands and supply chain disruptions caused by geopolitical shifts are exposing the limits and the fragility of the current "take-make-waste" model. This linear approach may have worked in the past but is not fit for our current era of industrialization.

"

$4.5 trillion

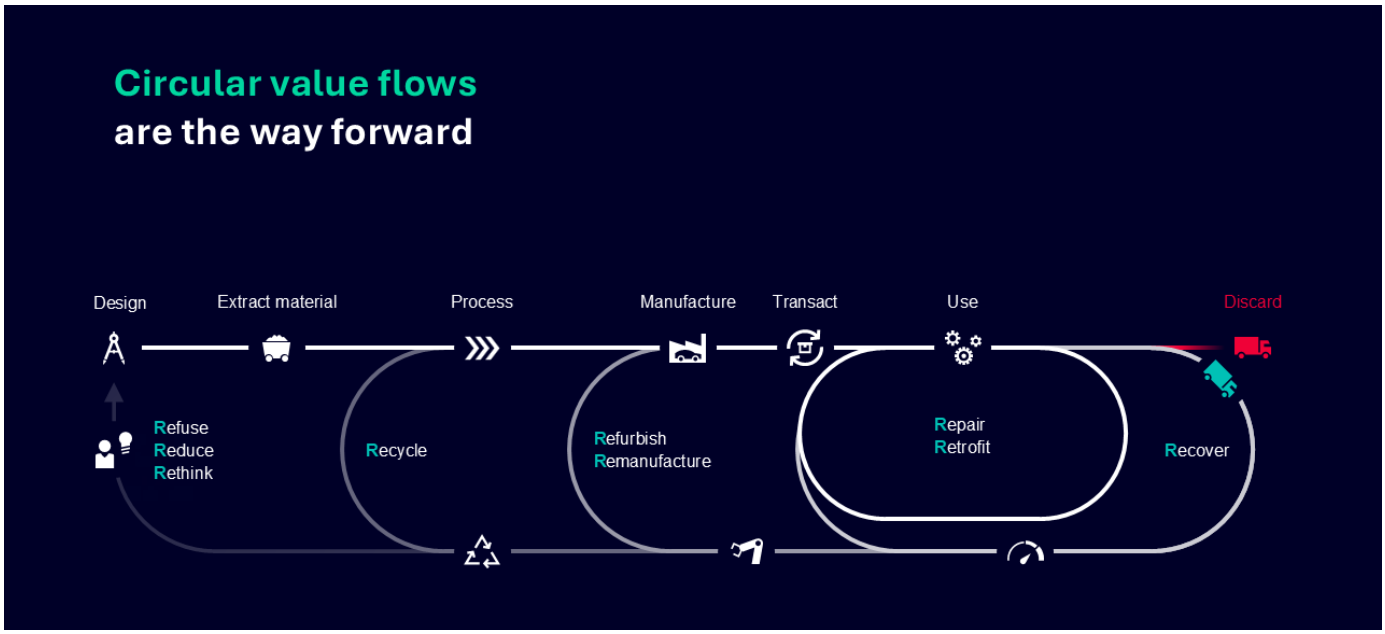
in economic value can be unlocked by 2030, as waste becomes a pathway to profit

Although the world's current waste generation is staggering, it is rich with latent opportunity. How? For businesses willing to embrace circularity, waste can become a pathway to profit, unlocking $4.5 trillion in economic value by 2030*.

Circularity is a strategy to redefine and eliminate waste while maximizing economic value. It enables organizations to rethink and revamp entire products, processes and value chains from the very beginning. By considering waste as a design flaw, manufacturers can reduce material dependency, cut costs and ultimately prepare for what lies ahead.

This whitepaper explores how, by combining the real and digital worlds, industrial companies can not only create circular practices but also gain a competitive edge. By connecting and optimizing design, manufacturing and value recovery through Digital Threads, Siemens enables organizations to keep materials in continuous circulation, driving both sustainability and economic advantage.

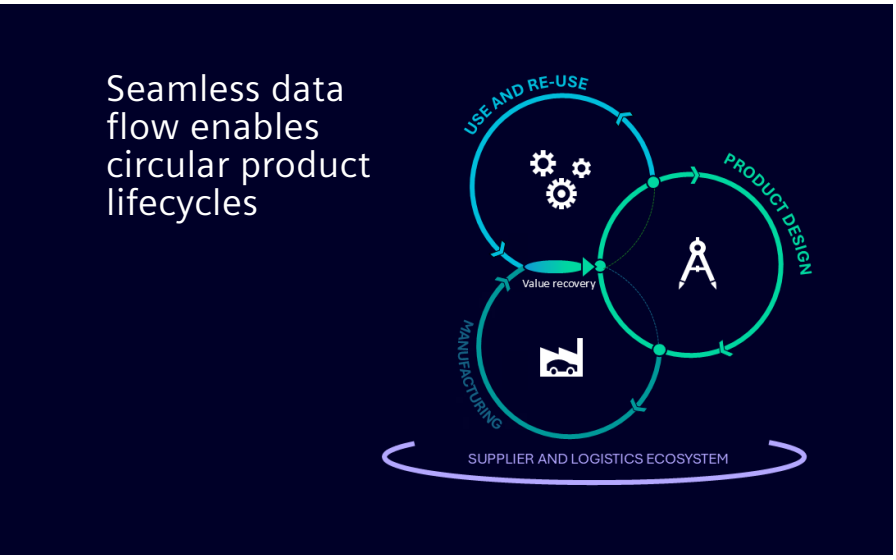
By embracing systems thinking, businesses can design products that are circular, ensuring materials remain in the loop.



*Source: Link

Taking the **Digital Thread approach**

According to the Ellen MacArthur Foundation, forward-thinking companies are reimagining their products and operations through a systems and systems thinking lens that aligns product design and process decisions with circular economy principles. By combining the real and digital worlds, companies are able to treat product development as an interconnected system. Integrating every stage of the lifecycle allows businesses to create dynamic feedback loops where insights from later stages can inform earlier decisions. The result is products that are designed for endless cycles of reuse, recovery and reintegration rather than single use.

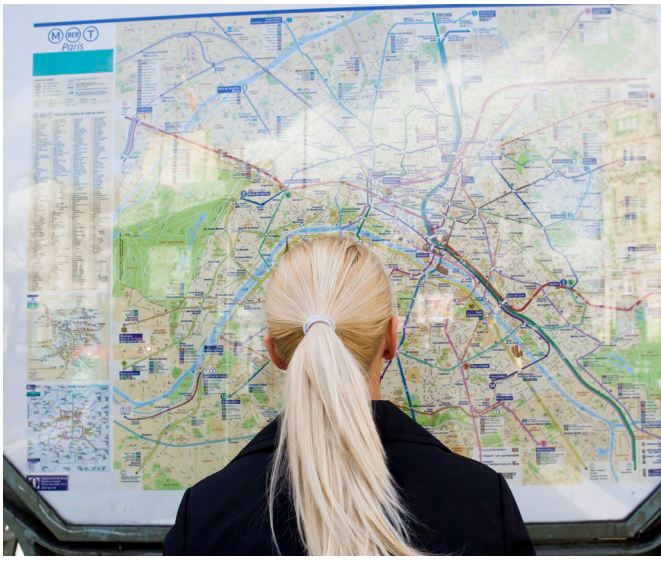


Connecting data is the key to achieving circularity across products, manufacturing and value recovery.

But circular product development is no simple task. Sustainability must be balanced with other factors like performance, cost, marketability and functionality. Every component of the system is influenced by another, demanding a sophisticated approach to managing data and complexity. This is where a Digital Thread becomes the solution.

Think of Digital Threads like red lines on a subway map, connecting data to find the most efficient route from point A to point B. A Digital Thread guides data seamlessly throughout the product lifecycle based on each company's specific business workflows, enabling teams to design with circularity in mind and continuously optimize every element as part of a larger, dynamic system.

Without this level of connectivity, identifying opportunities for improvement or understanding how one decision ripples across the lifecycle would be nearly impossible. Siemens has identified one key Digital Thread that serves as a roadmap for achieving circularity at scale that covers the areas of design, manufacturing and value recovery.



Digital Threads enable circularity by seamlessly connecting data throughout the product lifecycle.

Leveraging your Digital Thread **for circular design**

Eighty percent of a product's environmental impact is determined during the design phase*. That's why it's critical for designers to consider integrating circularity into their designs from the outset. Doing so can eliminate waste and cut costs early in development, but identifying where product designers should begin is often the challenge. The Digital Thread provides that guidance, helping product developers apply R strategies like reducing waste, reusability and recyclability from the beginning.

80%

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Embedding sustainability from the start

First, designers must strategically identify, document and trace every product requirement across the lifecycle. Traditionally, this has meant functional requirements, performance goals, quality attributes and user expectations. But the shift to circular design raises the bar.

Now, requirements must account for sustainability from the start—whether that means eliminating single-use plastics or building in modularity. The decisions made here ripple forward, shaping everything from design to manufacturing to end-of-life outcomes.

Supplier and material selection

Next, designers have to select suppliers who not only meet the established technical and regulatory requirements, but who also align with the organization's broader sustainability goals. Chosen suppliers should actively support circular economy principles and having the right partners at this stage builds the base for a sustainable and efficient supply chain.

The next step is material selection which now goes far beyond performance and aesthetics. While those considerations still matter, designers prioritizing circularity must also evaluate recyclability, favor secondary or bio-based materials, eliminate harmful substances and explore alternatives that support long-term value recovery.

*Source: Link

System definition

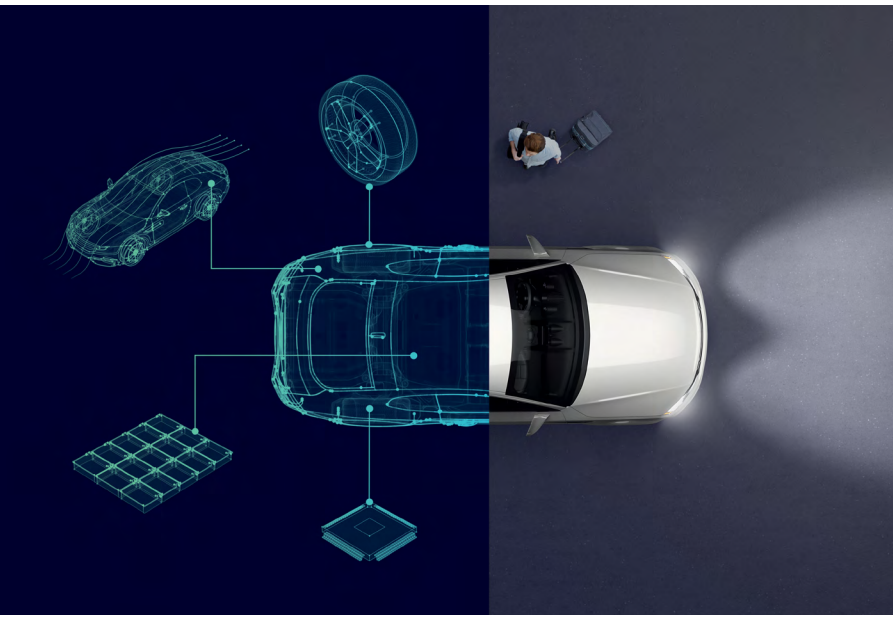
Designers then define the structure, components and boundaries of the system by detailing how it functions independently and in concert with other systems. To embed circularity at this stage, it's essential to evaluate potential points of failure and assess how easily the system can be repaired, maintained or upgraded over time. Equally important is conducting system-of-systems simulations to identify inefficiencies and minimize waste across both manufacturing and service operations. These insights enable smarter design decisions that extend product life and reduce resource consumption at scale.

Design, performance and in-service planning

Next, lifecycle assessments should be conducted early in the design process, not as a final check, but as a foundational tool for circular thinking. These assessments help teams evaluate a product's environmental impact across every stage of its lifecycle, from raw material extraction to manufacturing, use and end-of-life.

During the design phase, engineers and designers use software tools to create product concepts and run experiments that simulate performance under a range of real-world conditions.

For example, the Digital Twin enables rapid iteration and optimization which continuously enhances performance while reducing the need for costly, time-consuming physical prototypes. Products must also be designed for what comes next: upgrades, refurbishments, disassembly and adaptability through software-enabled capabilities. Integrating these factors early enables designers to create durable products built for longevity.



Finally, before a design is released, it's essential to plan for how the product and all its models and variants will be serviced throughout its lifecycle. This means proactively defining service and maintenance requirements early in development, including service intervals, required skill sets, specialized tools, service locations and clear, accessible maintenance instructions. This results in reduced downtime, extended product life and supports circular outcomes like repair, refurbishment and reuse, keeping products in use and in circulation for much longer.

Companies can leverage the Digital Twin to design products with sustainability and circularity embedded from the start.

Each of these considerations made during the design phase builds the first segment of our digital thread.

Circular design in the real-world

So, what does the Digital Thread for design look like in practice? And what companies are already leveraging circularity for success?

Clean Motion

Swedish company, Clean Motion, has adopted a circular model to build sustainable, lightweight and affordable electric three wheelers. Their mission was to design a simple yet energy efficient vehicle that reduces the need for resource-demanding batteries. Using Siemens' software portfolio, Clean Motion successfully created an optimized product development process and leveraged the Digital Twin to experiment with new ideas to ultimately select the best designs for both vehicle and factory.

By embracing a circular mindset, they have managed to create a vehicle that consists of only 270 parts weighing 280 kg, making it easy to maintain and incredibly efficient to assemble for scalability. In addition, the company is working towards a localized micro-factory business model that drives local employment economic development. Clean Motion has completely reinvented a small corner of the automotive industry by demonstrating how a digital and circular approach to design makes for smarter and cleaner mobility.

Clean Motion uses the Digital Twin and circular design to create lightweight, efficient electric three-wheelers with scalable production.

270
parts

280
kg

Clean Motion managed to create such a vehicle that makes it easy to maintain and efficient to assemble

Siemens Mobility improves lifecycle management by creating 3D models, cutting maintenance time by 30% and reducing costs.

30%
less maintenance time

50%
less time spent producing manuals

Siemens Mobility

Siemens Mobility empowers customers to improve the efficiency, reliability and environmental standards of road and rail transport.

Siemens has long recognized the necessity of circularity for ongoing success – and in this case, in the form of lifecycle management. Siemens Mobility has transformed traditional instruction manuals for maintenance by automating information flow from computer aided design models and bills of materials to create animated 3D models with written instructions for maintenance teams. The outcome? Siemens Mobility has seen that a complete link back to engineering documents results in 30% less time spent on maintenance and a 50% reduction in time spent producing manuals at a drastically lower cost.

Leveraging your Digital Thread **for circular manufacturing**

The next segment of our Digital Thread examines what plant managers should prioritize to minimize byproducts and waste, while enabling the reuse of materials and components across manufacturing workflows.

Smarter planning

Reuse rather than discard is the philosophy that drives the production planning stage.
The Digital Twin of Production supports circular manufacturing by identifying reuse opportunities through advanced material tracking and inventory analysis. It recommends alternative uses for components with minor defects, flags surplus or soon-to-expire materials and optimizes in-stock utilization. When integrated with circular strategies, planning software should also minimize byproducts and select recycled inputs which reduces reliance on virgin materials, lowers energy consumption and eliminates harmful byproducts.

Supporting circularity with adaptive production

An adaptive production approach enables businesses to improve product quality, reuse resources and minimize waste. Integrating AI, Digital Twins and robotics creates an increasingly autonomous environment where interconnected manufacturing plants go beyond the limits of traditional automation. These cutting-edge technologies are among the powerful tools manufacturers are using to create dynamic, intelligent systems that not only perform tasks, but also learn, make decisions, and evolve in real-time.

Adaptive production uses AI, robotics and the Digital Twin to enable flexible, resource-efficient manufacturing systems.

Technologies like Automated Guided Vehicles (AGVs) and modular production further enhance adaptability, allowing for the seamless integration of remanufactured or recycled components without major retooling. Additive manufacturing further supports circular strategies by using only the materials required, reducing scrap and enabling localized, on-demand production. It also opens the door to sustainable materials, such as recycled plastics and bio-based options, while embedding traceability through features like integrated QR codes.

Real-time monitoring in production execution is critical to circular manufacturing, enabling detection of resource waste and making instant adjustments. Additionally, embedded quality control ensures that recycled materials meet required standards, minimizing defects and preventing unnecessary scrap.

Circular logistics, storage and inventory

A connected Digital Thread extends beyond the production floor, linking logistics, inventory and storage to support circular manufacturing. Reverse logistics is essential for reintegrating returned products, refurbished components and reclaimed materials into the production cycle. This includes managing returns, coordinating collection and reuse and enabling product refurbishment. Optimizing these logistics networks reduces costs and emissions but may also require reconfiguring fleet management and transport operations. Effective storage strategies balance warehouse and repair facility locations and capacities, ensuring lean inventory levels without compromising material availability. Managing materials by expiration dates and optimizing space utilization are critical to maintaining sustainable processes.

Monitoring and maintaining equipment for longevity

Maintaining asset performance is critical to extending equipment life and maximizing resource efficiency. Continuous real-time monitoring of parameters like temperature, vibration and pressure enables performance optimization and early detection of wear. When paired with advanced simulation models called executable digital twins, this data can simulate operating scenarios, forecast failures and identify ideal operating conditions. These digital twins can even function as virtual sensors, providing insights from otherwise inaccessible points in the system to effectively measure the unmeasurable.

Effective service, repair and maintenance play a critical role in maximizing asset longevity. Predictive analytics pinpoints issues early, allowing maintenance to be scheduled precisely when needed. This reduces unplanned downtime and extends asset life. Efficient spare parts management ensures components are available for timely repairs, while identifying opportunities for upgrades and refurbishment enhances performance and resource utilization.

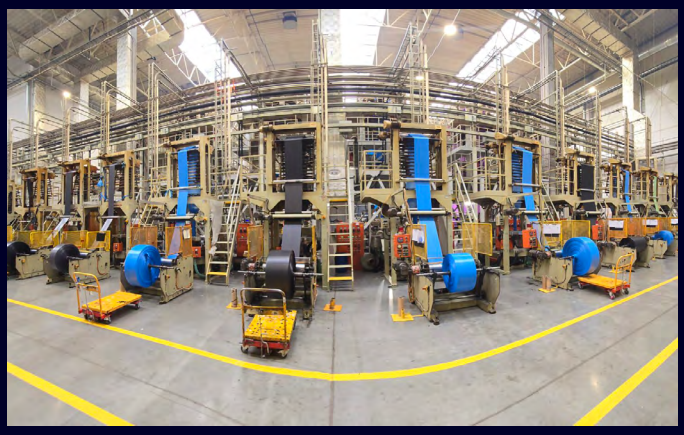
With these circular improvements made to the manufacturing process, the second stage of the Digital Thread is set to drive continuous optimization.

Use cases for **circular manufacturing**

Let's look at how companies are positioning their plant and operations managers for success by embedding circularity into their manufacturing processes.

Polipak

Polipak, a leading manufacturer of bags, foil sheets, and foil sleeves in Poland, is redefining how industrial waste is valued by transforming production waste into a raw material for new packaging. In an industry shaped by a legacy of disposable design, Polipak positions sustainability as a core business strategy and competitive differentiation. By implementing Siemens' advanced planning software and manufacturing execution systems, the company has increased the share of regranulate, a type of plastic that is made from recycled materials, in production from 30% to 90%, while simultaneously improving product and process quality. Through this closed-loop approach, Polipak reduces its environmental impact and demonstrates a scalable model for circular production.



With Siemens technology, Polipak transforms production waste into regranulate for circular packaging.

90%
recycled plastic used in production

Blendhub repurposes spent beer grains into nutritious protein powders using digital, localized food production.

Blendhub

Blendhub uses Siemens' Formulation and Specification Management, Digital Twin and Industrial Edge technologies from Siemens to transform spent grains from beer production into protein snacks.

These grains, still rich in plant-based vitamins, are carefully dried using a digitally optimized spray dryer. The powders are then produced in localized, cloud-connected hubs that adapt recipes to regional ingredients and needs. Blendhub ultimately turns food byproducts into accessible and sustainable nutrition.

Leveraging your Digital Thread **for value recovery**

This segment of the Digital Thread supports recyclers and product manufacturers to maximize a product's value in the operational phase and keep materials in the loop.

Monitoring products in use

First, by gathering real-time operational data and comparing it against expected performance, companies can identify underperforming components or signs of premature failure. This visibility allows for informed decisions about reuse, refurbishment, or recycling, ensuring maximum material and performance recovery. Artificial intelligence (AI) enables predictive maintenance by anticipating failures before they occur, which minimizes unplanned downtime and extends the useful life of components. This proactively reduces waste and maintenance costs while ensuring products deliver value longer, keeping materials and functionality in circulation rather than prematurely discarding them.

Digital product passports are gaining traction as a key solution within the circular economy, as they provide critical transparency into a product's lifecycle, supporting more informed and sustainable end-of-life decisions. By accessing detailed usage history and condition data, companies can evaluate whether a product is best suited for recycling, refurbishment or disposal. Modeling past use and predicting future performance also helps assess residual value. This insight uncovers practical pathways to extend product utility, transforming what was once considered waste into a new source of value and possibility.

Product service and maintenance

Once the decision is made to keep a product in use, service and support become essential for optimal long-term performance. Maintenance schedules and interventions must align with the specific conditions and usage patterns of each product to prevent failures and sustain performance. Equally important is a responsive after-sales supply chain. Ensuring timely access to spare parts and repair services reduces downtime and keeps assets running efficiently to reinforce product longevity and preserve value deep into the lifecycle.

Product upgrades and refurbishment

Keeping products in circulation depends on their ability to evolve. Upgrades enhance functionality, improve performance and help products stay competitive despite shifting market conditions. Refurbishment restores worn components, reinforces reliability and brings assets back to their original state. Together, these practices extend product life, reduce waste and support sustainability by delaying or eliminating the need for replacements. Using a Digital Twin here is essential as it can simulate and validate potential upgrades, ensuring each enhancement is efficient, intentional and aligned with future product iterations.

Value recovery

Lastly, value recovery is a critical step in circularity, focused on managing reverse logistics and warehousing to efficiently retrieve products at the end of their lifecycle. Effective collection, sorting and storage enable seamless pathways for reuse, refurbishment or recycling. Thoughtful dismantling and material recovery shape the effectiveness of this stage. By systematically deconstructing products and extracting valuable components, companies can reduce waste, lessen environmental impact and reintroduce recovered materials into the production cycle, turning the end of life into a new beginning.

Transforming waste by repurposing end-of-life materials into new, valuable resources.

Extending product life through circularity delivers value across the entire ecosystem. For manufacturers, circular design unlocks service-based opportunities, strengthens customer loyalty and creates new pathways for growth and innovation, proving that circularity is the solution for industries. For users, it lowers the total cost of ownership while offering flexible, customizable options that adapt to changing needs. And for recyclers, it ensures a reliable supply of materials and opens new revenue streams through secondary markets.

Proven approaches to **value recovery**

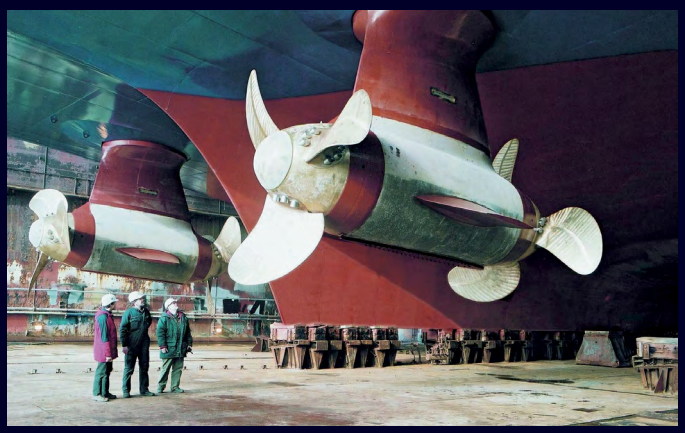
The following examples show how companies implement practical strategies to extend product life, recapture materials and keep resources in circulation.

Ford

Automotive giant, Ford, has made huge strides towards a circular business model by ensuring a transparent supply chain in spare parts logistics in the European market. The company has managed to integrate all supplier parties into a single network to bring transparency to the spare parts procurement process, including the multitude of transport options. They now have up to 230k parts in the European spare parts program and spare parts across 1600 suppliers and 24 regional carriers. By creating a connected, transparent ecosystem, Ford not only improves service efficiency but also ensures that parts are reused, refurbished or recycled wherever possible, minimizing waste and reinforcing a more circular approach to logistics.

Increased service efficiency

Increased reused/ recycled parts



Becker Marine Systems uses Digital Twin technology to create energy-saving devices that meet industry demands.

Becker Marine Systems

German marine company, Becker Marine Systems, retrofits vessels with energy-efficient devices to meet environmental regulation requirements. Leveraging Siemens' Digital Twin technology, they use simulation to design, evaluate and optimize specialized devices that are custom fit to the hull of each vessel.

As a result, their product, Becker Mewis Duct®, enables their customers to experience up to 10% annual power savings and has reduced roughly 19M tons of CO_2 for a typical bulk carrier to date. This data-driven approach extends asset value, delays costly replacements and supports a circular economy in maritime operations.

10%
power savings

Annual savings of Becker Mewis Duct® customers

19M
tons of CO_2

Reduction for a typical bulk carrier to date

Siemens creates circular products, embraces circular business and empowers circularity across sectors.

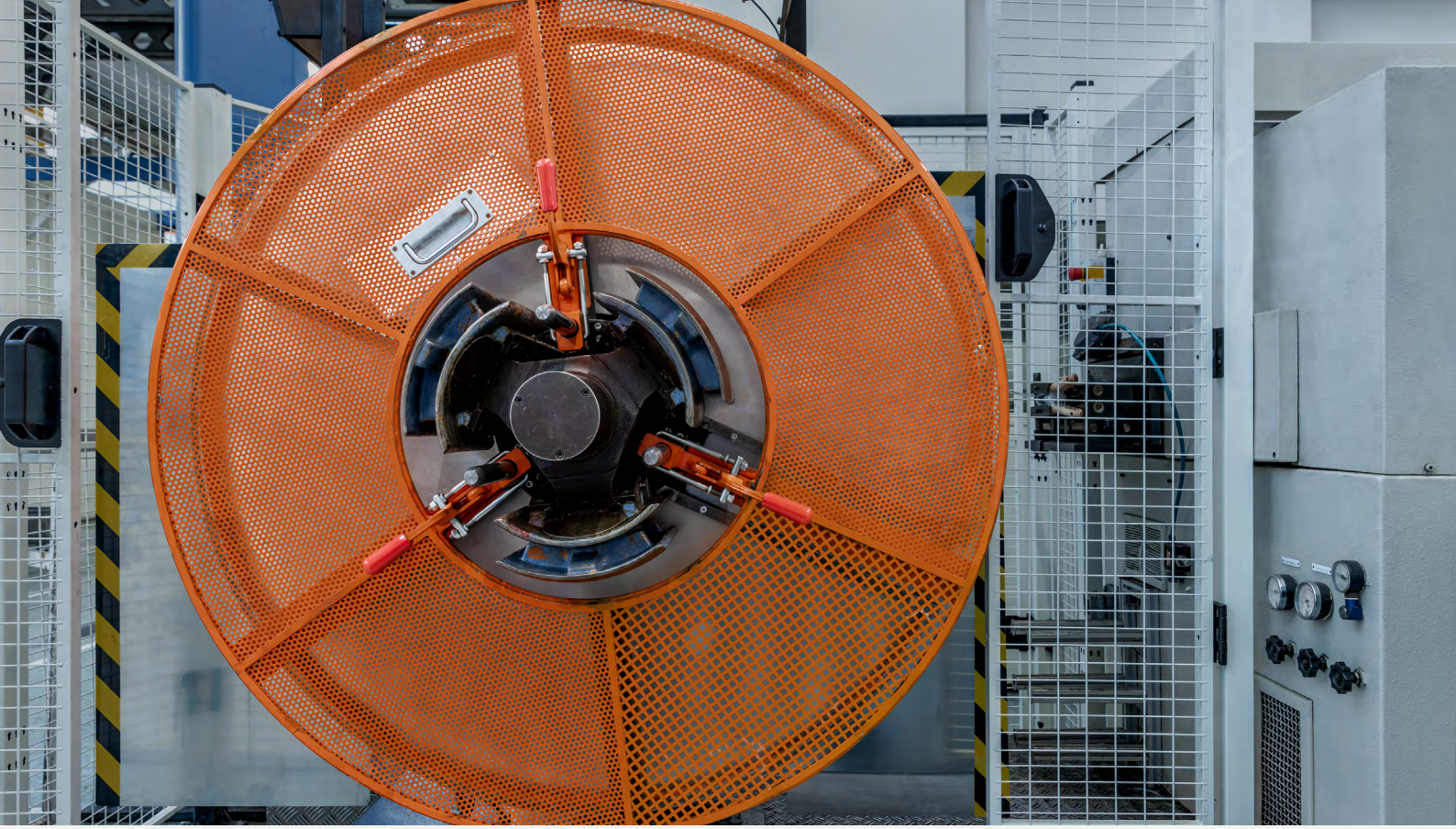
Doing more with less: **Siemens' holistic approach to circularity**

As pressure grows to decouple growth from resource consumption, Siemens is advancing circular strategies that align profitability with long-term sustainability. Our approach focuses on these core areas:

Creating circular products: We focus on sustainable materials, extended use, and end-of-life recovery. By improving transparency and adaptability across the product lifecycle, we create solutions that are both resource-responsible and market-ready.

Embracing circular business practices: We design for reuse, optimize secondary material use, and increase supply chain resilience. These efforts reduce material dependency and help minimize resource waste across operations.

Together, these pillars drive a circular ecosystem one built not only to reduce waste, but to create lasting value across the industrial landscape.



Looking forward

Circularity is a necessary response to a system under pressure. As waste accelerates and raw materials become harder to secure, the current linear model is running out of road. Circularity offers a smarter, more resilient path forward: one that keeps materials in circulation, reduces dependency on new materials and strengthens long-term performance.

This shift is already happening. Siemens is helping industries move beyond isolated sustainability efforts toward fully integrated circular ecosystems. By weaving circular principles through a connected digital thread, companies can design with intention, manufacture with flexibility and recover value well beyond a product's initial use.

This begins with small, practical changes like choosing better materials, optimizing for repair, enabling upgrades and recovering parts instead of discarding them. When linked across design, manufacturing, and value recovery, this creates a closed loop that reduces waste and multiplies value over time.

With the right tools in place, circularity becomes a way for businesses to improve sustainability and profitability. And in an industrial environment where efficiency, adaptability and longevity are essential, circularity is how forward-looking companies will lead.

To learn more,
visit **www.siemens.com/circularity**

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