Material Circularity Framework Principles for Discrete Manufacturing

An Industry IoT Consortium Foundational Paper

2024-06-05

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1 EXECUTIVE SUMMARY

This material circularity framework aims at helping discrete manufacturing industries, such as automotive, electronics, and machinery, to lower the environmental impact of their products through recycling and offer new value to customers and stakeholders. Circularity is a key principle of the circular economy, which aims to eliminate waste and pollution, extend product lifespan and maximize material reuse. It also supports the UN SDGs (Sustainable Development Goals) which promote responsible consumption and production and climate action.

Achieving material circularity can be challenging, due to the complexity and diversity of products and materials, the lack of adherence to circular design principles, the scarcity of standardized and transparent data sharing across product ecosystems on material flows and impacts, the trade-offs between different sustainability strategies, and the regulatory and market barriers that impede the adoption of circularity.

The framework encompasses the following elements:

<u>Material Circularity Radar Map and its measurement indicators:</u> A visual tool that conveys the current and potential circularity performance of products (using six dimensions). It also provides indicators to measure circularity performance over time and across different products.

<u>Considerations before you start:</u> A set of questions and criteria that define the scope, objectives, and boundaries of the circularity assessment, as well as the data sources, methods, and indicators to be used. The questions also examine the role of emerging and emergent technologies, such as digital twin, IoT, AI, robotics, and others, in enabling material circularity.

<u>Material Circularity Framework:</u> The framework guides how to apply the material circularity radar map, how to assess and prioritize circular opportunities, how to define the target state and the roadmap to achieve it, and how to implement and systemize the circular solutions.

<u>Material Circularity Standards, Laws, and Regulations:</u> A brief overview of existing and emerging standards, laws, and regulations (in several key regions and jurisdictions) that enable or constrain material circularity in discrete manufacturing.

This framework targets executives and technical and business decision-makers, engineers, supply chain professionals, environmental experts, etc. to help them develop and implement a path to better circularity in discrete manufacturing. It offers a practical approach to transition to, measure, improve, and communicate about material circularity.

2 MATERIAL CIRCULARITY IN DISCRETE MANUFACTURING

Discrete manufacturing is the production and assembly of distinct products, such as cars, furniture, smartphones, and planes, and where resulting products are easily identifiable and typically assigned serial numbers. This type of manufacturing differs from process manufacturing where products are undifferentiated, for example oil, natural gas, raw metals and salt. [*WIKI-DMNF*]

2.1 UN Sustainability Development Goals

The UN 2030 Agenda for Sustainable Development [*UN-SDG*], endorsed by all member states, offers a common vision for human and planetary well-being, both present and future. At the heart of that agenda are 17 Sustainable Development Goals (SDGs), as shown in Figure 2-1. These goals are a call to action for all countries (developed and developing) to implement initiatives aimed at addressing a broad spectrum of issues, such as health, education, gender equality, climate change, energy, and innovation. The goals have different timeframes for their attainment, but the overall target is 2030.

Thus, organizations should act urgently and strategically to align their business objectives with the SDGs and create value for their stakeholders and society [*MKSY-MANF*].

Figure 2-1: The 17 UN SDGs (Source: United Nations).

Depending on the organization, some goals may be more relevant than others. For discrete manufacturers, the most relevant goals are:

- Goal 7: Affordable and clean energy
- Goal 9: Industry, innovation, and infrastructure
- Goal 12: Responsible consumption and production ← most relevant
- Goal 13: Climate action

By investing in material circularity, discrete manufacturers can optimize their resource use, reduce their waste disposal costs, reduce their exposure to regulatory and reputational risks, and increase resilience and reputation [*PLM-DM*]. In this framework document, we describe the benefits (sections 2.3.3) that the investments (section 4.1.3) in these initiatives can generate.

2.2 LINEAR ECONOMY VS CIRCULAR ECONOMY

The first industrial revolution brought about a *linear economy*, which was based on collecting raw materials, using them to create consumer goods, and disposing of resulting waste products, with no concern for their ecological footprint and consequences.

The linear model resulted in excessive material waste and a significant negative impact on the environment. This has led to the development of the *circular economy* system, where product materials are supposed to never become waste and nature is regenerated. One of the principles and practices of *circular economy* is *material circularity* which is the process of keeping product materials in circulation through reuse, recycling, refurbishment, and remanufacture.

2.3 MATERIAL CIRCULARITY

As stated earlier, material circularity is a strategy to reduce the environmental impact and resource consumption of products by designing them to be durable, reusable, recyclable, or adaptable to different purposes. The strategy requires changes to manufactured products, the organization, and its ecosystem of suppliers, customers, and partners.

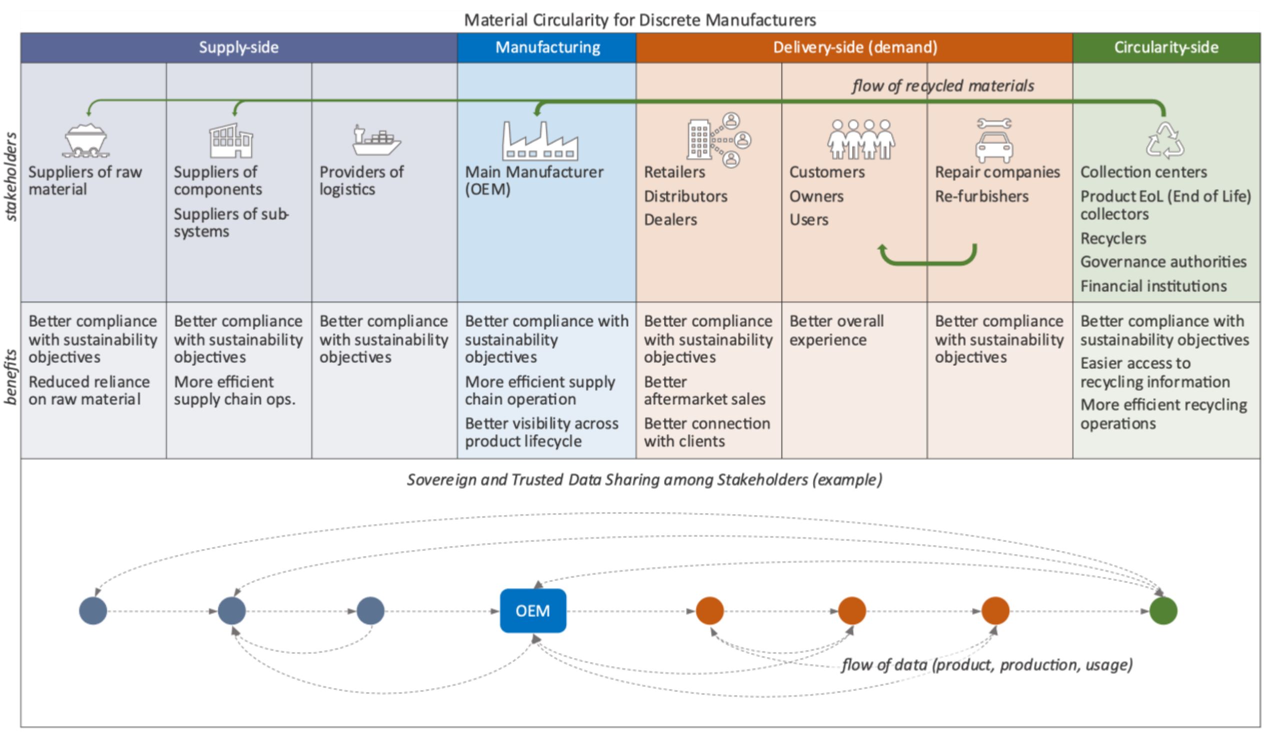

Figure 2-2: Material circularity for discrete manufacturing.

Figure 2-2 shows an example of a product lifecycle ecosystem, which consists of various stakeholders who interact with the material and product flows. It also indicates the data sharing and exchanges that take place among the stakeholders within the ecosystem. Lastly, the diagram demonstrates the benefits that material circularity can offer to the different stakeholders.

2.3.1 Product Lifecycle

The process of keeping product materials in circulation requires an understanding of the different stages of the lifecycle of a product, from the acquisition of its materials to its creation, usage, and up to and including the disposal action of the product at the end of its life (EoL).

In a linear economy, the EoL action is to send the product to a refill dump site. In a circular economy, some or ideally all of the product components and contents are extracted for reuse/recycling, and what little remains is sent into a dump site.

The typical stages of the product lifecycle are as follows:

Raw material supply: This is the sourcing of the raw materials used in the product.

Component and subsystem manufacture: This is the sourcing of the components and subsystems needed to include into the product, such as brakes and tires in a car. These items are usually obtained from third-party suppliers. The proportion of these items in the final product may vary depending on the product.

Transportation to main OEM: This is the logistics function related to the transportation, warehousing, and customs clearance of sourced materials, components, and subsystems to the main manufacturer for final assembly and configuration into the products.

Product manufacture: This stage involves the conceptualization, requirements gathering, design, manufacturing, assembling, configuring, testing, certifying, boxing, and releasing of the product to the sales inventory. It also includes after-sales services such as repairs and refurbishing. This stage also includes the assembly of sourced components and subsystems into the product.

Transportation to distribution outlets: This is the logistics function related to the transportation of finished products to sales outlets.

Product sale: This stage involves selling and distributing the products in the market.

Product use: This stage involves using the product. In most cases, it represents the longest stage in the product's lifecycle.

Product repair/maintenance: During their usage, products may require repair and maintenance.

Product refurbishment: This stage involves restoring a product that has been refurbished in place or returned to the manufacturer for various reasons, such as defects, damages, excessive wear & tear, or customer dissatisfaction.

Product content recycling: This stage occurs at the end of the useful life of the product where the whole product or parts of it are reused, repurposed, recycled, or disposed of.

2.3.2 Circularity of Packaging vs Contents

Material circularity involves making changes to product packaging and product contents, refer to the NIST concept for the Circular Economy diagram in Figure 2-3 [*NIST-CIRC1*] and the markers we have added to show where circularity applies for product packaging and product contents.

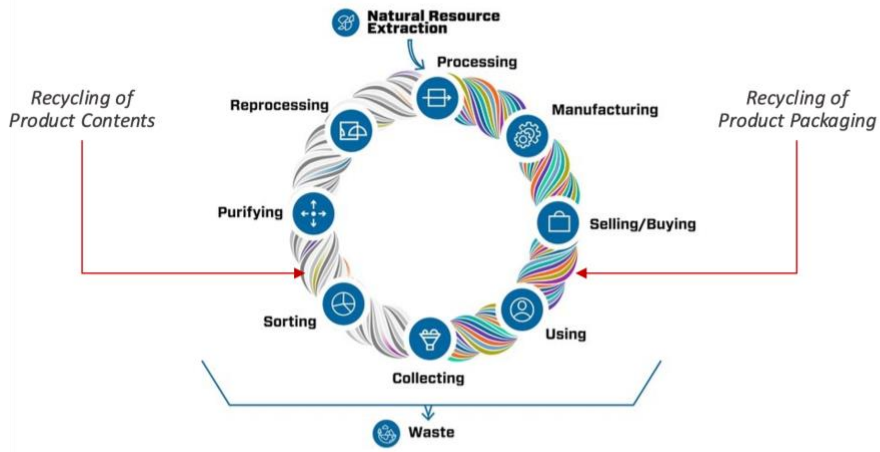

Figure 2-3: What is a circular economy (Source: NIST).

Product packaging is the material that wraps and protects products from manufacturer to consumer. Packaging can be made circular by using recycled or renewable material, reducing packaging amount, or by making it reusable or recyclable. These initiatives are typically quick to implement, as they require no changes to the product design or production processes.

Product material contents can be circular by using recycled or renewable material, reducing material intensity, or by making the product modular, repairable, or upgradable. These initiatives have more environmental impact, as they reduce energy and resource use in product lifecycle. However, these initiatives may be slower to implement, as they need more innovation, investment, or collaboration in product design and production. Also, these initiatives may face challenges like technical feasibility, quality standards, or market acceptance.

Material circularity can also refer to the capture, storage and processing of carbon emissions generated by production processes that involve the burning of fuel. Refer to section 2.5.1.

To achieve material circularity, discrete manufacturers must adopt a strategic and holistic approach that aligns with their business goals and customer demands. They can optimize resource use, cut costs, and increase customer value by addressing both product packaging and contents. However, the pace of these efforts varies depending on product features, market conditions, type of product, regulations in various jurisdictions, and stakeholder preferences.

In this framework, we discuss material circularity for both product packaging and product contents, but we focus more on the latter, which is more challenging.

2.3.3 Benefits

Gartner states that "a sustainability strategy treated as a siloed or compliance-based approach will generate little outcomes" [*GTNR-SUST*]. As access to capital and overall shareholder value is increasingly tied to corporate sustainability performance, business leaders are viewing sustainability programs not as a cost of doing business, but as a way to create new value, minimize the impact of disruptions, and differentiate themselves from the competition.

Embracing material circularity can lead to significant short, medium, and long-term benefits for the organization itself, the ecosystem and society at large:

<u>Reduced need to mine/create virgin materials:</u> Material circularity helps reduce the need to create or extract new virgin materials from their sources.

<u>Fewer landfills and reduced environmental impact:</u> Material circularity helps reduce the environmental impact (for example less landfills) and comply with emerging regulations and standards on circular economy. According to a WEF report [*WEF-CIRC1*], such practices can reduce greenhouse gas emissions by 45% by 2030 and 85% by 2050. These practices also can help manufacturers avoid fines and penalties and gain government incentives and subsidies.

<u>More stability in material supply chains:</u> Circularity enables manufacturers to create more value from products and materials and mitigate material price volatility and supply chain disruptions. Examples of such value include extending lifespan and functionality of products, recover and reuse materials and components from products, and many more. This is critical for scarce and strategic materials, as it reduces the dependence on single source suppliers.

<u>Reduced costs and environmental impacts:</u> Using less raw materials and energy and generating less emissions and waste lowers operational expenses and environmental footprint. For example, the World Economic Forum estimated that circular economy practices could save $700 billion per year for the consumer goods sector alone [*WEF-CIRC2*].

<u>New revenue streams and customer value:</u> Offering second- and third-life opportunities can extend the product lifecycle and create new sources of income and customer loyalty. For example, Philips sells lighting as a service, where customers in industry pay for the amount of illumination they consume, and Philips collects the old lighting equipment at the end of the service [*POLCY-GAP*].

<u>Enhanced innovation and competitiveness:</u> Leveraging digital technologies such as IoT, digital twins, and AI in support of circular economy practices, can improve supply chain resilience, product quality, performance, and customization. For example, Caterpillar uses IoT sensors and data analytics to monitor and optimize the condition and performance of its equipment, and its remanufacturing and repair processes [*ENG-CIRC*].

<u>Meet customer expectations for eco-friendly products:</u> Material circularity helps manufacturers meet customer expectations for eco-friendly products and reduce waste. By creating environmentally friendly products and by staying in touch with customers, manufacturers can improve their corporate image and get feedback and insights about how to enhance their products and services. This way manufacturers can offer more sustainable solutions to customers and increase their loyalty and satisfaction. Generally speaking, the circular economy can generate significant benefits to stakeholders and society at large (Accenture [*ACTR-CIRC*]):

- Additional economic output of $4.5 trillion by 2030
- Millions of new jobs and opportunities
- 30% cost savings of raw materials

- Up to 70% customer retention

<u>Note:</u> Material circularity can also be a source of business opportunities and competitive advantage. Manufacturers that embrace circularity can become leaders and innovators in that space, creating value for themselves and their stakeholders.

Discrete manufacturers should evaluate the trade-offs of investing in material circularity, across multiple time horizons. If these investments are justified, manufacturers should adopt a holistic approach that integrates the principles of material circularity with their business vision, roadmap, and execution. In addition, manufacturers should understand that adding circularity to a product does not always mean that recovered materials should be re-conditioned and refined for reuse in similar products. The cost of re-conditioning, refining, and transporting recovered materials can in some cases render them too expensive as compared to virgin material [MDPI-CIRC].

Organizations should assess the environmental impact of circularity as they may counteract the expected benefits. This is particularly relevant for products sold in areas that lack recycling facilities. In these cases, a more viable option might be to divert the reclaimed materials to lower-level applications, e.g. turning used milk bottles into deck boards instead of new milk bottles.

2.3.4 Challenges

Implementing material circularity in discrete manufacturing environments is not without its challenges. Below are examples of these challenges:

<u>Established products and conventional production environments can be difficult to change:</u> It may not be feasible to adapt products originally designed and manufactured with a linear economy mindset to the circularity model.

<u>Lack of technology capabilities:</u> Achieving material circularity may require advanced technologies and skills to design, produce, track, and recycle products. For example, they need digital twins, additive manufacturing, and smart labels to create, and identify them.

<u>Inconsistent, incomplete, and obsolete industry regulations and standards:</u> Common standards and regulations are needed to facilitate the exchange of products and their reuse across different sectors and regions. For example, they need standardized product specifications, labeling systems, and certification schemes to ensure their quality and safety.

<u>Lack of end-to-end responsibility and reporting:</u> Most material circularity regulations call for extended producer responsibility (refer to section 2.3.5) which holds the manufacturer responsible for ensuring the circularity of its products throughout their lifecycle. This responsibility involves financial and reporting considerations.

<u>Weak interconnections among value chain actors:</u> Collaboration across the value chain (suppliers, users, regulators, and competitors) is essential for creating and capturing value from circularity. For instance, circularity requires establishing partnerships and networks to facilitate the sharing and pooling of resources, information, and best practices. Educating users on the principles of circularity can enhance their engagement and support for the circular initiative.

<u>Negative customer sentiment:</u> Customers may have negative sentiments about vendors and their products due to "greenwashing" (refer to section 4.1.5) or the perception that reused / recycled materials are somehow inferior to virgin materials or new products.

2.3.5 EXTENDED PRODUCER RESPONSIBILITY

EPR is a policy approach that makes producers responsible for the environmental impacts of their products throughout the product chain. The concept was introduced in 1990 by Swedish professor, Thomas Lindhqvist, to the Swedish Ministry of the Environment.

The EPR approach is a "polluter pays" approach that fosters a "cradle-to-cradle" mindset that shifts the environmental protection responsibility (physically and/or economically, fully or partially) from product waste upstream toward the producer. This implies that consumers' discarded products and packaging should be recovered, recycled, and reused for new products.

EPR incentivizes producers to consider environmental aspects when designing products. It also seeks to integrate eco-friendly features of products and production processes throughout the product lifecycle. The approach can use various instruments and apply to different product categories, depending on factors like environmental impact of products, market structure, consumer behavior, and existing waste management ecosystems.

The EU was the first jurisdiction to adopt the EPR approach. Germany implemented it in 1991 for packaging material. In 2002, the EU issued the WEEE directive (Waste Electrical and Electronic Equipment) to eliminate "electronic waste" from landfills when discarding electronic and electrical devices (these products contain materials with significant polluting effect). WEEE set the rules for collecting and recycling such equipment at the end of their lifecycles and identified 10 waste categories for these rules.

Below are a few examples of EPR requirements for product producers:

- Pay a fee per product to a Producer Responsible Organization (PRO) that recovers products at the end of their lifecycle [*PWC-EPR*], with sanctions that can be applied for non-compliance.
- Meet collection targets for products and ensure proper sorting and recycling [*EU-EPR1*].
- Report carbon footprint of products and use a minimum bar for material content that is recycled [*EU-EPR2*].
- Adopt eco-design principles that enhance durability, reparability, recyclability, and energy efficiency of their products [*EU-EPR3*].
- Provide product passports that include information on the materials, components, and environmental performance of their products [*SPR-EPR*].

Similar EPR environmental policy principles have been adopted by a number of countries and jurisdictions.

> *<u>Note:</u> The "Legal Framework Study of EPR" report by Cyclos offers policy and business decision-makers provides a solid knowledge base on EPR schemes. [*EPR-LGL*].*

2.4 Stakeholders in the Ecosystem

The manufacturing ecosystem is a network of organizations that collaborate to create value in the manufacturing process. This ecosystem can include suppliers, customers, competitors, partners, regulators, and other stakeholders that share information, resources, capabilities, and risks. A manufacturing ecosystem can also leverage advanced technologies such as IoT, digital twin, AI, cloud computing, and cybersecurity to enable smart manufacturing [*DLT-CIRC*].

> *Note: Stakeholders can play multiple roles. For instance, the Main OEM may be a Re-furbisher. Also, the customer, owner, and user of a product may be the same party or three different parties, depending on whether the product is consumer or industrial. For example, a personal car may have one customer, owner, and user, while a rental car may have different ones.*

2.4.1 Supply-side Stakeholders

The upstream side of the ecosystem includes entities providing manufacturers with the materials and sub-components required to build the products, namely:

Raw Material Suppliers: These are the suppliers of the raw materials needed to manufacture the product as well as the materials consumed during the manufacturing process (e.g. fuel).

Component and Sub-system Suppliers: These are the suppliers of the sub-systems and individual components that are incorporated into the final product (example car brakes)

Logistics Providers: These are the providers of transportation services for delivering raw materials and components from their suppliers to the Main (OEM) (see below).

2.4.2 Main OEM

This entity manufactures the product with the overall responsibility to design, assemble, test, package, market and sell the product. In some cases, this responsibility may encompass the provision of maintenance, repair, and aftermarket services.

2.4.3 Delivery-side Stakeholders (demand)

This downstream side of the ecosystem consists of entities that sell, distribute, and deliver products to the market (the Main OEM may also sell products directly to customers) plus the entities that use, maintain, repair, and upgrade the products:

Retailers/Distributors/Dealers: These are the entities (regional and global) that sell and deliver products to customers.

Customers/owners: These are the entities (organizations or individuals) that acquire products, lease them, or use them on an as-a-service basis. These entities can be the actual users, or they can be solution providers that integrate the products into their solutions.

Users: These are the organizations or individuals who utilize the product as intended. For example, a laptop may have multiple users within a company or a single user as an individual. Products such as vehicles and other high-value goods may change users as they are resold or repurposed. Product sharing (e.g., cars or equipment) is another usage mode.

Repair Companies: These are the entities that provide product repair services. They may be the Main OEM, a distributor/dealer, or an independent services company.

2.4.4 New Circularity-side Stakeholders

To achieve material circularity, there needs to be a third chain (also referred to as "reverse logistics") in the ecosystem with a corresponding group of stakeholders and entities that support the extension of the product lifecycles or their recycling at the EoL:

Collection centers: These places are set up by municipalities and state authorities for consumers to drop off used products that have reached the EoL state for further recycling action. Collection centers can also be for-profit organizations.

Product End of Life collectors: These entities collect used products from collection centers and send them to re-furbishing centers or to recycling centers. In the EU, these organizations are called Producer Responsible Organizations or PRO.

Re-furbishers: These entities recondition products, extending their useful life, and reduce waste. The process may also involve the extraction of product parts for future spare parts use. There are different variations and nomenclatures for refurbished products such as factory-refurbished, manufacturer-refurbished, certified, or pre-owned.

Recyclers: These entities de-manufacture the products (dismantle them into components) at their EoL, recover salvageable material, refine the material to support its re-use and recycling in other applications, and finally dispose non-salvageable material in a sustainable manner.

Recycling Governance Authorities: These government entities are responsible for establishing the recycling policies and mandates within the jurisdiction. Enforcement may be done by these authorities at this level or at a lower level. Please refer to section 8.2.1 for a description of the EU Strategy for Circular Economy, as an example of circularity initiatives by authorities.

Non-governmental Organizations: NGOs can promote material recycling in discrete products. They can educate the public on the impact of recycling materials on waste, organize community waste materials collection and recycling drives, and cooperate with governments and industries to develop and implement material circularity policies, standards, and programs.

Academic and National Laboratories: These are laboratory facilities, run by academic institutions and/or funded by government agencies, that research materials and processes that help with circular initiatives. They engage with manufacturers on innovative ideas and collaborate with them on proof-of-concept field trials, helping to improve manufacturing processes, reduce waste, and deploy new sustainable materials. These laboratories also engage with regulatory authorities (e.g., recycling governance authorities), to develop realistic policies and goals to help achieve their circular economy initiatives. Examples in the US include the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratories (ORNL).

Financial Institutions (indirect): Financial institutions, such as banks and insurance companies, can provide loans and coverage for manufacturing projects. They also include investors, such as shareholders and venture capitalists, that fund and support manufacturing enterprises. These stakeholders have an economic motivation to require better sustainability practices from manufacturers, as they can reduce costs, risks, and liabilities, and enhance reputation, performance, and profitability.

2.5 Material Circularity and Other Sustainability Initiatives

Material circularity requires a holistic and systemic approach that involves collaboration across the whole product value chain. This means aligning design, production, distribution, and product end-of-life functions and stakeholders with material circularity goals, integrating material circularity into product innovation, customer satisfaction, and competitive advantage strategies and objectives, and supporting and engaging leadership and employees in the initiative.

Material circularity may benefit from external collaboration and partnerships with other actors in the value chain (e.g., suppliers, customers, regulators, and competitors).

Caution: Some cases may justify some level of separation between material circularity initiatives and other product related functions (e.g., required specialized skills, knowledge, and resources not available or compatible with other functions). Other cases may entail different or conflicting objectives and incentives between different functions and stakeholders (e.g., reduce material consumption, and extend product lifespans vs. increase sales and market share).

Organizations should analyze their context, capabilities, and aspirations, and then decide on the best arrangement for material circularity

2.5.1 Carbon Emission Reduction Initiatives

Material Circularity and Carbon Footprint Reduction are the cornerstones of Goal 12 which is *Responsible Production and Consumption*. For many organizations, reducing carbon emissions is the top priority among all sustainability goals.

Carbon scopes 1, 2, 3, and 4 are categories of greenhouse gas emissions [*CEMS-SCP*] that are defined by the Greenhouse Gas Protocol [*GRNHS*] which is used to measure and report emissions from different sources and activities that an organization is responsible for or influences:

- Scope 1: emissions from sources that an organization owns or controls directly.
- Scope 2: emissions by the suppliers of energy to an organization.
- Scope 3: emissions that occur in the ecosystem, upstream and downstream
- Scope 4: emissions that are avoided due to the design and use of more energy-efficient or environmentally friendly products

Redesigning products to support material circularity may have positive or negative impacts on carbon emission initiatives, depending on how it is implemented and measured:

Positive impact examples:

Furniture company: Designing products to be modular, durable, and easy to disassemble, reduces the need for new materials and associated scope 3 emissions for extraction and transportation. It also enables the manufacturer to offer repair, refurbishment, and remanufacturing services, further lowering scope 1 and 2 emissions.

Clothing brand: Using recycled cotton for garments reduces the use of water, land pesticides and fertilizers, lowering emissions from the upstream supply chain. It also encourages customers to return used clothes for recycling or donation, reducing the downstream scope 3 emissions.

Smartphone manufacturer: Using recycled materials, such as bioplastics, metals, and glass reduces scope 3 emissions from the extraction and processing of virgin materials. It also encourages customers to return old phones for trade-in, thus reducing electronic waste.

Negative impact examples:

Food packaging company: Claiming to use biodegradable materials for products, but not providing evidence or certification for this claim or not informing customers about proper disposal methods, can lead to products ending up in landfills or incinerators. This releases methane or carbon dioxide and increases scope 3 emissions from the end-of-life stage.

Car company: Producing EV cars that use lithium-ion batteries, which have a high energy density and long lifespan without considering the environmental and social impacts of sourcing lithium from jurisdictions with poor governance records increases scope 3 emissions from the raw material extraction and transportation.

Carbon Capture and Storage: One particular technology that has a direct impact on material circularity is carbon capture and storage. This technology presents a valuable avenue for discrete manufacturers to substantially mitigate their CO_2 emissions while enhancing their material circularity. Manufacturers can capture carbon emissions directly from their operations and reuse them in other processes to create beneficial chemical byproducts. These byproducts can in turn be reintegrated into the manufacturing process or developed into new products, thus promoting carbon neutrality and fostering a circular economy.

Moreover, this method opens up potential new revenue streams through the generation of high-value chemicals. For example, by using electrolysis to extract carbon monoxide from CO_2 and combining it with hydrogen, synthetic hydrogen fuels and various organic compounds can be synthesized.

Current implementations of carbon capture have predominantly been on a large scale (e.g. power plants, steel manufacturing), proving the technology's effectiveness yet highlighting its limited immediate applicability for discrete manufacturing due to scalability, cost, and integration challenges.

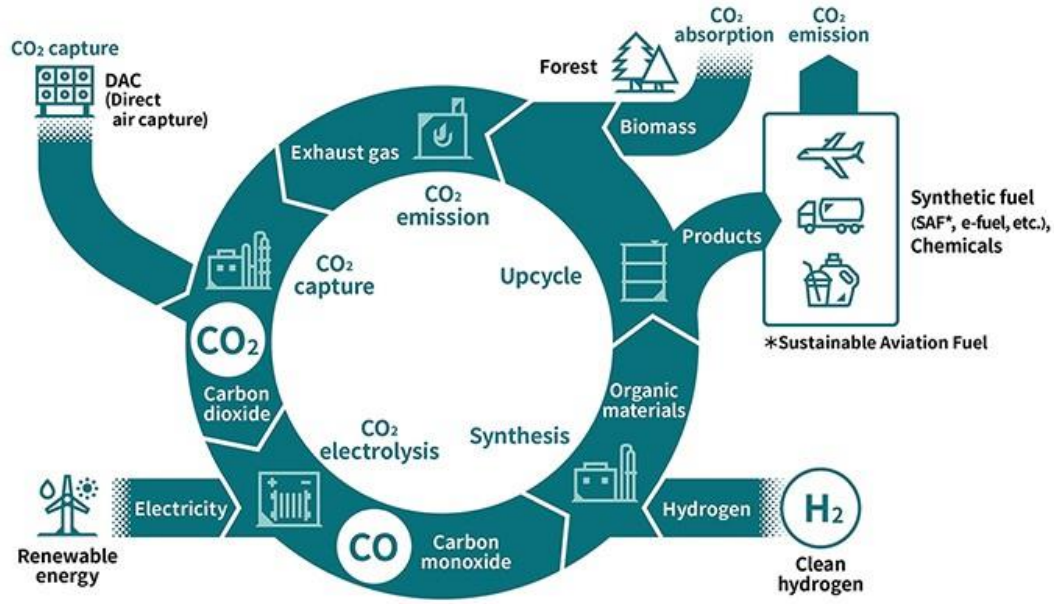

Figure 2-4: Power to chemicals CO_2 electrolysis process (Source: Toshiba).

As this technology matures, localized point source capture systems will become more viable to deploy. Such systems can target specific emission sources (e.g. exhaust stacks) and seamlessly integrate their emissions into process optimization systems to enhance sustainability efforts. This adaptation signifies a promising strategy for discrete manufacturers to reduce emissions and contribute to a decarbonized society, acknowledging the current limitations while looking forward to innovative solutions.

2.5.2 Other Sustainability Initiatives

Efforts to achieve material circularity may positively impact or be impacted by other sustainability initiatives in the organization. Thus, these efforts must be aligned and respect the relative level of priority of other sustainability initiatives. Below are a few examples of how material circularity can positively impact other UN SDGs [*SDG-CIRC1*][*SDG-CIRC2*].

Good Health and Well-being (SDG3): Reducing exposure to hazardous chemicals and pollutants, material circularity can improve the health and safety of workers and consumers. It can also promote healthy behaviors by encouraging the use of durable and recyclable products.

Decent Work and Economic Growth (SDG8): Material circularity can create new jobs and business opportunities in sectors such as waste management, repair, remanufacturing, and renewable energy. It can also boost the productivity and competitiveness of industries by lowering resource costs and waste, and by increasing the value and quality of products and services.

Sustainable Cities and Communities (SDG11): Material circularity can support the development of sustainable urban systems by optimizing the use of infrastructure, improving efficiency, and fostering social inclusion and participation. It can also reduce the environmental footprint of communities by minimizing the generation of waste and emissions.

Responsible Consumption and Production (SDG12): Material circularity is a key strategy to achieve this goal, as it promotes the efficient use of resources, the reduction of waste and pollution, and the shift to sustainable consumption and production. It can also enable consumers and producers to make informed and responsible choices about products and services.

Climate Action (SDG13): Material circularity can mitigate and adapt to climate change by lowering greenhouse gas emissions from resource extraction, processing, and disposal, and increasing the use of renewable energy and materials.

Life Below Water (SDG14): Material circularity can help protect marine environments by preventing the leakage of plastics and other harmful substances into the oceans, and by restoring the natural cycles of nutrients and carbon. It can also support the sustainable use of marine resources and ecosystems, and the livelihoods of coastal and fishing communities.

Note: Material circularity may affect other sustainability goals adversely. The energy consumed by the recycling processes (sort, clean, transform, transport) may increase the product's carbon footprint rather than reduce it. These wider environmental and social factors of sustainability should also be considered.

2.5.3 Digital Transformation Initiatives

Sustainability (including material circularity) and Digital Transformation (DX) are sometimes referred to as the *Twin Transition*. Many organizations that have sustainability aspirations also have ongoing digital transformation initiatives. Sustainability and Digital Transformation mutually leverage each other. The relationship and interdependencies between them take place at multiple levels: technical, operational, and mindset.

This topic is discussed in detail in IIC's Industry Digital Transformation Framework, currently under development at the IIC.

How Digital Transformation efforts help with Material Circularity:

Improve Products and Make them Smarter: Implementing IoT and AI technologies to monitor products and provide feedback about their performance, condition, and usage helps manufacturers improve product quality, reliability, and efficiency, and produce new products, and potentially create new revenue streams from data and services [*NIST-CIRC2*].

Implement Smart Supply Chains: Adopting digital platforms to track material flows, transactions, and ownership of products and materials throughout their lifecycle enhances the transparency, traceability, and security of the circular economy, and leads to the creation of new business models and opportunities.

How Material Circularity efforts help with Digital Transformation:

Help cost justify part of the Digital Transformation Investment: The incremental investments in Material Circularity such the digitalization of products and the creation of data ecosystems that cover the full product lifecycle that extend beyond the organization's boundaries can help in the cost justification and the urgency of Digital Transformation efforts.

Create new revenue streams and customer value: Offering second- and third-life products, services, and solutions extend the product lifecycle, and create new revenue streams and customer value [*BAIN-CIRC*][*PTC-DX*]. By offering equipment monitoring and servicing (via as a Service models), equipment can be maintained at optimal operating conditions for a much longer period of time, benefiting both manufacturer and consumer.

3 MATERIAL CIRCULARITY RADAR MAP

The material circularity "radar map" or spider diagram (Figure 3-1) is an important planning tool that can visually present to management and circularity team, the organization's current and desired performance for various circularity indicators.

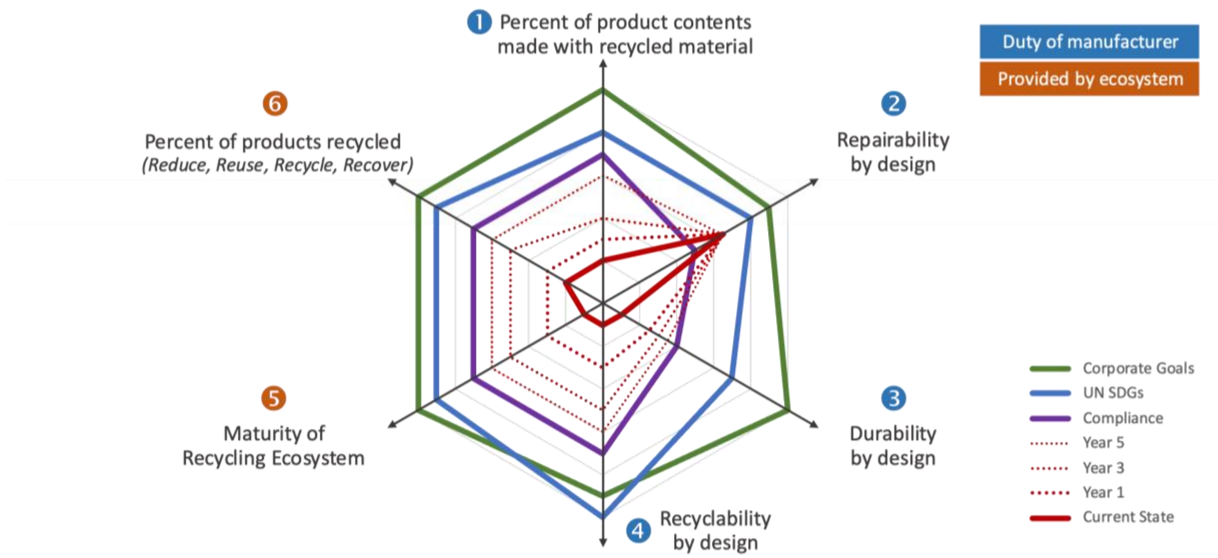

Figure 3-1: Material circularity radar map example.

The radar map is a two-dimensional chart that shows multiple approximate quantitative variables along several radial axes:

- Radial axes represent various material circularity indicators
- Concentric polygons represent the current state of material circularity of a product (and progress being made), the compliance requirements, the material circularity targets based on the UN SDGs, and finally the targets established by the organization itself. Polygons that are closer to the perimeter areas are better.
- In the example in Figure 3-1, the current state of repairability-by-design (red) already exceeds the minimum compliance requirements (purple), while the corporate goals (green) for recyclability-by-design are set to be lower than the UN SDGs

The overall strategy is as follows:

- Identify the indicators and their scope (axes) – different set of indicators may be required
- Determine the current state (red line) of material circularity (and its progress)
- Define the states that represent compliance (purple line) and corporate goals (green line)
- Determine the roadmap to advance the current state over time to reach the compliance and corporate goals
- Execute the roadmap and measure/report on the progress

The position of the "current state" (and its progress) along the axis should be based on a mix of measures. Some of these measures may be subjective and some may be based on specific parameters related to the nature and material composition of the product and the compliance timeframes defined in regulations and laws.

The radar map tool can be also used to represent the material circularity of products at different levels of granularity:

- Product(s) sold globally
- Product(s) sold in a jurisdiction (which may have specific circularity requirements)
- Aggregate view of material circularity of a full product portfolio of a manufacturer, either sold globally or in a particular jurisdiction

3.1 Material Circularity Indicators

The axes represent the important indicators of material circularity, six in this example map.

3.1.1 Percent of Products Made with Recycled Material

This indicator shows how well the manufacturer is reducing its environmental impact from a material recycling point of view. It is the percentage of the contents of a product and its packaging that comes from recycled/reprocessed material as opposed to virgin material.

This assumes that the recycled/reprocessed material is of sufficient technical grade and quality to make it usable in a new product. It also assumes that the reuse of recycled material into new products is economical, strategically sound, and ecologically feasible. This issue is strategic for materials that are scarce or are dependent on unreliable supply chains. The ecological considerations include the environmental impacts, the energy needed to recycle, reprocess, and transport the material versus the energy needed to create/mine and transport virgin material.

The calculation of this indicator will vary depending on the product, source and quality of recycled material, and the standards and regulations that apply. As shown in Figure 3-1, the work involved in increasing this indicator and maximizing it is under the control of the manufacturer.

3.1.2 Repairability by Design

Repairability by design is an indicator [*WIKI-RPAIR*] of how well a product has been designed so that it can be repaired and maintained throughout its lifecycle, saving costs, reducing waste, and increasing customer satisfaction.

Repairability by design includes the following characteristics:

- It is durable, robust, and resilient to wear and tear
- It can be disassembled and assembled with standard tools and techniques
- It comes with clear and comprehensive documentation for repair and maintenance
- It has training, knowledge transfer, and certification programs
- It has spare parts and repair tools readily available
- It has modular and interchangeable components that can be updated or replaced

Refer to section 8.2.1. for a description of the Ecodesign Regulation in the EU which aims at making products more energy-efficient, durable, repairable, and recyclable.

The Repairability by Design indicator aligns with the SDG12 (responsible consumption and production) and supports the SDG7 (affordable and clean energy), SDG9 (industry, innovation, and infrastructure), and SDG13 (climate action). As shown in Figure 3-1, the work involved in progressing the value of this indicator is under the control of the manufacturer.

3.1.3 Durability by Design

Durability by design is a key and subjective indicator of how well a product can withstand normal wear and tear of its intended use, without compromising its quality, performance, or safety. Durability by design [*HUD-DRB*] includes the following characteristics:

- It is made of materials that resist wear, corrosion, and degradation
- It meets or exceeds the quality, performance, and safety standards
- It is designed for efficiency and simplicity, avoiding unnecessary complexity
- It allows easy access to parts that need regular inspection and maintenance

This indicator aligns with the SDG12 (responsible consumption and production) and supports the SDG7 (affordable and clean energy), SDG9 (industry, innovation, and infrastructure), and SDG13 (climate action). As shown in Figure 3-1, the work involved in progressing the value of this indicator is under the control of the manufacturer.

3.1.4 Recyclability by Design

Recyclability by design is a key indicator of how well a product can be recycled at the end of its lifecycle, reducing environmental impact and resource consumption. Recyclability by design [*EU-CIRC2*][*RECOUP*] includes the following characteristics:

- Its materials can be recycled easily, either for the same product or a different product
- It meets the standards of compatibility with existing recycling processes
- It is designed for modularity and standardization, avoiding obstacles to recycling
- It allows easy disassembly and separation of components into different material streams
- It provides clear and comprehensive documentation and labeling for recycling

This indicator aligns with the SDG12 (responsible consumption and production) and supports the SDG7 (affordable and clean energy), SDG9 (industry, innovation, and infrastructure), and SDG13 (climate action) [*DSGN-CIRC*]. As shown in Figure 3-1, the work involved in progressing the value of this indicator is under the control of the manufacturer.

3.1.5 Maturity of Recycling Ecosystem

The maturity of recycling ecosystem is a key indicator of how well the recycling system is developed and integrated in a specific context, such as a country, a region, or an industry [*CA-CMPST*][*UN-CIRC1*]. A mature recycling ecosystem has the following characteristics:

- It has adequate and accessible recycling infrastructure, facilities, and services
- It recovers, reuses, and recycles a large and high-quality amount of recyclable materials
- It engages and collaborates with various stakeholders in the recycling system
- It has effective and enforced regulations, standards, and incentives for recycling

This indicator aligns with the SDG12 (responsible consumption and production) and supports the SDG7 (affordable and clean energy), SDG9 (industry, innovation, and infrastructure), and SDG13 (climate action) [*MDPI-SMM*]. As shown in Figure 3-1, this indicator is defined by the ecosystem, i.e. it is not determined by the manufacturer.

3.1.6 Percent of Products Recycled (Reduce, Reuse, Recycle, Recover)

This indicator measures the percentage of products that are recycled instead of discarded, either by the original manufacturer or by a third-party recycler [*GREEN-CIRC*]. It shows how well a manufacturer is following the principles of material circularity and minimizing its environmental impact by using fewer virgin resources and generating less waste [*EPA-CIRC1*][*CA-ECO*]. The definition and calculation of this indicator may differ depending on the product type, recycled material source and quality, and applicable standards and regulations.

This indicator also reflects the four Rs of waste management:

- Reduce the materials and energy needed to produce a product
- Reuse the product (or components) for the same or a different purpose
- Recycle the product or its components into new products, materials, or substances
- Recover useful materials or energy from the product (or components), such as composting, incineration, or anaerobic digestion

As shown in Figure 3-1, this indicator is defined by the ecosystem, i.e. it is not determined by the manufacturer.

3.2 States of Material Circularity

In Section 3.1, we discussed the six axes of the Material Circularity radar map, the material circularity indicators. In this section, we focus on the concentric polygons in that radar map, which describe the different states of material circularity in the product.

- Current state of the material circularity in the product
- Progress of that state over a multi-year horizon
- Material Circularity compliance requirements (with deadlines) in the jurisdiction

- Material Circularity goals (with deadlines) defined in the UN SDGs
- Material Circularity goals (with deadlines) defined by the organization's leadership

3.2.1 Current State of Material Circularity

This state refers to the degree of circularity that a product has achieved so far, based on the material flows and impacts associated with its lifecycle. This is represented by the thick red polygon in figure 3-1. This current state can be measured and compared using various indicators, such as the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation [*EMF-MCI*], or the Circularity Indicators tool developed by Granta Design [*ESTM-CIRC*].

These indicators can help manufacturers to identify the circular value and potential of their products, as well as the risks and opportunities for improvement. This state is influenced by the maturity of the recycling ecosystem [*WIKI-CIRC*].

The current state of material circularity of a product is directly related to SDG12 (responsible consumption and production). It also contributes indirectly SDG7 (affordable and clean energy), SDG9 (industry, innovation, and infrastructure), and SDG13 (climate action) [*UL-CIRC*].

3.2.2 Progress of that Current State over time

The Material Circularity radar map in Figure 3-1 shows multiple concentric polygons (red dotted lines) that depict future progress of material circularity that a product achieves over time.

3.2.3 Material Circularity Compliance Requirements

Compliance requirements for material circularity (purple concentric polygon in figure 3-1) are the minimum de jure (i.e. mandatory) requirements defined in laws, regulations, and standards that discrete manufacturers must follow to ensure that their products are designed, produced, and managed in a way that supports the principles of a circular economy. Compliance requirements for material circularity can come from various sources, such as:

<u>Government regulations and policies:</u> These are the laws, regulations and directives that set the minimum targets (goals and timeframes) for material circularity [*ISO-CIRC*]. These compliance targets may incorporate economic carrots and sticks: financial incentives (example grants and tax breaks) if the guidelines are met and severe fines if they are not met.

<u>Industry standards and certifications:</u> These are de facto guidelines and criteria that define the best practices and performance levels for material circularity [*EMF-MCI*].

The mandatory nature of achieving compliance (goals and timeframes) with material circularity laws and regulations means that the efforts needed to achieve such compliance should justified based on return on investment (ROI) guidelines that are similar to the ones used for other compliance obligations (privacy, product safety, etc.)

3.2.4 Material Circularity Goals as Defined in the UN SDGs

The blue concentric polygon line corresponds to the material circularity goals (requirements and timeframes) defined in the UN SDGs that correspond to the product. The non-mandatory de-jure nature of these compliance requirements (goals and timeframes) means that the efforts needed to achieve them should be cost justified from an ROI perspective.

3.2.5 Material Circularity Goals set by the Organization

The green concentric polygon line corresponds to the material circularity goals and timeframes as defined internally by the organization's leadership. The non-mandatory de-jure nature of these requirements means that the efforts needed to achieve them should be cost justified from an ROI perspective. Often, these involve adherence to company compliance rules that go beyond regional regulations and industry standards.

4 Considerations Before You Start

As the organization prepares itself to embark on the circularity journey, it should reflect on a number of important considerations, refer to Figure 4-1, and understand their dynamics in order to determine the optimal material circularity vision and strategy.

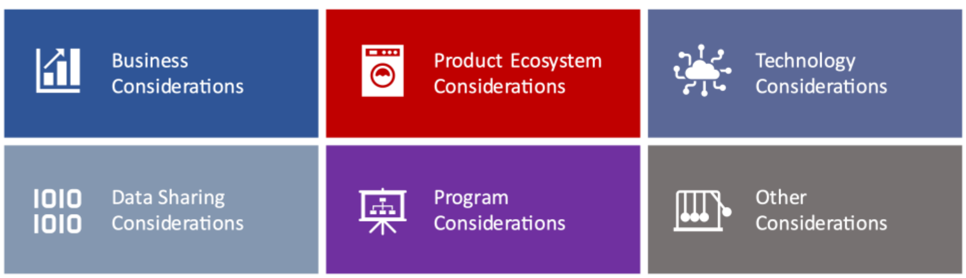

Figure 4-1: Considerations before you start.

4.1 Business Considerations

This section builds on the previous discussion of the benefits of material circularity in section 2.3.3 and explores the business considerations and timeframes for implementing material circularity initiatives.

The organization should conduct a comprehensive assessment of the business case for material circularity, which entails analyzing the potential benefits, investments, risks, and trade-offs of adopting circular practices. Moreover, the assessment should take into account external factors that may affect the organization's material circularity, such as the demand and preferences of the market and customers, regulatory requirements and incentives, competitive pressures and opportunities, and social expectations and impacts.

4.1.1 Government Incentives

Some government authorities in different jurisdictions offer incentives for material circularity initiatives. These incentives comprise tax breaks or grants that facilitate the adoption of circular economy practices. Manufacturers should evaluate the accessibility and applicability of these incentives and formulate suitable strategies and measures to leverage them efficiently.

4.1.2 Legal & Regulatory Compliance Requirements

Manufacturers in different jurisdictions face a wide range of laws and regulations related to mandatory material circularity:

- Existing laws and regulations that have been updated and strengthened
- New laws and regulations
- Laws and regulations that are being planned or developed for future release

Requirements may also be driven by standards and industry alliances. In section 8, we describe some of these laws, regulations, and standards.

Depending on local market dynamics, laws and regulations, jurisdictions may have variations and differences in circularity requirements in areas related to scope of the circularity requirements, timeframes for achieving compliance, impact of requirements on ecosystem partners, sanctions for failing to achieve compliance within the specified timeframes, reputational damage for failing to meet the compliance obligations within the timeframes, and more. Also, some laws and regulations may also focus on particular product categories (example batteries), while others may focus on specific materials in products (example rare earth).

> *Important:* *Discrete manufacturers must investigate these laws and regulations and analyze their scope, mandatory compliance requirements, and timeframes, and set their priorities accordingly. They must also assess the extent, severity, and consequences of sanctions that can result from non-compliance. Forward thinking companies may also want to take part in the process of creating new regulations through standards bodies, consortia, and government industry initiatives.*

4.1.3 Business Case for Circularity

The organization should define the business case for material circularity and how it aligns with the organization's vision, mission, values, and strategic goals. This should include the potential benefits, costs, risks, and trade-offs, as well as external factors that may influence the organization's material circularity, such as market demand, customer preferences, regulatory requirements, competitive pressure, and social expectations.

The organization should also assess the necessary investments needed to achieve the above. These investment will encompass a wide range of areas, such as:

Product redesign: Manufacturers may need to invest in modifying and possibly redesigning their products to enhance modularity, standardization, ease of disassembly, and compatibility with recycled materials. This may result in higher costs, but also higher value.

Management system augmentation: Manufacturers may need to add capabilities to their management systems to facilitate the collection, sorting, and processing of used products and materials. This may involve functions related to the following areas:

- Reverse logistics
- Digital platforms
- Tracking and tracing technologies
- Partnerships

Human resource development and upskilling: Manufacturers may need to invest in training their workforce and possibly hiring new talent who is knowledgeable about material circularity.

Recycled material utilization: Recycling materials may be more expensive than using virgin materials, and this should be weighed against the environmental and long-term cost savings.

Process adaptation: Using recycled materials may require changes to production processes, such as adjusting parameters, equipment, testing, and recertification methods. Organizations should evaluate the feasibility and impact of these changes.

Product usage data leverage: To recycle a product at its EoL, the manufacturer may need to remain connected with the product and its user. This requires investments in digitalizing products using technologies such as IoT and digital twin, which help manufacturers leverage product usage data in functions such as DPP (Digital Product Passport).

EoL recycling-related activity participation: Manufacturers may need to invest in EoL recycling activities, such as collection, disassembly, separation, and reprocessing, to recover materials and reintroduce them into new cycles. They should also assess the viability and impact of these activities, as well as the potential for creating new value streams and advantages.

Achieving the circularity goals within the stated timeframes requires the right level of investment in terms of financing, organizational changes, programs, etc.

4.1.4 Effect of Circularity on Company Brand Image

Material circularity is a key driver of customer loyalty and environmental sustainability, and positively influences the manufacturer's brand image with customers. Customers are prepared to make purchase choices that favor manufacturers that are responsible and sustainable, and that offer products that are designed and delivered in a way that benefits the environment.

Hence, customers expect manufacturers to:

- Recycle products to preserve the value, quality, and reusability of materials
- Reuse products (and parts) into new ways, extending their lifespan
- Repair damaged or malfunctioning products economically to reduce waste
- Ensure that material circularity respects privacy and confidentiality of customers

Manufacturers should understand the evolving expectations of customers by maintaining their connection with them. This can also bring further value such as cost savings, longer useful product lifespan (through repairability and durability), and innovative products.

4.1.5 PITFALLS OF GREENWASHING

Greenwashing is the practice of promoting a product or a policy so that it appears to be more environmentally friendly than it really is. The causes for greenwashing may be *willful deception* or *simple ignorance*. In either case, it is a practice that undermines the efforts of sustainability in general and material circularity in particular. Here are examples of greenwashing:

- Hotels that ask guests to reuse their towels, while they do not implement proper green practices for cleaning these towels (although this does reduce the wash load)
- Energy companies that claim to be investing in clean energy, while they continue to produce and sell fossil fuels that contribute to climate change
- Products that use labels such as "natural" or "eco-friendly", without providing evidence or certification to back up their claims

In 2023, the EU issued the “Green Claims Directive” [*GRWSH-EU*] which is intended to fight greenwashing by setting strict rules for environmental claims on products. The directive ensures that such claims are transparent, reliable, and based on a product’s full life cycle impact. The directive aims to help consumers make informed and sustainable choices. Several well-known consumer brands have been accused of making misleading eco claims in their product advertising with potentially significant fines. [*GRWSH-BBC*][*GRNWSH-EACT*]

Discrete manufacturers should define their objectives clearly and realistically (scope and timeframes) and assess their ability and capacity to deliver. They should also communicate their vision and plans honestly to their stakeholders, avoiding misrepresentation or exaggeration.

4.1.6 SIMILAR INITIATIVES BY COMPETITORS

Customers may prefer competitors with a better material circularity track record: a significant threat to lagging manufacturers. Manufacturers should compare their material circularity indicators against their competitors and improve and differentiate.

4.1.7 EXTERNAL CIRCULARITY EXPERTISE

Manufacturers may seek the assistance of external material circularity experts to augment their internal resources working to material circularity. These experts can provide thought leadership and assist and provide guidance in multiple areas, such as designing, producing, and managing materials and products in a circular way. They can also provide impartial or fresh perspectives that add innovation and credibility to material circularity initiatives.

<u>Assessment:</u> Experts can evaluate the current state of the manufacturer’s material flows, identify the opportunities and challenges for circularity, and measure the environmental, economic, and social impacts of the initiative, using quantitative and qualitative methods.

Advice: Expert can provide guidance and recommendations on how to implement circular strategies, such as designing for durability, modularity, and recyclability, choosing low-carbon and renewable materials, optimizing material use and efficiency, and collaborating with suppliers and customers, based on best practices and case studies.

Assistance: Experts can provide assistance regarding the execution of the circular strategies, such as providing training, tools, and resources, facilitating stakeholder engagement and alignment, and monitoring and effectively communicating and reporting about progress.

4.2 Product Ecosystem Considerations

This section addresses the material circularity considerations for the products and the ecosystem across the product lifecycle: conception, design, production, operation, usage, and end of life.

The organization should determine the environmental impact of the product, its resource efficiency, and its value retention throughout its lifecycle. It should also find ways to boost the products' circularity, such as lowering material inputs, prolonging product lifespan, enabling reuse, repair, refurbishment, remanufacturing, and recycling, and reducing waste.

Table 4-1 below outlines the role of stakeholders at each stage of the product model lifecycle:

A. Description	B. Conception	C. Design	D. Production	E. Usage
Material Supplier	Supply materials that can be recycled and reused	Supply materials that can be recycled and reused	Nothing	Nothing
Component Provider	Supply components that have high percentage of recycled material Contribute where possible to Main OEM's reparability, durability, and recyclability objectives	Supply components that have high percentage of recycled material Contribute where possible to Main OEM's reparability, durability, and recyclability objectives	Nothing	Nothing
Main OEM	Envision packaging for maximum recyclability Envision product to be digitalized (IoT, digital twin, AI, etc.) Envision product to be: - Repairable by design - Durable by design - Recyclable by design Focus on Material Suppliers and Component Providers that support the above Collect feedback from retailers and users	Design packaging for maximum recyclability Design product to be digitalized (IoT, digital twin, AI, etc.) Design product to be: - Repairable by design - Durable by design - Recyclable by design Focus on Material Suppliers and Component Providers that support the above Collect feedback from retailers and users	Redesign packaging for maximum recyclability Consider adding digital technologies to capture usage data Make product content and repair information available to relevant stakeholders	Make product content and repair information available to relevant stakeholders Leverage connection with users to capture usage data Offer digital services (ex: software / firmware upgrades, performance monitoring, predictive maintenance) that extend the life of the product

A. Description	B. Conception	C. Design	D. Production	E. Usage
	about product preferences	about product preferences		
Retailer	Nothing	Nothing	Implement product upgrade/exchange programs for customers (with incentives) Engage with Main OEMs and re-processors to handle returned products (recycle, refurbish, etc.)	Implement product upgrade/exchange programs for customers (with incentives) Engage with Main OEMs and re-processors to handle returned products (recycle, refurbish, etc.)
User	Nothing	Nothing	Nothing	Collaborate with recycling entities at product EoL
Collector	Collaborate with Main OEM and recycling stakeholders re product recyclability and repairability	Collaborate with Main OEM and recycling stakeholders re product recyclability and repairability	Collaborate with Main OEM and recycling stakeholders re product recyclability and repairability	Request information from Main OEM to make EoL decision (refurbish or recycle)
Refurbisher	Collaborate with Main OEM and collectors re product refurbishing potential	Collaborate with Main OEM and collectors re product refurbishing potential	Request product repair and refurbishing information from Main OEM	Request product repair and refurbishing information from Main OEM
Recycler	Collaborate with Main OEM and collectors re product recycling	Collaborate with Main OEM and collectors re product recycling	Collaborate with Main OEM and collectors re product recycling	Collaborate with Main OEM and collectors re product recycling

Table 4-1: Product considerations for material circularity.

The columns in this table represent a macro view of the stages of the product lifecycle while rows correspond to the stakeholders and their roles in each lifecycle stage:

- Column A: represents the different stakeholder roles described in section 2.4.
- Column B: Represents products that are still at the conception stage and thus should therefore incorporate the fruits of material circularity initiatives being implemented.
- Column C: Same as above but represents products that are already in the design stage.
- Column D: Same as above but represents products that are already in production.
- Column E: Represents products that were sold before material circularity initiatives were implemented and are in use now.

As the table shows, each stage has its own set of challenges and opportunities. This requires collaboration and coordination among the stakeholders.

4.3 Technology Considerations

Circularity initiatives are typically enabled by a mix of technologies: well-established, emergent, and emerging. These may be digital technologies, for e.g. digital twin and IoT, others may be focused on physical material handling, for e.g. material separation, and finally some are focused on business processes and on managing product information across their usage cycle.

The use of technology in enabling material circularity is an involved subject and merits its own section in this framework. Refer to section 5 for details.

4.4 Data Sharing Considerations

Discrete manufacturers need to manage product and production data in a way that enables the design and delivery of products and services that are circular by nature, meaning they can be durable, repairable, reusable, and recyclable, and that meet the changing expectations of stakeholders, especially users [*EMF-MCI*].

Manufacturers must also establish a trusted data exchange across the ecosystem, involving suppliers, customers, regulators, and other partners. This will allow them to improve their supply, demand, and circularity chains in terms of visibility, efficiency, resilience, and collaboration. It will also enable them to evaluate and communicate [*TSTEP-MCI*] the environmental and economic benefits of circular strategies, such as extending product life and quality, recovering materials from waste streams, optimizing material flows across the product value chain and lifespan, and reducing risks and environmental impacts [*GRNBZ-MSR*].

> *Note: Figure 2-2 has provided an example of data exchanges across the ecosystem and the product lifecycle. The example showcases the EU Digital Product Passport.*

To accomplish the above objectives, the management and exchange of product and production data must address the following considerations:

- Availability and quality: Data about material stocks and flows, circular activities, and impacts at different levels (product, region, etc.) accessible, accurate, consistent, complete, and timely [*MDPI-CELM*].
- Architecture: Data storage, processing, transmission, scalability, performance, and more.
- Interoperability, sharing and accessibility: Data formats, semantics, structure, protocols, and platforms must be standardized (example DPP discussion in section 8.2.1) to enable trusted data sharing and exchange among different stakeholders and systems in the circular economy [*SPR-CIRC*].
- Security, privacy, and confidentiality: The data confidentiality and privacy risks and trade-offs associated with data exchange (collection, storage, and use) between ecosystem partners must be addressed. These risks and trade-offs include data breaches, cyberattacks, and ethical issues.
- Lifecycle governance: This covers the management of the data lifecycle and its alignment with the lifecycle of the product and the regulatory mandates within the jurisdictions.

To address these challenges, discrete manufacturers need to adopt data-sharing approaches that are based on common standards, platforms, and governance mechanisms.

> *<u>Dataspace Concept:</u> An emerging concept in data management and data infrastructure. It is a federated and open infrastructure for sharing sovereign data between organizations and systems across domains and ecosystems, common policies, rules, and standards. Sharing data allows using it in new and innovative ways to produce new value, e.g. analyzing the data in real-time to gain insights into operations and making better decisions.*[1]

4.5 PROGRAM CONSIDERATIONS

Material circularity poses significant organizational challenges that require the establishment of a program that has a clear strategic vision, leadership, skills, and communication strategy.

<u>Program Vision and Mission:</u> The material circularity program must have a clear and compelling vision and mission statement that articulates the desired future state of the organization in terms of circularity. The mission should define the specific objectives, timeframes for achieving them, and the actions needed to achieve them.

<u>Executive Sponsorship:</u> The Material Circularity Program must have strong executive sponsorship that sets the overall vision and objectives of the material circularity initiative, and mandates and empowers its implementation across the organization. This is needed in order to ensure the commitment, support, and accountability of the organization's top management to the initiative.

<u>Program Team and Leadership:</u> The material circularity program must have a multidisciplinary and cross-functional team of experts from different departments and functions such as product design, engineering, manufacturing, supply chain, logistics, marketing, sales, finance, legal, and sustainability. The team should be familiar with the material circularity mission and objectives and should have the required skills (each in his or her domain) to achieve these objectives.

The program team must be led by an executive leader who is mandated and empowered by the executive sponsor to execute the program:

- Transform the overall vision into a real strategy and achievable program outcomes
- Oversee the planning, execution, and evaluation of that program
- Deliver the outcomes specified in the vision and mission statement
- Engage with stakeholders, internal and external, and ensure their participation
- Arrange, coordinate, and manage budgets and other resources
- Engage with regulatory authorities regarding activities and achievements of the program
- Manage the circularity-related communication within the organization, Especially the communication with the executive sponsor and leadership of the organization
- Engage with external stakeholders and manage the communication with them

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1 *https://link.springer.com/chapter/10.1007/978-3-030-98636-0_1*

<u>Managing Budgets and Costs:</u> The material circularity program should consider the nature of circularity requirements from two perspectives. Regulatory requirements that are obligatory and non-negotiable should be met in the most economical way possible. See section 3.2.3 for more details. Voluntary requirements that are aligned with the strategic vision (for instance, a corporate mandate) should be supported by adequate cost analysis and ROI evaluation. See section 3.2.5 for more information.

The program leadership should clearly differentiate these requirements and communicate them effectively to the executive sponsors and financial leaders of the organization. They should also reflect them in the roadmap and priorities of the program.

<u>Managing Mindset Challenges:</u> The program leadership must address initial and persistent mindset challenges on the need and urgency of material circularity. There may be resistance to change from a perception that it will disrupt existing business and operating models, profitability, competitiveness, supply chains, and consumer behavior. Some changes may be mandatory due to regulatory deadlines, while others may have a strong business case based on cost reduction, competitive standing, brand reputation, and more.

Internal and external stakeholders may lack motivation due to the upfront costs of circularity, its low returns, long payback, uncertain demand, and limited infrastructure. Manufacturers should incentivize circularity by aligning targets and rewards with objectives, providing assistance for circularity projects, and creating collaboration opportunities across the value chain.

Manufacturers that lack sufficient knowledge and skills in implementing material circularity, may seek help from external material circularity experts to help augment their in-house knowledge using various services. These services may cover design, production, and management of materials and products in a circular way. Refer to section 4.1.7.

<u>Engaging with Stakeholders:</u> The program team must maintain an effective engagement with the various stakeholders, across the product ecosystem, through a consistent communication strategy that conveys to these stakeholders the program's vision, mission, and value, as well as what is expected of them. This communication is 360 degrees, and cuts across seniority levels and organizational boundaries.

<u>Measuring Progress:</u> One of the main responsibilities of the program team is to develop objective and subjective metrics for measuring the current state of material circularity and its progress towards established goals, and to overlay these metrics on the radar map (refer to section 3). The subjective metrics may include perceptions and opinions of stakeholders involved in or affected by the material circularity initiative.

Table 4-2 below describes some of these objective and subjective metrics [*MDPI-CELM*][*NIST-CIRC2*][*NIST-CIRC3*][*UN-CIRC2*][*WBCSD-IND*] for each of the six axis of the radar map:

Indicators	Objective	Subjective
Percent of products made with recycled materials	Weight of recycled materials used in product (or percentage of total weight of product).	Environmental benefits of using recycled materials, for e.g., reduced

Indicators	Objective	Subjective
		greenhouse gas emissions and natural resource depletion
Repairability by design	Availability and affordability of parts, tools, and manuals for repairing a product, and effort required to repair.	Customer satisfaction, loyalty, and trust resulting from a product that can be repaired, and its lifespan extended.
Durability by design	Expected (and measured based on field data) lifespan of a product, in number of years, cycles, or hours of use.	Quality, reliability, and performance of a product that meets or exceeds customer expectations and needs.
Recyclability by design	Percentage of a product's materials that can actually be recovered and reused in the same or another product.	Innovation and competitiveness of a product that incorporates recycled materials or enables recycling.
Maturity of maturity by design recycling ecosystem	Level of development and integration of available and qualified recycling resources and stakeholders.	Collaboration, coordination, and communication among stakeholders in the recycling ecosystem, as well as public awareness and engagement on the benefits of recycling.
Percent of product recycled	Weight or economic value of recovered materials and reused in the same or another product (or percentage of total weight of materials that could be recycled).	Economic and environmental value generated by recycling a product, for e.g., cost savings, revenue generation, emission & waste reduction, etc.

Table 4-2: Objective and subjective indicator for material circularity.

Managing Risk: The program must address risk issues related to the identification, analysis, and assessment, and provide action plans for dealing with threats and uncertainties that may affect it. These risks include:

- Price volatility and supply disruptions of raw materials, which may compromise the profitability and competitiveness of circular products
- Technological challenges to enhance the productivity, quality, and efficiency of recycling processes, as well as to identify suitable substitutes for scarce or hazardous materials
- Regulatory and policy barriers that may impede the adoption and implementation of circular practices, such as product take-back schemes, EPR, or environmental taxes
- Social and behavioral factors that may affect the demand and acceptance of circular products, such as consumer preferences, awareness, trust, and willingness to pay

The program should mitigate these risks by designing policies and incentives that foster material circularity, and by increasing transparency and collaboration among the different stakeholders in the product and value chain.

Coordinating with Other Programs: The organization is bound to have other ongoing programs (example safety, digital transformation, carbon emission scopes 1, 2, 3, etc.) The material circularity program team should coordinate its efforts with the other program teams and align, coordinate, and harmonize its activities with the activities of these programs.

4.6 Other Considerations

There are also considerations related to the following areas, such as:

Adapt and transform operation of organization: Section 3.1 has recommended an array of product changes to meet the circularity objectives: repairability-by-design, durability-by-design, recyclability-by-design, and more. Such changes entail adapting the organization's processes related to product design, material acquisition, manufacturing, packaging, tracking throughout their lifespan across the ecosystem, repairing them, and ultimately recycling contents.

Collaborate across the organization: Material circularity is a cross-functional initiative that impacts different groups within the organization, who need to understand the importance and value of collaborating in the workings of this initiative. Appropriate incentives may be needed at various levels of stakeholders.

Collaborate across the product ecosystem: Material circularity is a cross-organizational initiative that impacts different stakeholders across the product ecosystem and society at large, who need to understand the importance and value of collaborating and participating in this initiative.

Measure progress of initiative: Discrete manufacturers should also implement methods and systems to help them in measuring (qualitative and quantitative) and reporting (internally and externally) about the progress of the material circularity initiative as per section 3.

Evaluate benefits on other functions: Improving the durability and repairability of products will have a positive impact on sales, product reputation, and brand image.

5 Enablers of Material Circularity

The Material Circularity initiative can be enabled by a wide range of emerging, emergent, and well-established technologies, physical systems, and digital systems. Table 5-1 describes various material circularity functions and the technologies and systems that can enable them:

Material Circularity Functions	Technology and System Enablers
Enable the design and development of new materials and products that are more durable, repairable, reusable, and recyclable.	• Engineering design systems • Digital Twins • AI enabled design processes and co-pilots
Enhance the production and distribution processes of products, and make them more efficient, flexible, and resilient.	• Robotics • Industrial IoT • Additive manufacturing • Carbon capture and storage systems • Distributed ledger

Material Circularity Functions	Technology and System Enablers
	• Digital Twins
Create new business models and platforms that enable the sharing, leasing, or remanufacturing of products and services.	• E-commerce tools • Recommerce tools • Mobile platforms • As-a-service platforms such as Predictive Maintenance and/or Asset Performance Monitoring platforms
Create data sharing platforms that facilitate the sharing of product data and the tracking of products across the ecosystem, including product recycling. Refer to section 4.4 for details)	• Digital Twins • IoT sensors • AI, image recognition • Distributed ledger • Mobile platforms • Collaborative platforms • RFID and location-based platforms
Facilitate the collection, measurement and monitoring of physical and chemical properties and conditions of products and materials, throughout their lifecycles.	• Digital Twins • IoT sensors • Edge devices • AI-based image recognition
Facilitate the de-manufacture and mechanical separation of products at the end of their lifecycle. This includes the following: • Identification of material contents for recycling • Extraction of this material • Sorting of this material • Reprocessing of this material for reuse in new applications	• Robotics • AI-based image recognition • Smart labels • Chemical separation tools • Thermal separation tools • Biological separation tools • Material refining systems

Table 5-1: Material circularity functions enabled by technologies and systems.

The diagram in Figure 5-1 illustrates some of these technologies and systems:

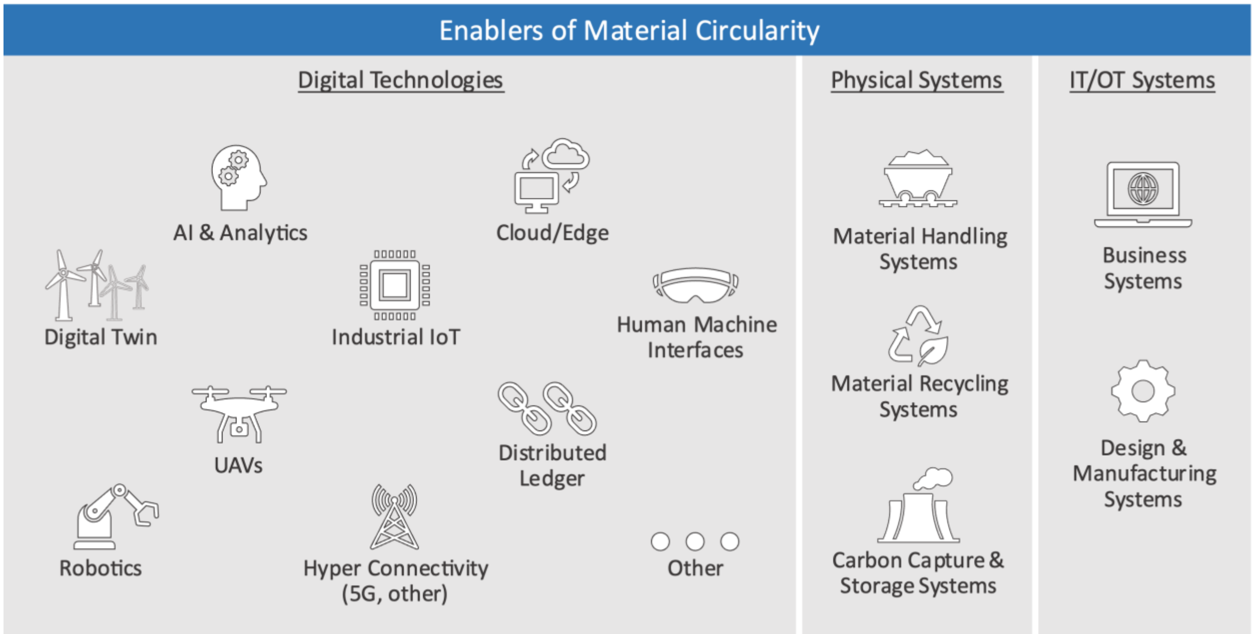

Figure 5-1: Technology and system enablers of material circularity.

5.1 Digital Technologies

5.1.1 Artificial Intelligence

AI (including Generative AI) can enable and enhance material circularity, by applying circular-economy principles, such as recirculating, reusing, and optimizing the use of materials. Image recognition is an AI technology that enables computers to analyze and understand visual data, such as images or videos, and perform tasks based on the content.

Some examples of how AI can be used for material circularity are:

- Assist in the design of circular products that are more durable, modular, and recyclable, by using iterative machine-learning processes and generative AI for rapid prototyping and testing.
- Assist in tracking the condition, location, and availability of products throughout their lifecycle, and analyze real-time and historical data to enable data-driven decisions for reconditioning, remanufacturing, or recycling.
- Help create transparent and decentralized information systems for material circularity, where different stakeholders in the value chain can access and share relevant data about products and materials.
- Help optimize the reverse logistics infrastructure required to “close the loop” on products and materials. This can improve the sorting and disassembly of products, the remanufacture of components, and the recycling of extracted materials.
- Help translate between the various data formats that product data will be stored under at different stages of circularity

5.1.2 Digital Twins

Digital twins are defined as a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity [*DTC-DTWIN*]. They enable material circularity in many ways, such as:

- Design products that are more durable, modular, and recyclable, and their performance and environmental impact, and test them in virtual scenarios.
- Use data input from IoT sensors to help track the condition, location, and availability of products and materials throughout their life cycle to enable better data-driven decisions for reconditioning, remanufacturing, or recycling.
- Create a transparent and decentralized information system for material circularity, where different value chain actors can access and share data about products and materials.
- Test circularity scenarios by running digital twin models of entire circular ecosystems forward far in time under different sets of assumptions to optimize the overall process.

It is important to note that digital twins vary in their level of individualization and granularity:

<u>Product model or product group:</u> The digital twin may represent a product model or product group with the same design and specifications, modeling their average or typical characteristics and behavior. This helps the manufacturer optimize the design, production, and distribution of products, as well as evaluate virtually their performance and environmental impact.

<u>Product unit:</u> The digital twin may represent a specific product unit (down to the serial number level), modeling its unique characteristics which may have variations in manufacturing, usage, or maintenance. This enables more precise and personalized decision making for each product unit, such as reconditioning, remanufacturing, or recycling, based on its actual condition, location, and availability. It can also create a transparent information system for material circularity, where different stakeholders can access and share relevant data about each product.

Digital twins can conceivably model entire circular ecosystems, including raw material producers, supply chains, manufacturers, distribution, use, and recycling / refurbishment. Consumer, organizational and societal choices could eventually be incorporated into these models to make them more predictive in the presence of the human elements.

It is important to note that the choice of the level of individualization and granularity of digital twins will depend on the context, capabilities, and aspirations of the organization, as well as the potential benefits and risks of different organizational arrangements.

5.1.3 Industrial IoT

IoT technology and the associated IT/OT convergence can help with material circularity in many ways. IoT sensors can be embedded into products during the manufacturing stage. These sensors can capture operational and usage data about the products in the field and send this data to the manufacturer (or other entities) for further processing and extraction of insights. These insights can be used to extend the useful lifespan of the product (preventive maintenance) and help in improving product designs.

IoT sensors can also be deployed on production lines to collect real time data on the recycled material used in products and the energy consumption and emissions associated with that aspect of the manufacturing process.

IoT actuators can control the physical parameters of manufacturing processes to improve their quality and efficiency.

5.1.4 Robots

Robots are cyber-physical machines that can perform complex actions automatically, often by following a computer program [*MWBST-RBT*]. Robots may be used to automate and enhance material circularity initiatives, such as:

- Reduce wasted materials during production, by performing precise movements
- Separate different types of waste, such as plastics, metals, etc., for recycling or reuse
- Dismantle and recover components from complex products, such as electronics, vehicles, appliances, etc., for remanufacturing or refurbishing

5.1.5 UAVs

Unmanned Aerial Vehicles (UAVs) cyber-physical flying crafts that can be controlled remotely or autonomously. They can help with material circularity in several ways, such as:

- Collect data about the location, condition, and availability of materials and resources
- Recover materials and products from waste sources, such as landfills or construction sites, and enable their reuse to reduce waste and optimize logistics and emissions
- Transport recycled materials and products between circular facilities or end users, especially for remote areas
- Deliver recyclable materials and products to circular facilities to reduces logistics impact
- Efficiently and quickly deliver repair parts from centralized warehouses to the location of a product under repair or refurbishment
- Optimize and monitor material and resource use to avoid over-extraction of materials
- Monitor and reduce resource extraction, land use, and pollution levels, and support renewable and low-impact sources

5.1.6 Other Technologies

Material circularity initiatives can also leverage other technologies, such as:

- Edge devices are computing devices located close to the sources of data, such as sensors, cameras, or smartphones. They can be used in material circularity to perform data processing, storage, or analysis locally, reducing latency and bandwidth consumption.
- Distributed Ledger technology can be used to securely track the origin, ownership, and lifecycle of materials and products, ensuring traceability and accountability.
- Communication technologies (for e.g. 5G, etc.) can be used to enable efficient data collection, analysis, and communication for material circularity initiatives, such as smart waste management, intelligent logistics, and predictive maintenance.

- Human Machine Interface technologies such as extended reality can be used to assist in field-based task functions, and to educate, engage, and empower stakeholders for material circularity initiatives, such as awareness campaigns, and training programs. For e.g., AR / VR / XR technologies can help visualize many aspects of circular material and product flows and train the workers in procedures needed to support circularity.
- Smart labels that use radio-frequency identification (RFID), quick response (QR) codes, or near-field communication (NFC), can be scanned to capture information about products, their origin, ingredients, or expiration date.

5.2 Physical Systems

These systems can perform the physical separation, extraction, and refining of materials to be recycled:

- Biological separation tools that help in purifying biological products, such as proteins, nucleic acids, or cells, based on their physical or chemical properties, such as size, shape, charge, solubility, or affinity.
- Chemical separation tools that help in separating mixtures of substances based on their chemical interactions, such as extraction, chromatography, or distillation.
- Thermal separation tools that help in separating mixtures of substances based on their different thermal properties, such as boiling point, melting point, or vapor pressure, such as evaporation, crystallization, or freeze drying.
- Magnetic separation tools use attraction to collect ferrous metals and eddy current systems to collect non-ferrous metals.
- Density-based separation tools like float tanks or air tables to separate materials based upon their density.
- Material refining systems that can improve the quality, purity, or value of raw materials, such as metals, by removing impurities, contaminants, or unwanted components.
- Carbon capture and storage systems separate and capture CO2 emissions from sources like thermal power plants, for example using a chemical absorption process to selectively capture CO2 at specific temperatures. [*CCS*]. There are also non-chemical-based carbon capture strategies being explored.

5.3 IT/OT Systems

5.3.1 Business Systems

This can include a wide range of business systems and software applications, such as:

- Collaborative platforms that enable teams to communicate, share information, and work together on projects or tasks.
- Mobile applications on devices such as smartphones and tablets, that provide users with access to various functions, such as communication and productivity.
- Recommerce applications that facilitate the resale, refurbishing, reuse, repair, redistribution, or donation of products that are no longer needed.

- E-commerce tools that facilitate the online buying and selling of goods or services, such as websites, marketplaces, and payment systems.
- As-a-service cloud-based platforms that provide customers with access to software, hardware, infrastructure, or other resources on demand.

5.3.2 Design and Manufacturing Systems

This can also include a wide range of systems and software applications, such as:

- Systems such as computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), and finite element method (FEM) that assist engineers in designing, analyzing, manufacturing, and testing products or systems.
- Additive manufacturing (3D printing) can create products or parts from digital designs, without the need for cutting, drilling, or machining of excess material, by using techniques such as layering, melting, or binding of materials. This can help reduce material waste [*MKSY-DAVOS*] and save energy and resources and enable the design and creation of customized and personalized products or parts using recycled materials.
- Computer Numerically Controlled (CNC) machine tools improve the accuracy and efficiency of subtractive manufacturing processes, reducing waste and scrap.
- Nesting software optimizes the location of multiple types of parts on sheet stock.

6 Material Circularity Framework

In the preceding sections, we have examined different aspects of material circularity, the product ecosystem, the stakeholders, the circularity radar map which helps to visualize the progress of product circularity efforts, the various considerations that discrete manufacturers should assess and evaluate during the early stages of the initiative, and finally the range of technologies and systems that enable material circularity.

This section puts things together in a framework as depicted in figure 6-1.

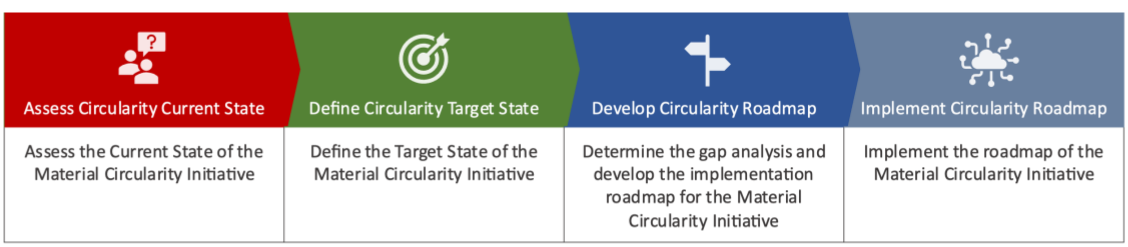

Figure 6-1: Material circularity framework for discrete manufacturers.

The framework is broken down into four phases:

- Assess the current state
- Define the target state
- Define the roadmap
- Implement the roadmap

It is important to note that some of the activities related to the first two phases can take place in parallel, and that both of these phases must be completed before the development of the roadmap can start. The vision and roadmap MUST also be realistic, achievable technically and financially, and free of greenwashing (refer to section 4.1.5). Also, the outcome of each phase should be clear and meaningful, and it should enable and guide the subsequent phase.

Finally, there may be feedback loops between different phases (not shown in diagram) to allow for adjustments based on new insights gained during execution. For example, the target state (or roadmap) may need adjustment based on insight gained during the implementation.

6.1 Assess Current State

This phase consists of assessing the current state of circularity initiative within the organization.

Considerations	Description
Business	Assess the current state of material circularity within the organization, benchmark the performance of the organization against relevant industry standards and best practices, and analyze the lessons learned from past circularity efforts which may have been unrealistic, unsuccessful, or suffering from greenwashing.
Product	Assess the current state of material circularity from the product perspective, e.g., material contents, packaging, recyclability, repairability, etc., broken down by regional preferences and material type priorities. This work should also include the overlaying of this information onto the circularity radar map, its axes and measurement units.
Ecosystem	Assess the current state of material circularity from the perspective of the product ecosystem, the material and data flow, and the maturity of the recycling resources which are available locally (by type of products and materials to be recycled).
Technology	Assess if and how already deployed technologies can be leveraged to enable or assist in the enablement of material circularity.
Data	Assess the current level of product-related data sharing across the ecosystem.
Program	Assess the current state and spirit of collaboration between the different stakeholders, both internal to the organization and across the ecosystem.

6.2 Define Target State

This phase consists of defining the target state of the circularity initiative.

Considerations	Description
Business	Define the target state for material circularity, including its strategic objectives and business outcomes: • Analyze the legal and regulatory landscape and how they apply • Analyze the UN SDGs and how they apply to the organization • Survey available and upcoming government incentives • Assess the impact of the circularity initiative on brand image and bottom-line • Analyze the impact on other initiatives within the organization (e.g., carbon emissions and digital transformation)

Considerations	Description
	• Compare the circularity initiative with similar initiatives by competitors • Perform a preliminary ROI analysis
Product	Articulate how the defined target will impact the product design, e.g., durability-by-design, recyclability-by-design, repairability-by-design, etc., by regional preferences and material type priorities. This work should also include the overlaying of this information onto the circularity radar map, its axes and measurement units.
Ecosystem	Articulate how the defined target will impact the product ecosystem in terms of requirements for the partners and their stakeholders, and the maturity requirements for recycling resources (by type of products and by type of materials to be recycled).
Technology	Identify the digital technologies that can enable or assist in the enablement of material circularity, e.g., IoT, digital twin, AI, robotics, extended reality, UAVs, etc.
Data	Identify the scope and policies of product-related data sharing across the ecosystem that would facilitate material circularity and enable its processes. Also, identify prospective data models and standards.
Program	Define the scope of the circularity program that will drive the implementation of the strategy. The program should have an executive sponsor and an empowered executive leader to guide it and execute its mission.

6.3 Develop Roadmap

This phase consists of performing a gap analysis between the current and target states and developing a multi-phase roadmap (with milestones) for the implementation of the material circularity initiative within the organization. Requirements formalization, systems engineering, and system architecture are part of this phase.

Considerations	Description
Business	Perform a gap analysis (focused on business) between current and target states of the circularity initiative and define a roadmap to bridge these gaps, such as: • Modify the business models • Invest in changes to products and packaging, expanded ecosystem, new technologies to enable circularity, alignment with other initiatives, etc. • Invest in reporting processes with regulators
Product	Perform a gap analysis (focused on products) between current and target states of the circularity initiative and define a roadmap to bridge these gaps, such as: • Modify product design and packaging • Modify product material contents • Implement technologies to enable circularity (recover/recycle materials)
Ecosystem	Perform a gap analysis between above mentioned states with a focus on the product ecosystem and define a roadmap to bridge these gaps. • Identify and engage with recycling facilities and resources • Expand repair and refurbishing services

Considerations	Description
	• Define a federated and trusted data sharing environment between the different organizations and systems across the different domains (refer to section 4.4)
Technology	Define the technical roadmap for implementing the technologies. Use digital modelling, simulation, and optimization to enable the design and development of new materials and products that are more durable, repairable, reusable, and recyclable, and align production processes with the above. Also, define a digital twin of the entire circular process.
Data	Define the roadmap for implementing the dataspaces needed to facilitate the federated and open infrastructure for sovereign and trusted data sharing across the product ecosystem, including the recycling partners. Select data abstraction models, database formats and standards to be used in implementation.
Program	Develop the program mission and structure: • Identify the resources needed (internal and across the ecosystem) • Define the metrics and KPIs • Define the communication and reporting strategy

6.4 Implement Roadmap

This is the implementation phase of the material circularity roadmap.

Considerations	Description
Business	Implement the business aspects of the roadmap
Product	Implement the product aspects of the roadmap
Ecosystem	Implement the ecosystem aspects of the roadmap, including the data sharing environment described in section 6.3
Technology	Implement the technology aspects of the roadmap
Data	Implement the data aspects of the roadmap
Program	Implement the program aspects of the roadmap

The above implementation tracks include data collection, troubleshooting, optimization and adapting / tuning the process based upon feedback from later steps.

7 Conclusion

Material circularity enables discrete manufacturers to transform their linear production models into circular ones, where materials are kept in use for as long as possible, and waste and emissions are minimized. By adopting material circularity, discrete manufacturers can unlock new opportunities for innovation, differentiation, and value creation, while also achieving cost savings, resource efficiency, improved customer loyalty, and stronger compliance with standards, laws, and regulations.

This framework document is a valuable tool for discrete manufacturers at every stage of their material circularity journey. The framework presented the material circularity radar map, a planning tool that helps discrete manufacturers assess their current and desired states of circularity using different indicators, and align and streamline their material circularity efforts, both internally and externally. The report also examined some of the critical considerations that discrete manufacturers should address before embarking on their material circularity journey.

These considerations span business, products, ecosystem, technology (e.g., Digital Twin, IoT, AI, 3D Printing, Robotics, UAVs, AR/XR/VR, etc.), data sharing, and program management domains. The report then integrated all these elements into a framework that covered the main phases of the material circularity initiative, and provided a concise overview of related standards, laws, and regulations in major jurisdictions.

In closing, it is fair to say that material circularity is an urgent and expanding need. It is both a moral obligation and a strategic advantage for discrete manufacturers to innovate, take calculated risks, experiment with new solutions, and disrupt the status quo. The issues and guidance provided in this document were framed with all this in mind. Material circularity is the future of discrete manufacturing, and the future is here.

8 Standards, Regulations, Best Practices

A major driver for material circularity in the market is the fast-evolving landscape of standards, government guidelines, laws, and regulations, across many regions:

- Existing rules are getting stronger
- New rules are emerging
- More enforcement is happening

Material circularity requirements vary in scope, compliance timeframes, and penalties. For example, the EU has circularity criteria for electronics, textiles, and furniture, such as durability, reparability, recyclability, and recycled content.

A “rising tide effect” occurs when large markets establish standards for material circularity, creating benefits for smaller or adjacent markets. This happens because manufacturers often prefer to sell the same compliant product across different markets, rather than creating different versions for each market. For instance, the circular economy policies of the EU and China influence other countries that trade with them or export waste to them. This fosters material circularity initiatives worldwide and motivates countries to participate. The Springer report “Policies for Material Circularity: the Case of Lithium” [*SPR-LITHM*] examines various policies and value models for material recycling and illustrates the “rising tide” phenomenon.

Discrete manufacturers should monitor and adapt to various circularity frameworks. They should also balance their circularity compliance efforts with other obligations they may have, such as privacy, safety, and many others.

In this appendix, we cover a number of international standards as well as initiatives and legislations in several jurisdictions:

- Europe: EU, UK
- North America: US, Canada
- Asia Pacific: China, Japan, South Korea

8.1 INTERNATIONAL STANDARDS

Standards can provide guidance to discrete manufacturers on how to design, produce, use, and reuse products in ways that minimize waste and environmental impact, while maximizing resource efficiency and value creation. This list of such standards is too long to include here. This appendix provides an example of them. International standards are often referenced by, or form the basis for, various regional or national standards.

ISO 14040 Series: This is a set of standards [*ISO-14040*] that provide guidelines for conducting lifecycle assessments (LCAs) of products, processes, or systems. LCAs are methods to evaluate the environmental impacts of a product throughout its lifecycle, from raw material extraction to disposal or recycling. The ISO 14040 series consists of four environmental standards covering the principles and framework, requirements and guidelines, data format, and examples of how to apply the standard to goal and scope definition. The standard also supports the development and implementation of environmental policies and strategies, such as ecodesign, eco-labeling, and environmental management systems.

ISO/DIS 59040: The ISO 59000 standards series aims at harmonizing the understanding of circular economy and supports its adoption. In that series, the ISO/DIS 59040 draft [*ISO-DIS*] offers a general methodology for information exchange ensuring the interoperability of circular economy related information, based on a Product Circularity Data Sheet (PCDS). The PCDS informs about a product’s circularity aspects: material inputs, circular production, durability, end-of-use options, and circularity benefits. The standard helps discrete manufacturers evaluate their products’ circularity performance and compare them with others, share circularity information with stakeholders (customers, suppliers, etc.), enhance the circularity aspects of their product design and production, and implement circular economy strategies and policies.

8.2 EUROPE

8.2.1 EUROPEAN UNION

The European Union (EU) is a global leader in circular economy. It promotes circular economy principles and standards in trade agreements, development cooperation, and global partnerships, and supports the development of critical raw materials that are vital for a circular and low-carbon economy. Some examples of the EU’s circular economy legislations are:

EU Circular Economy Action Plan: [*EU-CIRC1*] This is a prime example of a strategy to make nations more sustainable and competitive by transforming the way products are designed, produced, consumed, and disposed of. It was launched in March 2020 as part of the European Green Deal. The strategy identifies 35 actions that cover the entire product lifecycle, such as:

- New rules for product design: durability, reparability, recyclability, and energy efficiency
- Proposal for a directive on green claims to prevent false environmental claims
- Proposal for common rules to give consumers the right-to-repair their products
- Focus on sectors that use most resources and where the potential for circularity is high
- Revision of waste legislation for more recycling and less waste generation
- Circular economy monitoring framework to track progress and impact of circular actions

<u>Waste of Electrical and Electronic Equipment Regulation (WEEE):</u> [*EU-WEEE*] Aims at protecting the environment and human health from electronic waste, which can be harmful, wasteful, and valuable. It sets standards and goals for how to collect, process, reuse and recycle electronic waste, and helps prevent the illegal export of e-waste. This directive also requires EU countries to share data and reports on electronic equipment. This helps the EU fight illegal electronic waste trade and support a circular economy.

<u>Restriction of Hazardous Substances (RoHS):</u> [*EU-ROHS*] Aims at protecting the environment and human health from substances in electronic waste, which can be harmful and wasteful. This directive limits the use of ten toxic substances in electronic products, such as phones, computers, and appliances. These substances include lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBB) and many more.

<u>Proposal for Eco-design for Sustainable Product Regulation (EPSR):</u> [*EU-CIRC3*] Currently a draft and when finalized it will replace the current Ecodesign Directive (2009/125/EC), introducing more Ecodesign criteria for a broader range of products. It aims to make sustainable products the standard on the EU market. The criteria cover durability, reliability, reusability, upgradability, reparability, possibility of maintenance and refurbishment, and presence of substances of concern. A concise summary is available from the CIRPASS project [*EU-DPP1*].

<u>Digital Product Passport (DPP):</u> [*EU-DPP2*] Still under development and part of the ESPR, its aim is to enable the systemized tracking of products throughout their lifecycle (from birth to end of life or EoL). This traceability fosters and supports the material recycling process.

<u>Right to Repair:</u> [*EU-DPP3*] New legislation is being prepared to ensure that products can be repaired and hence achieve an extended lifetime. The EU parliament has endorsed its position on November 21, 2023. This supplements the ESPR.

<u>Ecodesign Regulation:</u> [*EU-RRPR*] This is a set rules that aims at making products more energy-efficient, durable, repairable, and recyclable. It covers various product categories, household appliances, TVs, servers, and lighting. The Right-to-Repair (part of this regulation) requires manufacturers to provide spare parts, repair information, and firmware updates for a minimum period of time. This regulation helps promote sustainable consumption, reduce waste, lower greenhouse gas emissions, save consumers money on energy bills and repair costs, as well as give them more choice and information when buying products.

Producer Responsible Organization (PRO): [*PWC-EPR*] [*EU-EPR1*] In the EU, the EPR policy approach (refer to section 2.3.5) is the PRO role - entities that handle the recovery of products at the end of their lifecycle (EoL). Producers join PROs and pay a fee per unit based on their sales forecast. PROs collaborate with municipalities to set up collection centers for unwanted products. PROs collect products and send them to re-recycling and refurbishing companies. Finally, PROs monitor and optimize the recovery process. Other jurisdictions may adopt a similar approach to the PRO.

8.2.2 United Kingdom

The UK has been at the forefront of material circularity, especially for product packaging and resource efficiency. Below are a few examples:

Extended Producer Responsibility (EPR): This legislation [*UK-EPR*] will eventually replace the current Packaging Waste Regulations with a phased implementation from 2023. It is an environmental policy that requires producers to pay the full costs of dealing with the waste they produce from when it is placed onto the market, through to the end of its life. The EPR will cover packaging, electrical and electronic equipment, batteries, and end of life vehicles.

Circular Economy Package Policy Statement: This statement [*UK-CIRC*], issued in 2020, explains how the UK will comply with the 2020 measures of the EU's Circular Economy Package. It also clarifies the roles and responsibilities of the national and local governments, businesses, and citizens in creating a sound material-cycle society.

Restriction of Hazardous Substances Regulations (RoHS): These regulations [*UK-ROHS*], enacted in 2012, limit the use of certain hazardous substances, such as lead, mercury, and cadmium, in electrical and electronic equipment. They aim to protect human health and the environment from the harmful effects of these substances and enable the recycling of these products.

8.3 North America

8.3.1 United States

The US has a diverse and dynamic landscape of material circularity initiatives and legislations, originating from various sources and levels of government: federal, state, industry, etc. This section explores some of these initiatives and legislations:

US Environmental Protection Agency (EPA): The Office of Resource Conservation and Recovery (ORCR) at the EPA was authorized by the US Congress to develop and implement a vision and path towards a circular economy, including the regulation of waste management (hazardous and non-hazardous) and develop grant programs for recycling infrastructure. Chief among their efforts is building a set of strategies around the circular economy, which involves material redesign, waste material reduction, and recapturing waste as a resource.

The ORCR also collaborates with other agencies to address issues with plastic waste, communicate best practices for used battery collection and labelling, disaster recovery, and align with international initiatives to protect human health and the environment [*EPA-CIRC2*]. For manufacturers, the EPA maintains a comprehensive list of laws and regulations that identify the industry affected, compliance information, and enforcement requirements [*EPA-CIRC3*].

<u>US NIST/ASTM:</u> The 2023 "Fostering a Circular Economy of Manufacturing Materials" [*ASTM-CIRC*] report by NIST presents the results of a survey and a workshop conducted by ASTM International's E60 Committee on Sustainability to identify the needs and challenges for circular manufacturing of materials.

The document outlines the drivers and barriers for circular manufacturing, such as economic, regulatory, social, and technical factors, and proposes five categories of standards to help manufacturers create more sustainable and circular products and processes, namely foundational, systems-support, design, production, and recovery/recycling. The report also provides examples of existing and ongoing standards activities related to circular manufacturing and also suggests areas for future work and collaboration.

<u>Manufacturing Associations:</u> With the US relying heavily on voluntary compliance of circular economy strategies, manufacturing associations in various vertical markets are developing initiatives and programs. To support EPR initiatives, these associations work along with federal and/or state government agencies to set up PROs that handle specific types of materials (ex: e-waste, textiles, hazardous chemicals, etc.) Some examples are:

The Consumer Technology Association (CTA), representing the U.S. consumer technology industry, has taken significant steps to promote sustainability and combat electronic waste. Their Greener Gadgets webpage maintains a Recycle Locator tool that allows consumers to find locations to recycle electronics, including televisions; they also provide repair locations and services from their member companies.

The National Association of Manufacturers (NAM) is the largest manufacturing association in the U.S., representing small and large manufacturers across various industrial sectors in all 50 states. They actively engage in circular economy initiatives to improve perceptions at the public, political, and industry levels; they also promote research and development of innovation technologies to enable circular manufacturing processes and sustainable product design.

REMADE Institute is a public-private partnership funded in part by the US Department of Energy's Advanced Materials and Manufacturing Technologies Office. In coordination with academia, national labs, industry, and other trade organizations, they develop technologies to reduce energy, gas emissions, and promote recycled material usage.

<u>California - Extended Producer Responsibility (EPR):</u> [*CAL-EPR*] This new law holds organizations accountable for the environmental impacts of their products from cradle to grave. It applies to products such as paint, pharmaceuticals, packaging, and batteries. The regulation has the following goals:

Reduce waste and increase recycling to ensure products and packaging are designed to minimize waste and maximize recyclability. By 2032, all packaging in California must be recyclable or compostable, plastic packaging production must be reduced by 25%, and packaging recycling rate must reach 65%.

Shift from a linear to circular economy model of production and consumption, where products and materials are reused, repaired, refurbished, or remanufactured.

Form a Producer Responsibility Organization (PRO), a collective entity that will manage compliance with the EPR regulation. The PRO will collect, transport, process, and report on products and packaging at the end of their use.

<u>California SB343 - Accurate Recycling Labels:</u> [*CAL-CIRC1*] This law prohibits packaging from including the "chasing arrows" symbol or any other recyclability indicator unless approved by a specific state agency process. This is meant to prevent consumer confusion and greenwashing and ensures that packaging is actually recyclable in California. This law will take effect in 2024.

<u>California SB54/AB1080 - Circular Economy and Plastic Pollution Reduction Act:</u> This set of bills require manufacturers and retailers to reduce waste generated from single-use packaging and products by 75% by 2030, through source reduction, recycling, or composting. It also establishes minimum recycled content standards for plastic packaging and products and requires them to be recyclable or compostable. These bills were introduced in 2020 and are still pending.

<u>California SB1018 - Recycled Content Mandate:</u> This law requires recycled content in plastic and glass containers, paper bags, reusable plastic carryout bags and plastic trash bags. In terms of plastic beverage bottles, the bill mandates 10% PCR by 2022, 25% PCR by 2026 and 50% by 2031. This law is intended to increase the demand and supply of recycled materials, and to reduce greenhouse gas emissions and landfill waste. This law took effect in 2022.

<u>California - Circular Economy Vision 2020:</u> [*CAL-CIRC2*] This vision, announced in 2018, sets the direction and goals for California's circular economy by 2020 and beyond. The document outlines four key strategies:

- Promote circular design and business models
- Enhance resource efficiency and recycling
- Expand domestic and international markets for circular products and services
- Foster innovation and collaboration among stakeholders

8.3.2 CANADA

Canada has enacted several laws and policies related to material circularity, for example:

<u>Circular Economy Vision 2020:</u> [*CA-CIRC1*] This vision, announced in 2018, sets the direction and goals for Canada's circular economy by 2020 and beyond. It outlines four key strategies:

- Promoting circular design and business models
- Enhancing resource efficiency and recycling
- Expanding the domestic and international markets for circular products and services
- Fostering innovation and collaboration among stakeholders

Plastic Resource Circulation Act: This act, implemented in 2021, aims to reduce the production and consumption of single-use plastic and increase the recycling and reuse of plastic waste. It introduces incentives for businesses that adopt circular product designs and systems and requires manufacturers and retailers to report their plastic usage and recycling rates.

Cross-border Movement of Hazardous Waste and Hazardous Recyclable Material Regulations: [*CA-CIRC2*] These regulations, enacted in 2005, regulate the transboundary movements of hazardous waste and hazardous recyclable material to prevent environmental harm.

8.4 Asia Pacific

8.4.1 China

China has enacted several laws and policies that aim to promote material circularity, especially for product packaging and resource recycling:

Promotion Law on Circular Economy: Enacted in 2008, this law defines the principles, objectives, measures, and responsibilities of the government, businesses, and citizens in developing a circular economy. It also encourages the adoption of circular product design, cleaner production, resource efficiency, waste reduction, and recycling.

Extended Producer Responsibility (EPR) System: This system, implemented in 2017, requires producers to take responsibility for the entire life cycle of their products, from design to disposal. It covers various product categories, such as electrical and electronic equipment, batteries, vehicles, and packaging. It aims to reduce the environmental impact of these products.

Opinions on Further Strengthening the Clean-up of Plastic Pollution: These opinions, issued in 2020, set out the key actions and targets for plastic pollution control in China. They include banning or restricting the production, sale, and use of certain single-use plastic products, such as bags, straws, and utensils; promoting the use of alternative materials, such as biodegradable plastics; and improving the collection and recycling of plastic waste.

8.4.2 Japan

Japan has been a pioneer in pursuing a more circular economy, with several laws and policies that aim to promote material circularity. Regulations in Japan regarding recycling, waste reduction, and environmental pollution have been in effect for several decades, including strict regulations to encourage the adoption of sustainable manufacturing practices. As part of the Paris Agreement (COP21), Japan's nationally determined contributions (NDC) include setting a 2030 GHG emission reduction target of 46% (from 2013 levels), and a longer-term goal of achieving net-zero by 2050. [*JPN-CRBN*]

Decokatsu is a national movement in Japan that promotes a shift in the behavior and lifestyle of citizens and consumers towards sustainability. The movement advocates for achieving carbon neutrality by 2050, with specific targets by 2030. Japan has also been a leader in advancing a circular economy, with various laws and policies that facilitate its implementation:

Basic Law for Establishing a Sound Material-Cycle Society: This law, enacted in 2000, provides the basic principles and framework for Japan's circular economy. It defines the roles and responsibilities of the national and local governments, businesses, and citizens in achieving a sound material-cycle society, where the environmental load is reduced, and the efficient use of resources is enhanced.

Circular Economy Vision 2020: This vision, announced in 2018, sets the direction and goals for Japan's circular economy by 2020 and beyond. It outlines four key strategies: 1) promoting circular design and business models, 2) enhancing resource efficiency and recycling, 3) expanding the domestic and international markets for circular products and services, and 4) fostering innovation and collaboration among stakeholders.

Plastic Resource Circulation Act: This act, implemented in 2021, aims to reduce the production and consumption of single-use plastic and increase the recycling and reuse of plastic waste. It introduces incentives for businesses that adopt circular product designs and systems and requires manufacturers and retailers to report their plastic usage and recycling rates.

Green Growth Strategy: Most recently, the Ministry of Economy, Trade, and Industry (METI) is promoting a voluntary “Green Growth Strategy”, which is a set of industrial policies to create a “virtuous cycle of the economy and the environment” [*METI-GGS1*]. This initiative provides strategic goals and guidelines; including fostering achievements in 14 industrial fields that are expected to grow and contributed to decarbonization (see Figure 8-1). It establishes a Green Innovation Fund of 2 trillion yen over 10 years to provide continuous support for companies that commit to these policies. Key metrics include [*METI-GGS2*]:

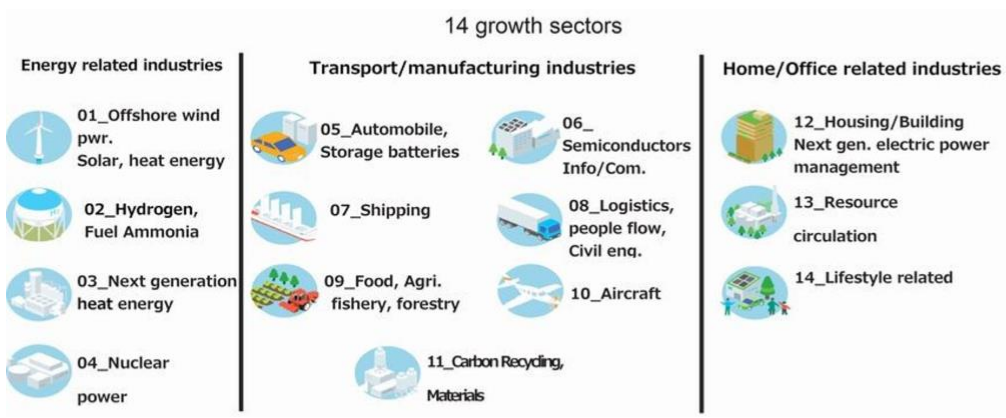

Figure 8-1: Sectors of Japan's green growth strategy (source: METI).

Bioplastics introduction: Introducing approx. 2 million tons of biomass plastics by 2030, which can reduce greenhouse gas emissions and use of depletable resources, as well as biodegradable plastics, which can reduce marine plastic waste and streamline waste treatment.

Energy recovery: Promoting technology development to ensure high-efficiency energy recovery from low-quality waste, such as heat storage and transportation technologies, methanization facilities, and combustion control technologies.

Resilience and disaster prevention: Recovering energy efficiently from household waste and utilizing waste treatment facilities as regional energy centers, which can also provide power and shelter during a disaster.

8.4.3 South Korea

South Korea has enacted several laws and policies that aim to promote material circularity, especially for product packaging and resource recycling:

<u>Resource Conservation and Recycling Promotion Act:</u> This act, enacted in 2000, provides the basic principles and framework for South Korea's circular economy. It defines the roles and responsibilities of the national and local governments, businesses, and citizens in achieving a sound material-cycle society.

<u>Packaging Material and Structure Evaluation System:</u> This system, implemented in 2020, requires businesses that produce or import certain consumer products to evaluate the recyclability of their packaging materials and structures, and label them accordingly. The system also bans the use of PVC materials and colored PET bottles for packaging and encourages the use of eco-friendly materials and designs.

<u>Disposable Products and Plastics Regulations:</u> These regulations, enacted in 2018, aim to reduce the production and consumption of single-use plastic and disposable products, such as plastic bags, cups, straws, and utensils. The regulations introduce fees, restrictions, and incentives for businesses and consumers to adopt reusable or recyclable alternatives.

9 References

[ACTR-CIRC] Circular Advantage: Innovative Business Models | Accenture *https://circularprocurement.ca/wp-content/uploads/2021/02/Accenture-Circular-Advantage-Innovative-Business-Models-Technologies-Value-Growth.pdf*

[ASTM-CIRC] Fostering a Circular Economy of Manufacturing Materials Workshop Report | ASTM *https://marketing.astm.org/acton/fs/blocks/showLandingPage/a/9652/p/p-039d/t/page/fm/0?utm_source=Google&utm_medium=Landing+Page&utm_campaign=ABM*

[BAIN-CIRC] How Companies Can Build a Supply Chain for the Circular Economy | Bain *https://www.bain.com/insights/how-to-build-supply-chain-circular-economy-tech-report-2022/*

[CA-CIRC1] Circular Economy |Canada.ca *https://www.canada.ca/en/services/environment/conservation/sustainability/circular-economy.html*

[CA-CIRC2] Cross-border Movement of Hazardous Waste | Canada.ca *https://www.canada.ca/en/environment-climate-change/services/managing-reducing-waste/cross-border-regulations.html*

[CA-CMPST] CCME Guidelines for Compost Quality | Canadian Council of Ministers
https://ccme.ca/en/res/compostgdlns_1340_e.pdf

[CA-ECO] 20 Recycling Statistics for Eco-Conscious Canadians in 2023 | Review Moose
https://reviewmoose.ca/blog/recycling-statistics/

[CAL-CIRC1] SB 343: Accurate Recycling Labels | CalRecycle
https://calrecycle.ca.gov/wcs/recyclinglabels/

[CAL-CIRC2] California governor signs full slate of circular economy bills | Waste Dive
https://www.wastedive.com/news/california-legislature-recycling-organics-newsom-plastic/606531/

[CAL-EPR] Extended Producer Responsibility (EPR) | CalRecycle
https://calrecycle.ca.gov/EPR/

[CEMS-SCP] What are Scopes 1, 2 and 3 of Carbon Emissions? | Plana Earth Academy
https://plana.earth/academy/what-are-scope-1-2-3-emissions

[CCS] CO2 Capture Technology Systems & Solutions, Thermal Power | Toshiba Energy Systems & Solutions
https://www.global.toshiba/ww/products-solutions/thermal/products-technical-services/zero-emissions.html

[DLT-CIRC] Manufacturing-ecosystems-exploring-world-connected-entpr. |Deloitte
https://www2.deloitte.com/us/en/insights/focus/industry-4-0/manufacturing-ecosystems-exploring-world-connected-enterprises.html

[DSGN-CIRC] Design for Recycling | EcoDesign
https://ecodesign-packaging.org/en/guidelines/strategies/design-for-recycling/

[DTC-DTWIN] Definition of a Digital Twin | Digital Twin Consortium
https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin/

[EMF-MCI] Material Circularity Indicator | Ellen Macarthur Foundation
https://ellenmacarthurfoundation.org/material-circularity-indicator/

[ENG-CIRC] 2023 Circular Economy Request for Information | Energy.gov
https://www.energy.gov/eere/ammto/2023-circular-economy-request-information-challenges-and-opportunities-increasing

[EPA-CIRC1] National Overview: Facts & Figures on Materials, Wastes & Recycling | EPA
https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

[EPA-CIRC2] EPA's Office of Resource Conservation and Recovery (ORCR), US EPA, *https://www.epa.gov/aboutepa/epas-office-resource-conservation-and-recovery-orcr*

[EPA-CIRC3] NAICS Sectors 31-33: Manufacturing | US EPA, *https://www.epa.gov/regulatory-information-sector/naics-sectors-31-33-manufacturing*

[EPR-LGL] Legal Framework Study of Extended Producer Responsibility, cyclos GmbH *https://wwfint.awsassets.panda.org/downloads/2019___wwf___epr_legal_framework_analysis_vf.pdf*

[ESTM-CIRC] Material-circularity-principle-2 | Eastman *https://www.eastman.com/en/media-center/news-stories/2023/material-circularity-principle-2-circular-economy*

[EU-CIRC1] EU Circular Economy Action Plan | EU *https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en*

[EU-CIRC2] What is recyclability? | RecyClass *https://recyclass.eu/recyclability/definition/*

[EU-CIRC3] Proposal for Ecodesign for Sustainable Products Regulation | EU *https://environment.ec.europa.eu/publications/proposal-ecodesign-sustainable-products-regulation_en*

[EU-DPP1] Factsheets, Training videos and Publications | CIRPASS *https://cirpassproject.eu/factsheets-training-videos-and-publications/*

[EU-DPP2] All You Need To Know About the EU Digital Product Passports | EU *https://psqr.eu/publications-resources/all-about-dpp/*

[EU-DPP3] EU rules encouraging consumers to repair devices over replacing them | EU *https://www.europarl.europa.eu/news/en/press-room/20231117IPR12211/new-eu-rules-encouraging-consumers-to-repair-devices-over-replacing-them*

[EU-EPR1] EPR in Europe - where is it going? | Lorax EPI *https://www.loraxcompliance.com/blog/env/2021/08/06/EPR_in_Europe_-_where_is_it_going.html*

[EU-EPR2] Extended Producer Responsibility | EU *https://www.europen-packaging.eu/policy-area/extended-producer-responsibility/*

[EU-EPR3] Extended Producer Responsibility Essential Guide | Compliance Gate *https://www.compliancegate.com/eu-extended-producer-responsibility/*

[EU-ROHS] Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) | EU *https://environment.ec.europa.eu/topics/waste-and-recycling/rohs-directive_en*

[EU-RRPR] Right to Repair | EU
https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698869/EPRS_BRI%282022%29698869_EN.pdf

[EU-WEEE] Waste from Electrical and Electronic Equipment (WEEE) – EU
https://environment.ec.europa.eu/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_en

[GREEN-CIRC] What Percentage of Recycling Actually Gets Recycled? | Green Matters
https://www.greenmatters.com/p/what-percent-recycling-actually-gets-recycled

[GRNBZ-MSR] Why data and measurement are key to a circular economy | GreenBiz
https://www.greenbiz.com/article/why-data-and-measurement-are-key-circular-economy-transition

[GRNHS] Greenhouse Gas Protocol | Green House Protocol.org
https://ghgprotocol.org/

[GRWSH-BBC] BBC article: Coca-Cola and Nestle accused of misleading eco claims

[GRWSH-EACT] EuroActiv article: EU lawmakers back hefty fines for companies making false green claims.

[GRWSH-EU] Directive of the European Parliament and the Council on substantiation and communication of explicit environmental claims (Green Claims Directive)

[GTNR-SUST] 2024 Tech Provider Top Trends: Sustainable Business Grows Up, Gartner,
https://www.gartner.com/document/5023032

[HUD-DRB] Durability by Design 2nd Edition: A Professional's Guide | Huduser.gov
https://www.huduser.gov/portal/publications/reports/Guide-Durability-by-Design.html

[ISO-14040] Environmental Management ISO 14040 Series | ISO
https://www.iso.org/standard/37456.html

[ISO-CIRC] Circular Economy: Building Trust | ISO
https://www.iso.org/insights/circular-economy-building-trust

[ISO-DIS] ISO/DIS 59040 - Circular economy — Product circularity data sheet | ISO
https://www.iso.org/standard/82339.html

[JPN-CRBN] Carbon Neutrality | Government of Japan
https://www.japan.go.jp/global_issues/carbon_neutrality/index.html

[MDPI-CELM] Core Elements Affecting the Circularity of Materials | MDPI
https://www.mdpi.com/2071-1050/14/14/8367

[MDPI-CIRC] Circularity in Practice | MDPI
https://www.mdpi.com/2071-1050/14/2/962

[MDPI-SMM] Sustainability Maturity Model as a Driver | MDPI
https://www.mdpi.com/2071-1050/14/12/7483

[METI-GGS1] Green Growth Strategy Through Achieving Carbon Neutrality in 2050 | Japan METI
https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/pdf/ggs_full_en1013.pdf

[METI-GGS2] Green Growth Strategy Through Achieving Carbon Neutrality in 2050 | METI Ministry of Economy, Trade, and Industry
https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/

[MKSY-DAVOS] From-trials-to-triumphs-in-building-materials-circularity,-takeaways-from-davos | McKinsey
https://www.mckinsey.com/industries/engineering-construction-and-building-materials/our-insights/from-trials-to-triumphs-in-building-materials-circularity-takeaways-from-davos

[MKSY-MANF] Building sustainability in manufacturing operations | McKinsey
https://www.mckinsey.com/capabilities/operations/our-insights/building-sustainability-into-operations

[MWBST-RBT] Robot Definition & Meaning of Robot | Merriam-Webster
https://www.merriam-webster.com/dictionary/robot

[NIST-CIRC1] Circular Economy | US NIST
https://www.nist.gov/circular-economy

[NIST-CIRC2] Circular Economy in Manufacturing | US NIST
https://www.nist.gov/el/systems-integration-division-73400/circular-economy-manufacturing

[NIST-CIRC3] Fostering a Circular Economy of Manufacturing Materials | US NIST
https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=935977

[PLM-DM] Discrete manufacturing: Become a leader in sustainability | PLM Group
https://plmgroup.eu/articles/discrete-manufacturing-become-a-leader-in-sustainability/

[POLCY-GAP] The Circularity Gap Report 2023 | Policy Commons
https://policycommons.net/artifacts/3370831/63c5511395a3b8eba384baa9_cgr20202320-20report/4169635/

[PTC-DX] How Discrete Manufacturers Can Achieve Digital Transformation | PTC
https://www.ptc.com/en/blogs/iiot/how-discrete-manufacturers-can-achieve-digital-transformation

[PWC-EPR] The Extended Producer Responsibility (EPR) in Europe | PWC
https://www.pwc.ch/en/insights/sustainability/the-extended-producer-responsibility.html

[RECOUP] Packaging Recyclability & Design | Recoup
https://www.recoup.org/our-work/packaging-recyclability-and-design/

[SDG-CIRC1] How the Circular Economy Can Help Realize the Sustainable Development | Circular Economy Earth
https://circulareconomy.earth/publications/the-circular-economy-and-the-sdgs

[SDG-CIRC2] How the circular economy can help us | Circle Economy
https://www.circle-economy.com/blogs/how-the-circular-economy-can-help-us-reach-the-sustainable-development-goals

[SPR-CIRC] Circular Materials and Circular Design—Review on Challenges | Springer
https://link.springer.com/article/10.1007/s43615-021-00085-2

[SPR-EPR] Concretising the role of extended producer responsibility in EU | Springer
https://link.springer.com/article/10.1007/s12027-020-00596-9

[SPR-LITHM] Policies for Material Circularity: the Case of Lithium | Springer
https://link.springer.com/article/10.1007/s43615-022-00171-z

[TSTEP-MCI] Quantifying Circular Economy with the Materials Circularity Indicator | ThinkStep
https://www.thinkstep-anz.com/resrc/blogs/quantifying-circular-economy-with-the-materials-circularity-indicator/

[UK-CIRC] Circular Economy Package policy statement | GOV.UK
https://www.gov.uk/government/publications/circular-economy-package-policy-statement/circular-economy-package-policy-statement

[UK-EPR] What is EPR | Swiftpak
https://www.swiftpak.co.uk/insights/what-is-extended-producer-responsibility-uk-updated-2023

[UK-ROHS] Restriction of hazardous substances (RoHS) | GOV.UK
https://www.gov.uk/guidance/rohs-compliance-and-guidance

[UL-CIRC] Define-and-measure-product-circularity | UL
https://www.ul.com/resources/define-and-measure-product-circularity

[UN-CIRC1] The Ecology of Recycling | United Nations
https://www.un.org/en/chronicle/article/ecology-recycling

[UN-CIRC2] Circular economy indicators: what do they measure? | UNEP
https://www.unep.org/news-and-stories/blogpost/circular-economy-indicators-what-do-they-measure

[UN-SDG] UN Sustainability Development Goals | United Nations *https://sdgs.un.org/goals*

[WBCSD-IND] Circular transition indicators | World Business Council for Sustainable Development
https://www.wbcsd.org/Programs/Circular-Economy/Metrics-Measurement/Circular-transition-indicators

[WEF-CIRC1] Towards the Circular Economy | World Economic Forum
https://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf

[WEF-CIRC2] This is how we turn more industries into circular economies | WEF
https://www.weforum.org/agenda/2023/01/industry-circular-economy-change/

[WIKI-CIRC] Circular Economy | Wikipedia
https://en.wikipedia.org/wiki/Circular_economy

[WIKI-DMNF] Discreet Manufacturing | Wikipedia
https://en.wikipedia.org/wiki/Discrete_manufacturing

[WIKI_RPAIR] Repairability | Wikipedia
https://en.wikipedia.org/wiki/Repairability

10 AUTHORS AND LEGAL NOTICE

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