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Circular Economy Practices and Sustainable Business Models for Environmental Protection

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Abstract

Over the past two centuries, economic growth has been driven by the linear model of industrial production, characterized by 'take–make–dispose' cycles. The economic growth over the last 200 years has been based on the linear model of industrial production, which implies 'take–make–dispose' cycles. It has resulted in the waste problem, high rates of GHGs, and resource losses. The circular economy provides a way to keep products, parts and materials in use for as long as possible, at the greatest value. If technology is the solution, then circularity is out of reach – it needs business to change how create, add and capture value. This paper examines sustainable business models and circular economy practices that complement each other to strengthen environmental protection. It presents the theoretical foundation of the regenerative economy, based on recent research and literature, explores sustainable business models that move away from selling a product in favorfavor of keeping value in the service, and proposes a closed-loopclosed-loop industrial model. It is a framework that links circular design, sourcing, production, delivery, use, reverse logistics, and value recovery, and is supported by digital enablers and orchestration of the circular economy. The paper provides an overview of implementation patterns in the manufacturing sector and the electronics industry, as well as in resource-intensive sectors; it identifies barriers and potential for implementing ecological improvements; and it presents ways to monitor improvement. It also identifies systemic problems such as greenwashing, regulatory inadequacies, and the tension between short-term gains and long-term stewardship. It ends with guidelines for corporate leaders, policy makers, and further research.

Keywords: Circular Economy, Sustainable Business Models, Environmental Protection, Closed-Loop Supply Chains, Product-As-A-Service, Industrial Symbiosis, Greenwashing.

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Breaking the Linear Axis: The Imperative for Industrial Regeneration

Since the Industrial Revolution, the use of raw materials, the conversion into consumer items, the purchase of those items, the utilization and finally the disposal have been largely linear in the global economy. This was manageable, as nature was abundant and its capacity to absorb pollution seemed limitless. These are no longer true in today's society. The use of materials globally has grown markedly in the last few decades, and much of the material being extracted is lost after only a short period of use. Waste landfills are filling up, plastic is piling up in oceans and soils, and electronic waste is one of the fastest-growing waste streams in the world. Mining, processing, and shipping virgin resources not only emit GHGs, but also play an important role in reaching climate tipping points. Anthropocene is based on the recognition that the human impact is becoming a significant factor in the functioning of the Earth's systems. Now, biodiversity loss is closely linked to societies' modes of goods production and consumption, deforestation, water stress, and climate change.

Lamba et al., (2024) suggest that these pressures are what are driving the recent increase in research activity on the circular economy. A growing awareness is that sustainable development cannot be achieved if the economic system is based on natural resources assumed to be infinite—or if the environment is treated as an infinite waste receptacle. These business costs are also becoming more prevalent with the linear model. Companies relying heavily on virgin materials are at risk due to fluctuating commodity prices, the disruption of global commodity value chains, and increased environmental regulations. Whereas an effective system was once in place, an ever-growing economic and environmental risk is now being added, and businesses are beginning to understand that resource security and environmental performance are closely linked in the business environment and with long-term competitiveness.

The circular economy is based on the premise that the linear economic model should be overturned, treating waste as a design failure and a resource. Designing a circular system means designing products to last; to be repaired, upgraded, and redesigned; and to be disassembled for reuse of product components and materials. The ultimate objective is to divest economic activity from limited resources; to have economic development not go hand-in-hand with degradation of the environment. It's not just about the technical processes; it's about concepts, business models, and more. The paradigm shift from linear use of raw materials to closed-loop material recovery should change business models. Awan and Sroufe state that designing circular business models is synonymous with linking Value Creation with Sustainability Goals (Awan & Sroufe, 2022). Companies need to rethink product design, customer use, and material recycling. The analysis reveals that sustainability in the circular economy is not a question of incremental technical improvements but of interacting with the design options, organizational skills, and market conditions.

There are certain sectors which prove this. In the metal processing industry, Ingaldi and Ulewicz show how a circular business model can foster innovation and continuous improvement in the processes by encouraging material recycling and enhancing process efficiency and by-product utilization (Ingaldi & Ulewicz, 2024). Puntillo presents the case of waste management to the reader and empirical evidence of the direct impact of circular economy business models on Sustainable Development Goals (Puntillo, 2023). In this sector, waste is no longer considered a disposal problem, but also as a source of secondary raw materials and energy. At the international level, Chabowski shows that, in the world, innovations in sustainable business models are increasingly globalized (Chabowski et al., 2025). Circular value chains are transnational and must be synchronized between multinationals, suppliers, and institutions, which have different institutional settings. In sum, these studies indicate it is possible to make money out of garbage, but only by purposefully redesigning the business logic all along value chains.

However, the research on the circular economy is yet to be consolidated. Some studies are purely technical, for example, recycling processes, material flow analysis, etc.; others focus on business models or on policy instruments. There are very few studies that take a holistic approach to combine these points of view to connect theory, business practice and environmental outcomes (Lamba et al., 2024). The potential of circularity issues like greenwashing, rebound effects and the persistence of linear structures in organizations and markets are also under-studied in the literature. The paper will seek to address these gaps by examining the theory of change behind the contribution of circular practices and sustainable business models for the protection of the environment, the potential technical, organizational and stakeholder enablers, and finally the design of a 'closed loop' industrial framework and how it can incorporate these elements, while outlining what implementation challenges and systemic vulnerabilities need to be overcome to ensure that circular models move towards a real contribution to the environment. A conceptual and integrative study approach is adopted. It reviews the most up-to-date literature and builds a framework, which is then compared to the practice of implementation in a number of sectors. The second section provides a summary of theoretical foundations, the third section provides a summary of the framework, the fourth section discusses implementation issues and environmental measurement, the fifth section discusses vulnerabilities, and the sixth section discusses recommendations and directions for further research.

Epistemic Foundations: Mapping Circularity and Organizational Architecture

There are some older theories, which, when combined, constitute a lexicon of 'regenerative economics' that inspires the circular economy. Industrial ecology is the science of identifying the flow of materials and energy through industrial systems, and considers the industrial systems as ecosystems, where the waste from one process is used as an input to another. Industrial symbiosis uses this concept in groups of companies or in industrial parks, in which the by-products, energy, water, or services are exchanged between different companies, leading to a reduction in resource use and waste generation. Cradle-to-cradle design implies that the materials of the product are engineered to circulate safely and indefinitely; the design should start from the first moment of the product. Every biological material is added to nature as nutrients, and every technical material is added with high quality as inputs in industry. These two constructs are both of a more regenerative nature rather than just trying to reduce environmental harm and impact.

Atstaja expands on this lexicon and discusses the sharing model in the circular economy (Atstaja et al., 2022). The lighter the usage of the products, the more the products have to be manufactured to meet the same need. Platforms, sharing of equipment, and collaborative use are thus an important aspect of the use of circular practice. These thoughts have one thing in common: One of the most important points to remember about secondary materials is that if there is no secondary material collection system, sorting equipment, or markets for secondary materials, then a product is not worth much if it is recyclable. Regenerative economics needs to be studied systematically together with both the bigger picture of how companies fit into it, and how companies relate to each other.

Organizational structures that are created to span the gap between the principles of circularity and market activity are called sustainable business models. A business model is an illustration of how a business plans to propose, create, deliver, and capture value. In a traditional linear model, emphasis is placed mostly on product sales, which disincentivizes the firm from shortening the product's useful life and, to some extent, even from selling more. Circular business models do this. Product-service systems are also referred to as product-as-a-service, where the cost of the product is not charged, but the function or performance of the product is charged, such as lighting, mobility, or machine uptime. Direct financial interest in promoting products that are durable, retrievable, and maintainable is placed in the provider as the product remains his or hers. Value is not destroyed when it gets to the point of sale and the business' focus shifts from sales to services.

The relationality of the value creation in circular business is highlighted by Tapaninaho & Heikkinen, (2022). It is based on the power of firm-to-firm, supplier-to-firm, customer-to-firm, community-to-firm, and regulator-to-firm relationships. The idea of circular value is created together with stakeholders. Suppliers are responsible for providing products that can be recovered, customers for returning products at the end of their useful life, and partners for managing reverse flows efficiently. Businesses that effectively manage these relationships can turn to the opportunities of circularity in the economy and the environment. Digitalization is an acceleration of this transition. In the digitalization era, Agrawal suggests that there is a definite link between the circular economy and sustainable performance of businesses (Agrawal et al., 2022). It proves that digital technologies can be used to trace the products, monitor the use, and co-ordinated reverse logistics, and consequently improve environmental and economic outcomes for the enterprises. The concept of the circular business model is not only applicable in manufacturing companies but, as shown in the case of the sustainable tourism platform 'Ecobnb' created by Del Vecchio et al., (2022) it can also be used in other sectors. Digital platforms can engage and support travelers in sustainable accommodation, and support sustainable behaviors in a service ecosystem.

There are a number of foundations; however, there are some gaps in the literature. First, it has to do with scalability. Numerous small-scale, local, and/or sector-specific circular programs have been successful. As pointed out by Försterling, there are high financial, regulatory, technological, and cultural hurdles to the transition to a circular economy in Europe using new business models (Försterling et al., 2023). Pilot projects remain rather unknown in terms of becoming a mainstream practice. The second loophole is with regard to rebound effects. Efficiency gains from circular practices can be negated by increased total consumption, for example, when lower-cost refurbished products or 'easy' sharing models increase overall consumption (Atstaja et al., 2022). Models and digital platforms can increase convenience and boost demand, but assessments of circular benefits rarely incorporate them (Del Vecchio et al., 2022). The third blind spot is that of systemic lock-in. Corporate structures, infrastructures, accounting systems and supply contracts have been designed for linear production and can be barriers to circular practices even when companies decide to be circular. Although there is little guidance available on how to change an organization as a whole, good stakeholder relationships and digital capabilities can help to overcome this lock-in (Tapaninaho & Heikkinen, 2022). The following section introduces a framework to fill the gaps, which combines technological, organizational and ecosystem aspects into one architecture.

Architectural Blueprint: Engineering Closed-Loop Industrial Systems

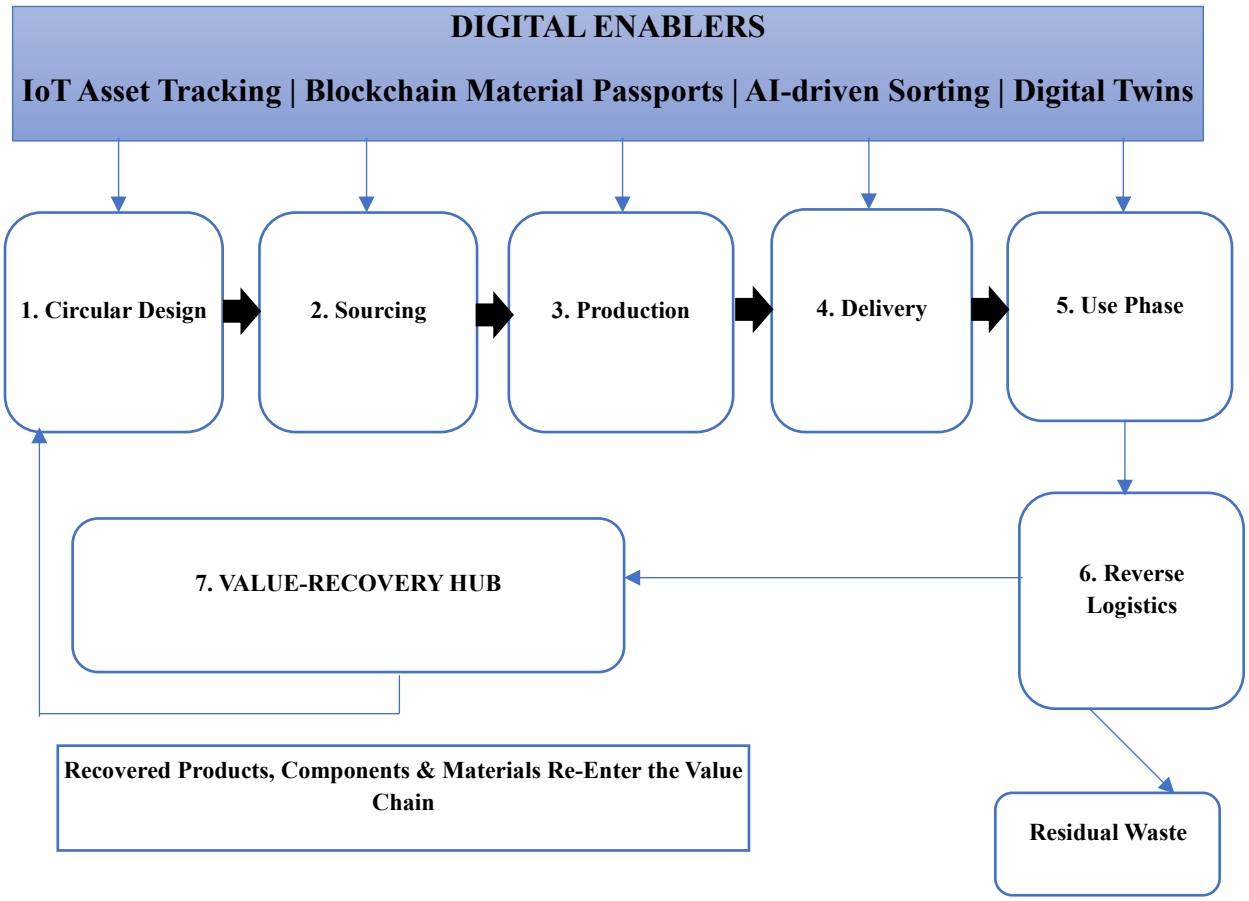


Fig. 1: Closed-Loop Circular Industrial Framework Integrating Digital Enablers and Value Recovery

Fig. 1 shows seven stages, each of which is linked to the others: circular design, sourcing, production, delivery, use, reverse logistics, and value recovery. The modular design, renewable inputs, clean production, and service-based delivery support resource efficiency. Monitoring and maintenance are used to extend the product life, and reverse logistics ensures the return of the product for reuse, repair, remanufacturing, upcycling, and recycling. By returning recovered products, components, and materials to the value chain, residual waste is minimized. Digital enablers like IoT tracking, blockchain material passports, AI sorting, and digital twins help to exchange information and coordinate operations. Ecosystem orchestration connects all of the above elements together and helps to enable collaboration across the circular production-consumption system, as a tool for facilitating sharing.

As shown in fig. 1, a closed loop of a circular industrial system is proposed. It has seven stages that are linked together with a layer of digital enablers above and a layer of ecosystem orchestration below. The most important aspect of the whole system is the design stage – most of the environmental impacts of a product will be decided at the design stage. In this context, the concept of eco-design is that of modules, standardized components, easy dismantling, use of non-toxic, recyclable materials, and the possibility of upgrading or repairing. The second phase is sourcing, with emphasis on recovering materials from other product cycles over a prolonged period of time, as well as renewable sources, resulting in a reduction of virgin materials. On the third level, production, clean and low-waste production processes are used; by-products are taken and, if possible, reused with other companies through the concept of industrial symbiosis.

The fourth stage is delivery. Here, Circular Business Models are preferred, like Product-as-a-Service, Leasing and Sharing, where the owner of the product remains in the background, and the provider is responsible for the product for its life. The use phase is the fifth phase, where the products are maintained in good working order during the life cycle via monitoring, preventive maintenance, and timely repair. The sixth step is the collection of products at the end of the use cycle through take-back schemes, return points, and collection networks (Reverse logistics). But in many

cases, the biggest drawback in the circular system is reverse logistics, since downstream activities must rely on a steady stream of returns to be carried out at scale.

The last stage is a value-recovery center to process returned products based on the hierarchy of value retention. Going further down the product chain, the more have to minimize the processing of the whole product, and the less the "embedded value" will be retained through reusing and repairing. Remanufacturing is the process of bringing used products or components back to like-new condition, and usually includes a manufacturer's warranty, as do new items. Upcycling is the process by which the recovered materials or materials with a new function are used to create value-added products. The raw materials are recovered; this is called recycling. It adds value, but it has the least embedded value because the product's form and function are lost. Finally, the products, parts, and materials recovered are returned to the value chain, thus closing the value chain. Any remaining waste is considered residual waste, and the framework aims to minimize it.

Digital technologies enable the closed loop, as give the information circular systems need at each step in the process. Internet of Things tracking uses sensors placed in products and assets to capture location, condition, and usage. The data can help the service provider plan routine maintenance before a failure occurs in product-as-a-service models, time returns, and estimate the value of the components left in the product. It also enables reverse logistics with product displays of where products are and when it can be collected. A blockchain-verified material passport is an electronic record detailing the components, source, maintenance, and ownership of material products. If the record is kept on a distributed ledger, it becomes tamper-proof and can be shared across the value chain without any risk that it will be tampered with. Recycling and remanufacturing companies can then sort materials correctly, and remanufacturers of secondary materials can verify that the material is high quality and comes from a reliable source.

However, the universal challenge of recycling waste to a high-quality standard is sorting mixed waste streams, and artificial intelligence can address it. Compared to manual sorting, the computer vision and machine learning systems on sorting lines are faster and more accurate in identifying materials, polymer type, and polymer components to enhance the purity and market value of recovered materials. Digital twins are virtual models of products, processes, or facilities that are continually updated with real-time data, so a company can test different product designs, production changes, and recovery plans before making changes in reality, reducing waste from experimentation and trial and error. The best technologies are when they're connected. The material passport, passport-based sorting decisions, and digital twins optimize the entire product life cycle through IoT data feeds.

No single company can close material loops on its own. Key to circular systems is the collaboration between the involved parties: designers, producers, logistics providers, recyclers, customers, financiers and public authorities. The framework thus has four pillars that are built on the orchestration layer. The first is a standard for product design, material classification, and data formats, enabling the movement of parts and materials across companies and industries without incompatibility issues. The second is data transparency, which involves the data-sharing agreements that outline the information that will be shared, who will be involved, and the circumstances. These arrangements aim to balance openness with the protection of any business confidentiality. The third is cross-industry symbiosis: relationships between companies connected to industrial parks or industrial platforms and sectoral associations whose by-products and needs complement each other regionally. These exchanges typically occur through a coordinating actor (usually a park manager, industry organization, or public agency). The fourth is policy alignment, aligning private incentives with the circular objective through extended producer responsibility, green public procurement, recycled content requirements, and tax incentives. Together, these foundations form a unified and sustainable circular system.

To complement the conceptual framework, a simple analytical model of material loops is introduced. Let r be the fraction of material that would be recovered and re-entered the value chain at the same quality at the end of each use cycle and let n represent the number of cycles in the loop. After the first cycle, one unit of virgin material provides one unit of service, after the second cycle one unit of service is provided, after the third cycle r^2 units of service are provided, and so on. The cumulative service multiplier is therefore $S(n) = 1 + r + r^2 + \cdots + r^{n-1} = \frac{1-r^n}{1-r}$, which approaches $S_\infty = \frac{1}{1-r}$ as n grows. The theoretical ceiling value increases dramatically from 2 units of service per unit of virgin input to 10 when the recovery rate goes from 0.5 to 0.9. The functionality of the circular design, reverse logistics and value-recovery capacity should therefore be assessed based on r, as the same gain when recovered at high percentages is much more valuable than when recovered at low percentages.

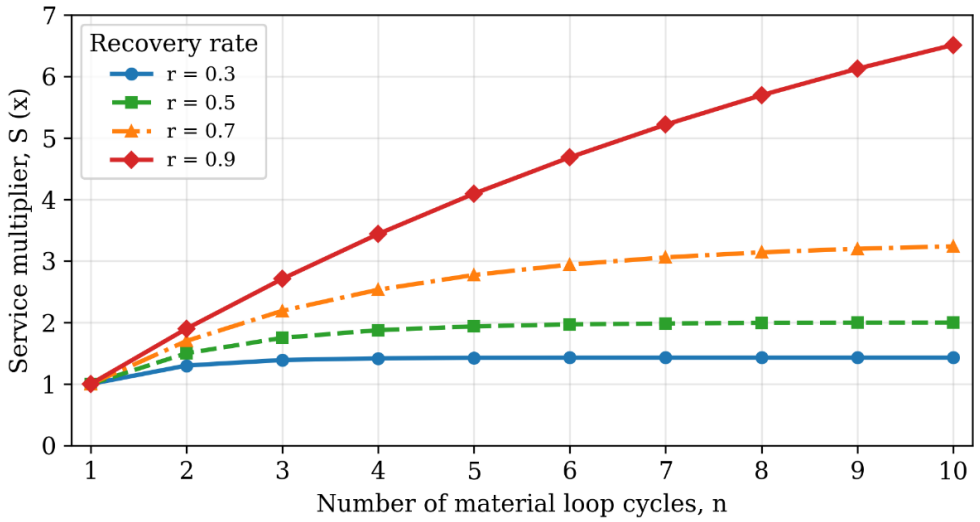


Fig. 2: Cumulative Service Multiplier of One Unit of Virgin Material across Loop Cycles at Different Recovery Rates

The number of material loop cycles (n) is plotted on the horizontal axis and the service multiplier $(S(n))$ on the vertical axis as shown in fig. 2, where $S(n) = \frac{1-r^n}{1-r}$. Four curves show the recovery rates of 0.3, 0.5, 0.7 and 0.9; each starts at a value of one, since first cycle always recovers exactly one unit of service. If the recovery rate is 0.3, the curve will level off quite rapidly around 1.4, so that after $2-3$ cycles, weak collection systems will waste a majority of the embedded material. If $x = 0.5$, then the ceiling is two; if $x = 0.7$, then the ceiling is about 3.3. The curve for 0.9 continues to climb up to ten cycles and remains capped at ten indicating that the highest return is achieved by using high recovery, but having many repeated cycles. The figure strongly backs the framework focus on reverse logistics and value recovery, as improving collection and recovery quality benefits more than just additional efficiency in one direction. Values are indicative and based on models and should be changed with measured recovery values if they can be found in the sector. Practitioners are able to read the figure, placing their present rate of recovery on the graph and indicating on the graph how many further cycles they can realistically expect for their product category.

Empirical Realities: Industrial Implementation and Environmental Impact

Different implementation patterns can be considered in the context of the framework across sectors. The practice of remanufacturing has existed for some time in industries like manufacturing, heavy equipment, particularly the automotive parts, industrial machinery, and construction equipment sectors. All engines, gearboxes, and hydraulic parts are returned, disassembled, cleaned, rebuilt, and resold, often with the same warranties as new parts. The use and reverse logistics and value recovery stages of the framework have similarities with this practice. It is based on the generation of incentives to return used components (deposits, exchange schemes, etc.) and on product designs that allow for easy non-destructive disassembly. The electronics industry is characterized by fast product changeovers and multi-component material formulations, which contain precious and critical metals. Take-back schemes, refurbishment programs, and modular designs where used batteries/screens can be replaced are becoming more popular. Notwithstanding, many devices are still glued together and made of mixed materials, which makes recovery still difficult in the informal collection systems. The key is circular design and reverse logistics, which is what this experience focuses on.

Another is the idea of creating an industrial symbiosis network. Another example is the eco-industrial parks (KALUNDBORG in Denmark is an example of this) where the potential for exchanging by-products (such as steam and water) and gypsum (between neighbor companies) is shown. The networks form part of the production and orchestration elements of the scheme, and are based on a high level of trust and a strong sense of geographical proximity with collaboration stretching back many years. Other examples are in areas such as lighting, office equipment, floor coverings, tires and industrial tools, which also feature product-as-a-service business models, sometimes not with the sale of products, but of the performance. The provider owns the product and also gets it back at the end of the contract, therefore recovering profits through durability and also recouping the product. In all these

areas, there's a uniform theme. The loop is best when design, delivery model, and reverse logistics are all planned in conjunction, and it is most likely to fall apart in the collection process, as it is usually the weakest link.

But there are a few common problems that hinder implementation. One of the most important constraints is capital constraints. Initial investments are common to circular models, for example, in the redesign of products, recovery centers, digital systems, and reverse logistics systems. In the product-as-a-service model, the service provider also has the asset on the balance sheet, and generates revenues over a period of time in staggered amounts throughout the service term. Businesses, especially SMEs, might lack the capital to make such investments, and traditional lenders might not have experience with the risk factors involved in circular business models. The second barrier is the fragmentation in the supply chain. Global value chains are not only full of independent global actors with different standards and incentives in the countries of origin, but it also makes it difficult to coordinate return flows across global value chains. The information about materials that is contained on the way from one owner to another is often lost, which hampers recovery of valuable materials.

Thirdly, there is consumer behavioral inertia. Ownership is more desirable than access for many consumers, second-hand/remanufactured products are sometimes seen as a lower quality product, and products are not easily returned. Lower returns decrease the economic rationale for recovery and reduce the materials that can be remanufactured and/or recycled. These behavioral changes must be supported by systems that make returns easy, provide information on product quality, offer quality-management assurances, and, in some cases, provide monetary rewards. The fourth one is again the poor quality and availability of secondary materials, and it remains unclear. These can differ greatly, and producers do not want to adopt them as substitutes for virgin materials. This uncertainty can be reduced through common standards, certification schemes, and material passports. Finally, many companies are used to a linear production process and lack the skills and expertise to develop service design, reverse logistics, remanufacturing, and data management; developing these skills and expertise will take time and continuous investment.

Table 1: Core Circularity Performance Indicators, Typical Formulation, Related Framework Stage and Desired Direction of Change

Indicator	Typical formulation	Related stage	Desired change
Lifecycle carbon footprint	kg CO_2-eq per functional unit, cradle to grave	All stages	Decrease
Landfill diversion rate	Waste diverted ÷ total waste generated × 100	Value recovery	Increase
Recycled content share	Recovered input ÷ total material input × 100	Sourcing	Increase
Resource productivity	Economic value added ÷ material consumed	Production	Increase
Product value retention	Residual value after use ÷ original value × 100	Use, delivery	Increase
Hazardous material and water use	Mass of hazardous input and water per unit output	Design, production	Decrease

Six indicators are listed in table 1, which together reflect climate, waste, material and economic performance. The first column identifies the indicator and the second column provides a typical version of the indicator, which can be used to replicate the calculation by firms. The lifecycle carbon footprint represents emissions per functional unit from extraction to end of life and should reduce as re-use and remanufacturing costs reduce the need for new production. The landfill diversion rate and recycled content share are the measures of the output and input side of the loop and are expected to rise. Resource productivity is the economic value added per unit of material consumed which indicates value creation in the absence of resource consumption. Product value retention is the measure of the value of a product after use, influenced by durability and maintenance. Use of hazardous materials and water should be reduced, as the benefits of other environmental categories should not be harmed by circular gains. The third column connects each indicator to the most dependent stage of the framework and the fourth shows the direction of the change desired. When combined, the indicators minimize the chance of a single good number masking the deterioration in some other area. These measures should be reported on a yearly basis in sector studies using well-documented system boundaries, assumptions and data sources to ensure consistency in results by firm, sector and year reported.

The same can be said for the climate benefit of the recovery. The average emissions after n use cycles for a new product are $E(n) = \frac{E[1+(n-1)\rho]}{n}$, where E is the emissions from a new product and ρ is the reduction in emissions per use cycle of a remanufactured product. The linear model (where the cycle must always contain a new product) remains constant at E, while the remanufacturing model with an average of d gradually decreases and approaches ρE, where the larger the saving, the more intense the remanufacturing. The calculation does not include emissions from transport and take-back, which will be added in practice, but demonstrates the importance of durability and multiple uses in comparison to the emissions from one recycling operation.

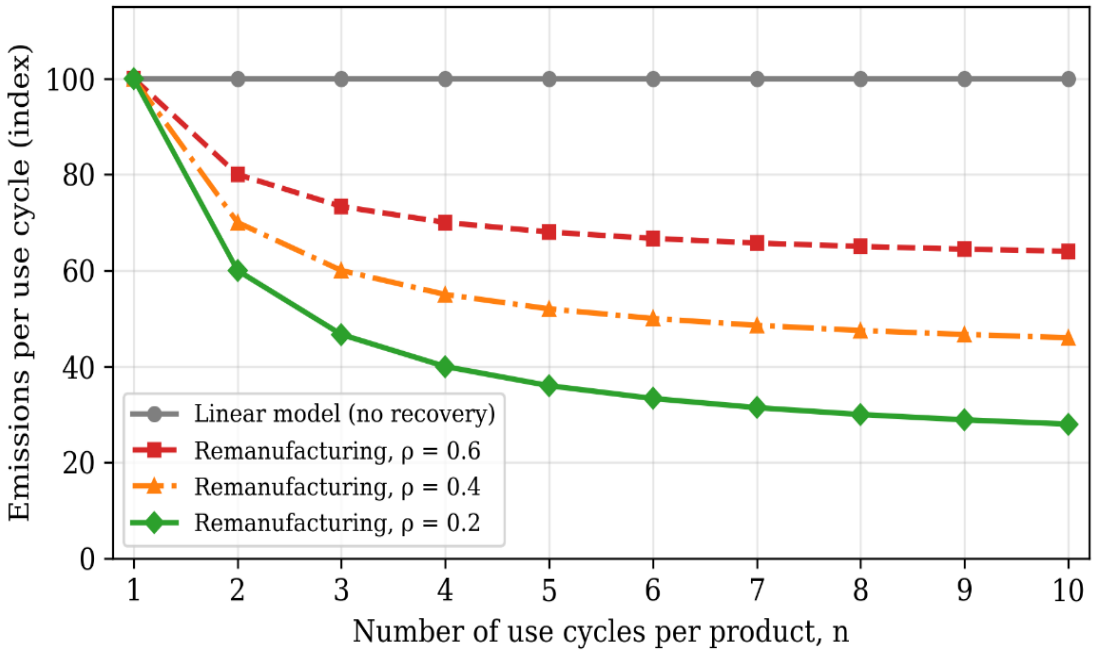


Fig. 3: Average Emissions per Use Cycle for Linear and Remanufacturing Pathways at Different Remanufacturing Intensities

Figure 3 presents the number of use cycles per product on the x-axis, and the average emissions per use cycle in an index format (with the linear model as a reference of 100) on the y-axis. The grey line represents the linear baseline and the value remains the same for each cycle because it is always a new product being produced. The other three curves are for remanufacturing intensities of 0.6, 0.4 and 0.2, following the relationship $E(n) = \frac{E[1+(n-1)\rho]}{n}$. The first unit is always made new hence all start at 100 in the first cycle. They then drop fast; most saving takes place in the first 4 cycles, and level off as they get close to their maximums of 60, 40 and 20. The indices after 10 cycles are approximately 64, 46 and 28. It shows that the most significant reduction in emissions in relation to the figures is from the long product life and repeated remanufacturing; and the process impact of each step in remanufacturing decides the final saving. Transport emissions have been omitted from the values, which are stylised. The curves can be used by the manager to estimate the number of cycles required to achieve the desired reduction and can also be used to compare alternative designs in a systematic way prior to an investment in remanufacturing capacity.

Virgin extraction is dependent on the growth of demand and recovery at the system level. When the total material requirement is increasing with time as $D(t) = D_0(1+g)^t$, and a fraction r of this is recovered with a process efficiency η, the virgin demand is $V(t) = D(t)(1-\eta r) = D_0(1-\eta r)^t$. Even with a high recovery rate, a growing economy means that virgin extraction will still increase at rate g: in a growing economy, a high recovery rate can only reduce the rate of increase in virgin extraction but still leave virgin extraction increasing at rate g. This is why it's important to put circular practices into the context of sufficiency measures, as discussed in the section on systemic vulnerabilities.

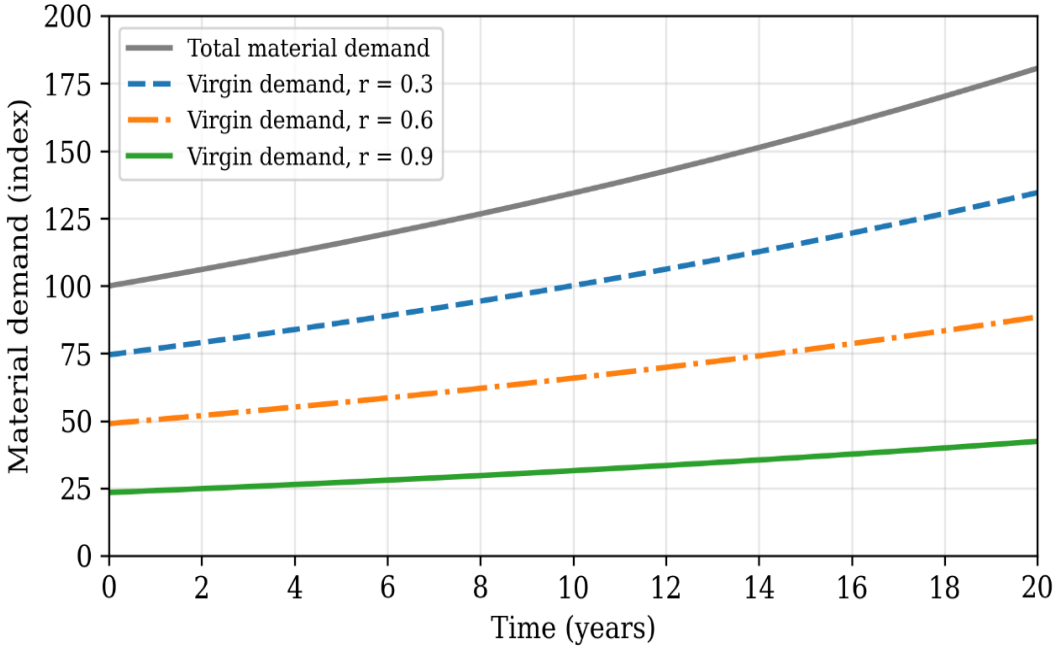


Fig. 4: Projected Virgin Material Demand over Twenty Years under Alternative Recovery Rates with Three Percent Annual Demand Growth

Fig. 4 presents time in years on the horizontal axis and material demand as an index on the vertical axis, with year zero set to 100. The grey curve is total demand, which grows at three percent each year, reaching about 181 after twenty years. The other three curves show virgin demand, calculated as $V(t) = D(t)(1 - \eta r)$ with a recovery efficiency of 0.85, for recovery rates of 0.3, 0.6 and 0.9. The curves are separated clearly: virgin demand starts at about 75, 49 and 24 and ends at about 135, 89 and 43. Higher recovery therefore reduces virgin extraction in every year, but none of the curves is flat, because each rises in parallel with demand. Even at a recovery rate of 0.9, virgin use in year twenty is higher than at the start. The figure demonstrates that circular practices lower the level of extraction rather than reversing its trend, and that growth in consumption must be limited if absolute environmental gains are desired. All values are illustrative model outputs. The comparison between the curves also shows how much recovery effort is needed to offset a given rate of demand growth over time under realistic growth conditions.

Having clear indicators of the impact of circular practices prior to and after the transition is crucial. The lifecycle carbon footprint – calculated from extraction to production to use and end of life – shows whether the circular practice has a positive or negative impact on the climate. When using reuses and remanufactures, the emissions that would have occurred during manufacture of new materials are generally reduced, as the energy expended in the materials and manufacturing process is retained. The landfill diversion rate is the percentage diversion of waste from Landfill and incineration to reuse, remanufacture, and recycling, and is one of the most effective ways to measure the success of the loop. Material circularity indicators allow companies to track and measure performance over time and can be used to benchmark products, including key components of the use of recovered materials, life extension, and end-of-life recovery. Resource productivity measures the value a firm generates for every unit of resource it consumes and can serve as a yardstick for how the firm decouples value creation from resource consumption. Product value retention can be determined by product life and use intensity. Use of dangerous materials and water use are also monitored, as these are impacts on the environment other than carbon and waste.

These indicators should be used in conjunction with each other. A transition that increases the recycling rate and increases the overall consumption may not result in overall environmental benefits. Measurement should also be in terms of methods of lifecycle assessment that are recognised and in this way claims can be credible and comparable between firms and sectors. To solve the greenwashing issues discussed in the next section, the best thing to do is to have a credible and transparent measurement.

Systemic Vulnerabilities: Governance, Greenwashing, and Structural Trade-Offs

Circular economy practices are increasingly gaining momentum and companies are increasingly tempted to "green wash" by announcing that have a recycling programme or a take-back scheme as an indication that in full transition. Lacks of independent verification, reporting with a high percentage of facts and figures, a high degree of recycling and vague claims lack trust. Common metrics, disclosure, third party certification and challenges can help separate fact from fiction in circular progress.

However, it is not possible to defend a never-ending consumption under circularity. Recovery processes involve using energy, creating environmental impacts, and leaving a reliance on virgin materials. So, other sufficiency measures like the reduction of use or product longevity must be combined with efficiency, reuse and recovery.

Policy instruments can also prevent the circular practices if waste categories prevent waste from being shared or if products in these categories have not been remanufactured in the product specifications. If waste is taxed at lower rates than the repair of the products, then waste can also be profitable. The most important priorities for reform are: Set clear criteria for recovered materials; Repair rights; Expand producer responsibility; Product information systems; Circular public procurement.

Tension is created by economic and ecological goals. Initial investments required for redesign, recovery infrastructure, recovery service models and benefits over time. Short-term goals and cash flow issues could be obstacles to adoption. In the interim, pollution and resource depletion costs are not being measured and the linear production is becoming more cost competitive. Commercial decisions for environmental performance incentives, financing for patients, transparent reporting and environmental pricing of appropriate harm can drive sustainable resource conservation and make lasting circular transformation.

Horizons Ahead: Strategic Synthesis and Future Trajectories

The circular economy together with business models, technologies and ecosystems promote environmental protection. Circularity is systemic when approached with the concept of industrial ecology, symbiosis and cradle to cradle design and sharing models. Profitability and durability - through Product-as-a-service and stakeholder value co-creation - and recovery. The proposed framework is to connect 7 stages: From circular design through value recovery, using digital technologies and Ecosystem coordination. It's not an easy journey to implement, as it involves integrated design, delivery and reverse logistics, but also presents capital investment challenges, weak value chain integration, consumer behaviour and capability challenges.

Focus needs to be placed on the concepts of modularity, reparability, safe materials, and viable leasing, sharing and service options, all facilitated by corporate leaders. Foster circular performance through greater convenience of take-back programs, recovery partnerships and digital tracking, and through lifecycle transparency. Policymakers need to prioritize improvement of repair rights, producer responsibility, and green procurement and environmental claims. Smaller companies benefit from industrial symbiosis platforms, fiscal incentives to avoid waste and pollution of resources and finance and technical assistance platforms.

The framework should be replicated in other industries, other regions and be related to measurable environmental outcomes, as well as be linked to critical moments. Bio-synthetic materials, decentralized repair/remanufacturing centres, employment impacts, informal waste workers, affordability and rebound impacts are priorities. To alleviate the overall environmental stress and contribute to sustainable transition towards fair circular production and consumption, citizens, researchers and policy makers must cooperate as well as companies.

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