THE 2021 WORLD MANUFACTURING REPORT

DIGITALLY ENABLED CIRCULAR MANUFACTURING

WORLD MANUFACTURING FOUNDATION

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2021 World Manufacturing Report: Digitally Enabled Circular Manufacturing

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WORLD MANUFACTURING REPORT

2021

DIGITALLY ENABLED CIRCULAR MANUFACTURING

Foreword

Dear Readers,

In recent years, the World Manufacturing Foundation has been undertaking activities that promote industrial culture worldwide. Owing to the long history of holding the annual World Manufacturing Forum, the World Manufacturing Foundation acts as a dynamic platform, bringing together stakeholders confronted with the evolving paradigms of manufacturing.

The first *World Manufacturing Forum Report: Recommendations for the Future of Manufacturing*, published in 2018, presented our vision for the future of manufacturing. The *2019 World Manufacturing Forum Report: Skills for the Future of Manufacturing* analysed the skills gaps phenomenon in the sector. Last year, the *2020 World Manufacturing Report: Manufacturing in the Age of Artificial Intelligence* provided insights on the successful and trustworthy adoption of Artificial Intelligence in manufacturing.

This year's edition will focus on Digitally Enabled Circular Manufacturing. The Report analyses the state of play in circular manufacturing, the potential of digital technologies to enable circular manufacturing, and policy and other enablers for circular manufacturing. The Report also outlines key recommendations, developed with a global group of experts, addressed to the manufacturing community and society at large to promote digitally enabled circular manufacturing.

This whitepaper and its key recommendations were presented and discussed at the 2021 World Manufacturing Forum held on the 20th to 21st of October, 2021. The Forum, entitled *Digital Technologies as Key Enabler for Circularity: Perspectives on the Future of Manufacturing*, was attended by manufacturing stakeholders from all over the world.

The World Manufacturing Foundation, through the World Manufacturing Report, commits to producing high-quality and non-partisan content on relevant themes and issues in manufacturing. I hope that this white paper will promote the importance of circularity in companies, for policymakers, in academia and society at large, and spur action to support digitally enabled circular manufacturing.

I thank the 2021 World Manufacturing Report Editorial Team and Advisory Board for their valuable contribution.

Prof. Marco Taisch
Scientific Chairman, World Manufacturing Foundation

WORLD MANUFACTURING REPORT

2021

DIGITALLY ENABLED CIRCULAR MANUFACTURING

Index

Executive Summary

The *2021 World Manufacturing Report: Digitally Enabled Circular Manufacturing* presents the state of play in circular manufacturing, identifies the applications of digital technologies to support circular manufacturing, analyses the key policy developments and enablers for circular manufacturing, and outlines key recommendations for a successful transition to digitally enabled circular manufacturing.

The circular economy paradigm is becoming increasingly relevant as more and more companies realise the real value and profitability of this new, more sustainable way of doing business. The circular economy relies on several strategies that extend the product life cycle through reusing, recycling, remanufacturing, and redesigning circular products and materials, with a view to reducing waste. This Report identifies key drivers to the circular economy, which include global initiatives such as the UN Sustainable Development Goals and other policy developments, innovation, collaboration across stakeholders, and business drivers. However, challenges need to be addressed such as the uptake of new business models, adequate standards and laws, and financial incentives, among others. Nevertheless, the benefits for manufacturers are profound, such as increased economic opportunities for manufacturers, a reduction in waste, the creation of more and better jobs, and a contribution to alleviating climate change.

Digital technologies are an important catalyst to achieve circularity in manufacturing value chains. Digitally enabled circular manufacturing supports three key objectives: resource efficiency, waste reduction, and reduced emissions. As outlined in the Report, digital technologies can support the transition to circular manufacturing at the firm level - which includes product development, production, and new business models - as well as at the network level.

The transition to circular manufacturing is a priority for many governments globally. Regional and national strategies to promote circularity vary in ambition, approach, and the emphasis put on the enabling role of digital technologies. The Report identifies key enablers for the circular manufacturing transition. Enablers at the consumer level include environmental awareness, increasing trust and transparency in relation to service providers, convenience and accessibility of sustainable products, and digital literacy. At the company level, enablers include demand for sustainable products, digital technologies, and circular skills, among others. At the value chain level, there is a need to improve data sharing, enhancing infrastructure and networks, and standardisation of requirements.

Finally, a set of Ten Key Recommendations addressed to manufacturing stakeholders have been outlined to achieve digitally enabled circular manufacturing. These recommendations focus on key topics such as promoting a circular mindset and instilling responsibility among consumers, enacting policies that address challenges related to a digitally enabled circular transition, building a proficient workforce with the right skillsets and competencies relevant in the changing paradigm, and promoting collaboration to build circular value chains.

Project Methodology

The World Manufacturing Report is a yearly whitepaper discussing key trends in the manufacturing sector.
To develop the Report, the World Manufacturing Report Editorial Team worked alongside an Advisory Board composed of individuals from universities and other organisations from more than ten countries. During the process, an extensive review of existing literature on the topic of circular manufacturing was undertaken; this includes scientific journals, policy papers, and other materials published within the last five years. These materials are complemented by expert interviews, which were also used to develop the Ten Key Recommendations outlined this report.

Experts come from multinational companies and SMEs, industry and trade associations, renowned universities and research associations, international organisations and governmental and non-governmental organisations. Experts were asked to provide their personal views on the main topics covered in the Report, focusing on their area of expertise.

This year's Report also features case studies written by Young Manufacturing Leaders. The Young Manufacturing Leaders initiative, co-funded by the European Union under the EIT Manufacturing Initiative, aims to create a global network of students and young workers interested in a career in the manufacturing sector. The YML Network issued an Open Call for case studies that highlight the use of digital technologies to support circular manufacturing and the winning contributions are included in this Report.

1

Circular Manufacturing State of Play

Circular Manufacturing - State of Play

As an emerging paradigm in the context of zerowaste, Circular Manufacturing perpetuates the reuse of resources in the form of materials and energy via an ingenious design of socio-technical systems and effective use of information to deal with challenges such as resource scarcity, waste generation, pollution, biodiversity loss, and climate change by managing the whole life cycle of a manufactured product from inception, through engineering design and manufacturing, to service and recovery, thus sustaining future businesses.

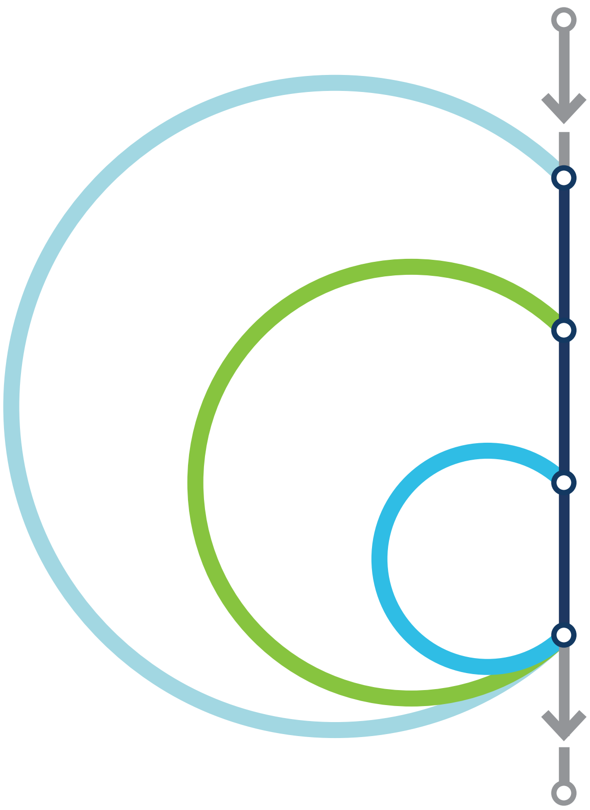
To date, there is no precise, comprehensive, and universally accepted definition of the circular economy, with many countries using their own interpretations or concepts developed by relevant organisations. This may potentially affect coherent international action, consistent application of guidelines and policies, and synergies between actions of different stakeholders. Nevertheless, the circular economy is fast becoming an active and rapidly expanding mainstream trend as ever more companies realise the real value and profits of this new, more sustainable way of doing business. A regenerative model in which manufacturers find ways to use materials and goods for a much longer time period, creating more than one product life cycle, fuelled by new digital technologies and new financing models (as well as technologies in general and entire business models), is driving forward this great innovation: the circular economy for manufacturers. This kind of innovation constitutes the core of what it means to be human: enabling wealth creation and success but with respect for the planet, supporting its survival for future generations. Manufacturers are really at the core of this new revolution and their efforts to shift to circular models, as some are starting to do, represent one of the greatest innovative challenges of our times. Besides, manufacturers can influence consumers' consumption attitudes through their value propositions to customers.

The circular economy relies on several strategies that extend the lifespan of products and eliminate waste through reusing, recycling, remanufacturing, and redesigning circular products and materials.[1] This shift in thinking impacts every part of the value chain and creates

Figure 1

Circular Economy Diagram

(Source: Closed Loop Partners)[2]



Extraction	− **Raw Materials**
Material Supply Chain	+ **Reduce material inputs** + **Replace with renewable materials**
Design & Manufacture	+ **Design for quality, durability and longevity** + **Use safe chemistry and healthy materials**
Distribution & Use	○ **Reuse** ○ **Repair** ○ **Rent & resell**
End of first file	○ **Remanufacture** ○ **Recycle**
Disposal	− **Waste to landfill**

a framework (Figure 1) for manufacturing companies. The future of manufacturing will see a gradual development towards a high-quality circular manufacturing industry, in which the demand for scarce raw materials is met by raw materials from the value chain wherever possible, considering the following five strategic goals[3] (Figure 2).

Figure 2

Five Strategic Goals of Circular Manufacturing

(Source: World Manufacturing Foundation)

- Redesign products and materials selection suitable for reuse[4]: The shift towards a circular economy starts with rethinking the initial design and manufacturing of the product, considering the product's second life reutilisation or the recyclability of materials. An example of this could be shifting from critical raw materials such as metals and minerals to generally available raw materials for increasingly complex products.

- Conserve and recover resources from the used products, and use them in the manufacturing of new products[5]: Increasingly, manufacturers are seizing new opportunities offered by the Internet of Things and in some cases, shifting to a more service-based model in the process. In this regard, manufacturing companies should develop processes and systems for taking back and refurbishing goods for a second life cycle. Here, the tracking technology could revolutionise manufacturers' ability to do this. They need to understand the material flows of their products, so that they can plan and facilitate the next cycle. This new capability is driving revolutionary change among manufacturers, many of whom are already keen to use it to optimise production processes and improve customer service.

- Develop new ways of production[6]: The demands of Circular Manufacturing imply change to materials, machines, products, and processes, all of which impact job design. The future global economy of products and services calls for large volumes of primary raw materials and energy. To that end, there is a genuine need for new production systems that use sophisticated printing technologies and includes products made of self-healing and shape-shifting materials that can prolong their shelf life.

- Implement a service-based model for circular products[7]: Along with the supply side, the demand for circular products and services will need to increase in order to complete the circular business cases. Companies and governments play a key role in this by adopting socially responsible procurement. In the past, manufacturers have sold assets to customers. However, in a world where you want to minimise waste, it is far better for the producers to retain ownership, instead selling a service to the customer. For customers, this tends to mean they get a better service overall with maintenance and quality at the heart. Manufacturers in turn can ensure they service and maintain the product and keep it in a good condition, prior to its next cycle.

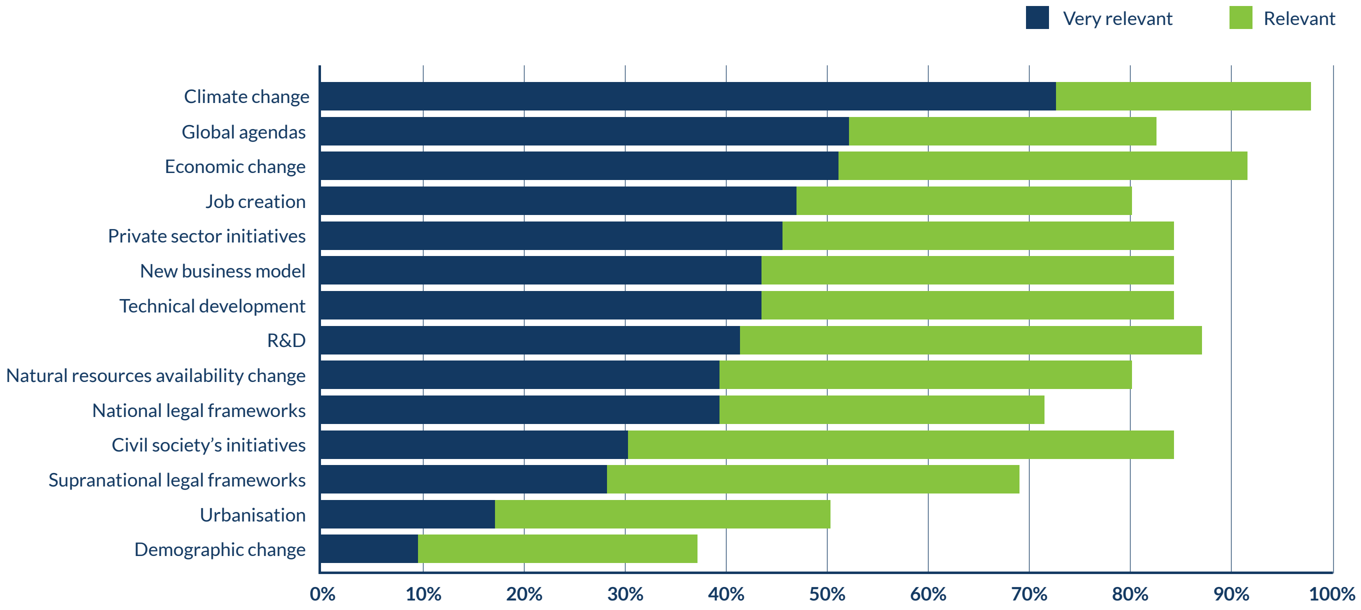
- Shift from fossil to renewable raw materials and eliminate use of toxic chemicals[8]: The circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and business models. For instance, it will soon be possible largely to replace fossil carbons by short-cycle carbons. This has already been achieved on a small scale with heavy chemicals such as ethanol, methanol, butanol, and acetic acid. When properly used, this contributes to reducing CO_2 and reduces dependency on scarce or volatile raw materials.

Drivers of the Circular Shift in Manufacturing

Figure 3

Drivers of the circular economy

(Source: OECD)



According to the results of the OECD Survey on the Circular Economy in Cities and Regions[9] (Figure 3), major drivers for transitioning to a circular economy are environmental (climate change, 73%), institutional (global agendas, 52%) and socio-economic (changing economic conditions, 51%). Besides, as highlighted in Figure 3, this circular shift is driven by job creation (47%), private sector initiatives (46%), new business models (43%), technical developments (43%), and research and development (R&D) (41%).

In this Report, we consider and classify the most important drivers as follows: sustainable development goals, innovation, policy, collaboration across stakeholders, and business drivers.

Sustainable Development Goals

The circular economy contributes to the achievement of the Sustainable Development Goals adopted by United Nations Member States.

The 2030 Agenda for Sustainable Development, adopted in 2015 by UN member states, includes 17 SDGs[10]. The circular economy appears to be a promising approach for achieving various goals. While it is strictly linked to SDG 12 on sustainable and responsible consumption and production patterns, other SDGs (i.e., 6, 7, 8, 9, 13, 15) are also relevant to the circular shift. Besides, it is key to supporting the global framework set out in the Paris Agreement.[11] Circular Manufacturing in the context of the UN 2030 Agenda and the Paris Agreement is discussed in Chapter 3: *Policy Developments and Enablers for Circular Manufacturing*.

Innovation

New technologies, materials, and delivery models support and enhance circular manufacturing systems.

New technologies offer vast opportunities for transforming the way we do business. In a circular economy, these technologies are driving new ways of creating value for both emerging and established businesses alike.[12] These new technologies offer unprecedent opportunities to implement a circular economy. Examples of these implementations could be AI for managing a product's life cycle, collaborative robotics and automation for sorting,

Figure 4

Sustainable Development Goals

(Source: United Nations)

disassembly, and remanufacturing in safe and competitive conditions as well as new processes and biomaterials.
One of the key factors to determine the life cycle of a product is its materials and place of origin. Thus, for circularity there is now a significant focus on material science innovation to re-evaluate what goes into products for a carbon-free future. [13]

Compared to traditional purchasing models, the innovative side of circular manufacturing regarding the business model is transferring ownership back to the manufacturers and producers in the form of leasing and subscription models.[14] In such models, companies sell their products as services and consider their products as valuable assets worth investing in.

Business Drivers

Companies need to change business models, regulatory environments should provide appropriate frameworks, and consumers need to shift their behaviour and mindset.

For a circular economy, all stakeholders should be engaged and have an important role to play. Through stakeholder engagement and an update of traditional business models, the circular economy can contribute to transforming the corporate culture to ensure the concurrent enhancement of economic, social, and environmental dimensions.[15] A successful transition to the circular economy depends largely on consumers, as they are the ones to demand sustainable change, and in turn create business opportunity. Few consumers make that step on their own, but new initiatives to help them are emerging. Services such as repairing, and refurbishing are gaining momentum and provide an alternative to replacing broken or outdated consumer goods. The option of sharing is also growing. This shift in consumer mindset motivates companies to distinguish themselves by offering products that can easily be repaired, instead of those made from components that are no longer available. One other example of this could be offering appliances (e.g., a washing machine) for which the consumer pays for the use instead of for the ownership. These products can then be replaced or refurbished when their end of life is near, or when the consumer's situation changes and they require a different product.[16]

Besides, market forces are important for advancing the transition to circularity. Investment is the necessary driver here in accelerating this advancement by encouraging innovation and enabling transformative companies to bring their solutions to scale.

Collaboration across Stakeholders

Partnerships align interest among multiple stakeholders and lead to a system-wide change.

In a complex global system, the circular economy includes every part of the value chain. The shift toward circularity is a collaborative effort and is not possible to be achieved by any one actor, company, or industry alone. Therefore, unprecedented collaboration across multiple stakeholders is required to align the interests of all manufacturing actors including customers, shareholders, business partners, and local communities as well as protecting the environment. In this regard, collaboration among multinational corporations is extraordinarily powerful. Besides, public-private partnerships and global commitments are of great importance for accelerating the circular economy. Las but not least, data sharing for manufacturing is an important enabler of collaboration among stakeholders. [17] Furthermore, manufacturers have a special role in circular transition. Since they can decide on product design, they control the manufacturing chain and can be focal actors in the reverse chain.

Policy

Legislation fosters circularity, resilience, and inclusivity across cities and countries.

Circular economy requires a holistic view to be effective. Policies make this happen from the very top. The role of policymakers is to create a suitable legal framework to enable circular economy businesses and set a vision for providing incentives to get diverse stakeholders on board. Hence, for achieving a successful circular economy, policies should be designed to support affordable and inclusive business models, and to consider all the risks new systems could pose. The importance of education, role of legislations, and allocation of investments are key factors that should be considered for designing effective policies to shift towards circular manufacturing.

Challenges Towards Building a Circular Economy

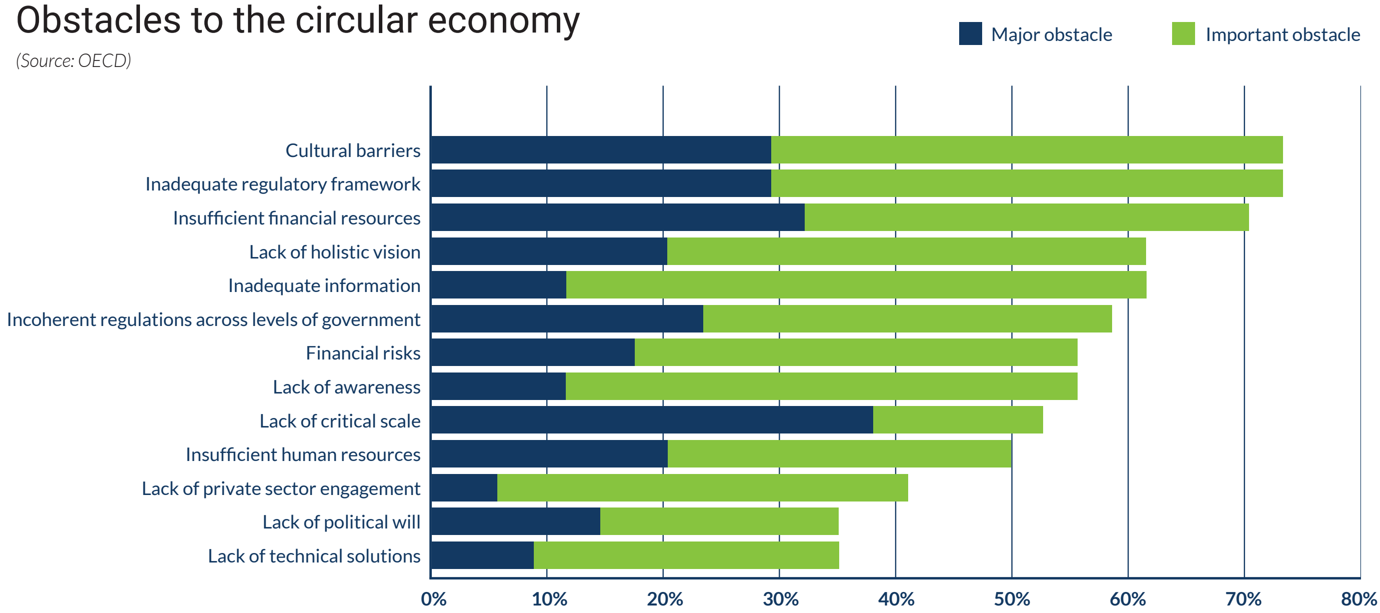
The transition to a circular economy presents a number of challenges.

Such challenges are, for example, linked to the uptake of new business models, adequate standards and laws, financial incentives, innovation, behavioural change, improved waste management, knowhow, and administrative capacity, among others. Major challenges towards building a circular economy are not related to the lack of technical solutions. Instead, lack of critical scale, cultural barriers, inadequate regulatory frameworks, and a lack of financial resources have been signalled as "major" obstacles by more than a third of the governments interviewed in the OECD Survey (Figure 5).[9]

Figure 5

Obstacles to the circular economy

(Source: OECD)



From the perspective of developing countries, some of the main challenges they face are as follows: insufficient understanding of potential benefits by key stakeholders; inadequate incentives for the private sector and lacking enabling environments for investment; lack of consumer awareness; a gap between respective policies and their implementation on the ground; and insufficient coordination between government agencies dealing with industry, economic, environment, waste and natural resources management issues.

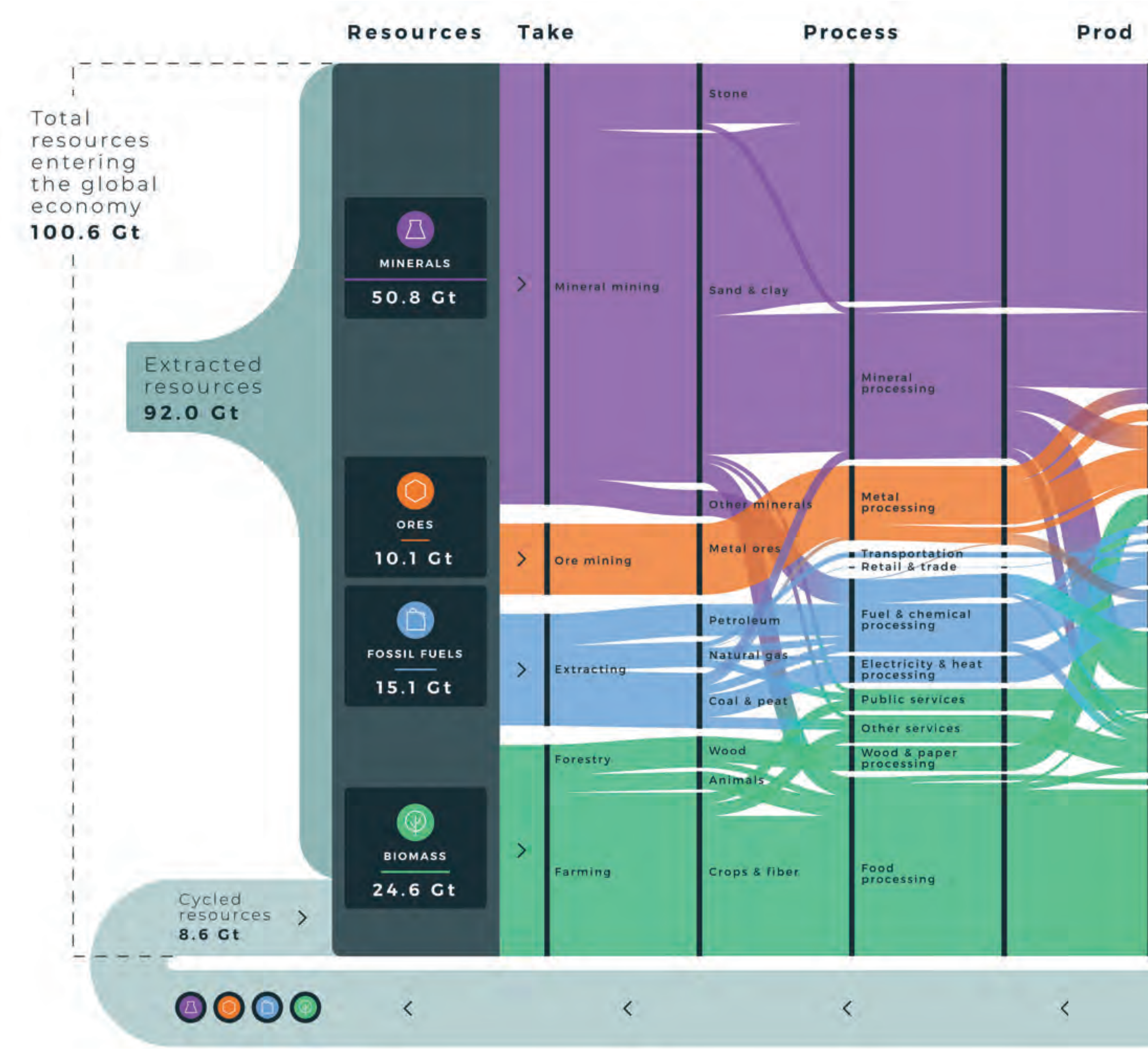
There are also several business-related and technical challenges towards building a circular economy. The major challenges of such are as follows[18]

- Quality issues in recycled materials
- Supply chain complexities
- Coordination problems between companies

Figure 6

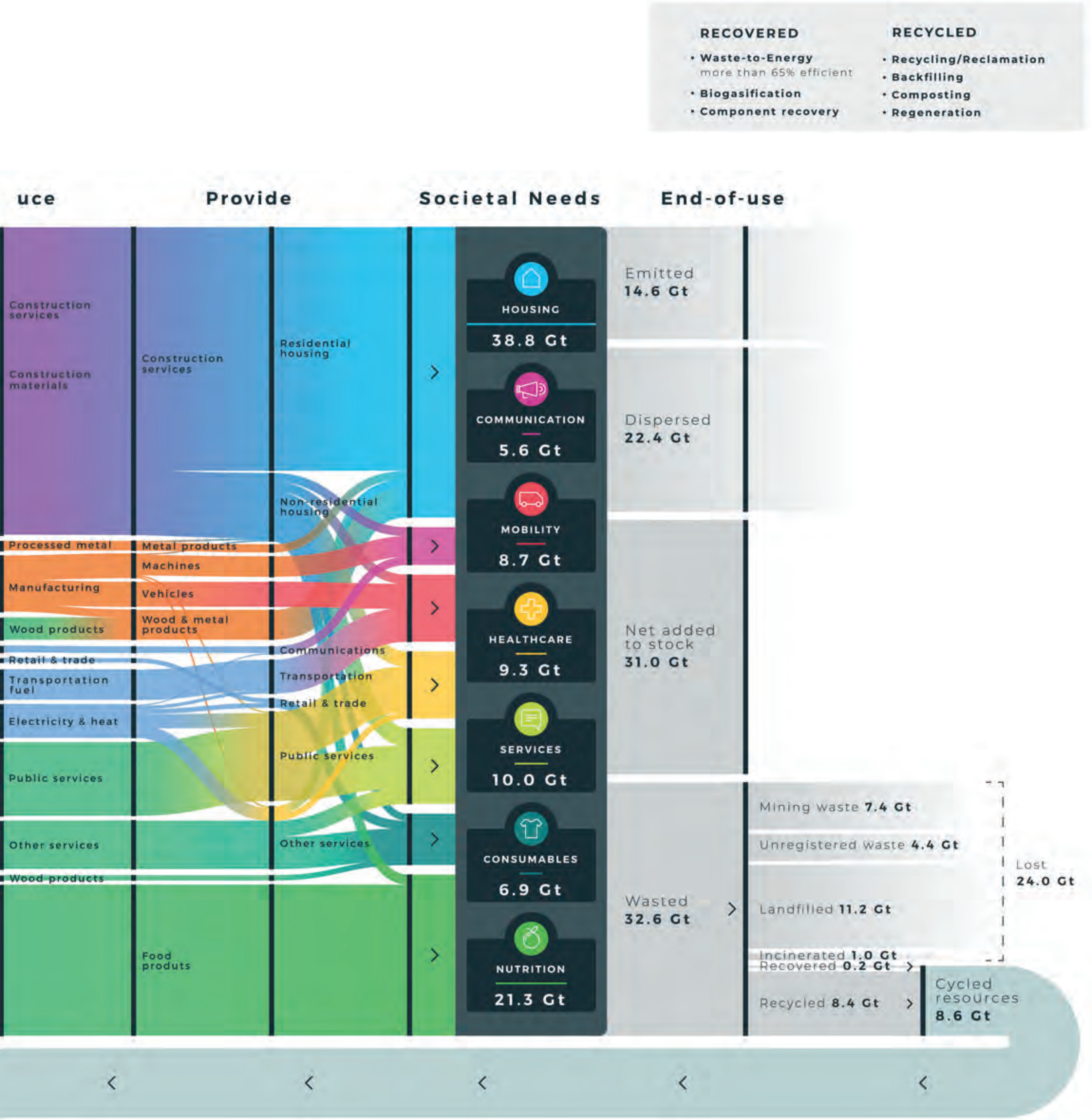
The global resource footprint

(Source: Circle Economy)



- High start-up/investment costs
- Increasing complexity in design and production of the product
- Poorly developed markets of secondary materials
- The issue of re-using and remanufacturing parts and components, which needs the establishment of cross-sectoral reuse chains
- Disassembly of products
- Insufficient monitoring approaches to follow the development of the circular economy

Furthermore, the circularity gap is widening. The latest Circularity Gap Report[19] from Circle Economy shows that, faced with the dual challenges of increased CO2 emissions and increased resource extraction, the global economy is only 8.6% circular (Figure 6).



Benefits of Adopting Circular Strategy

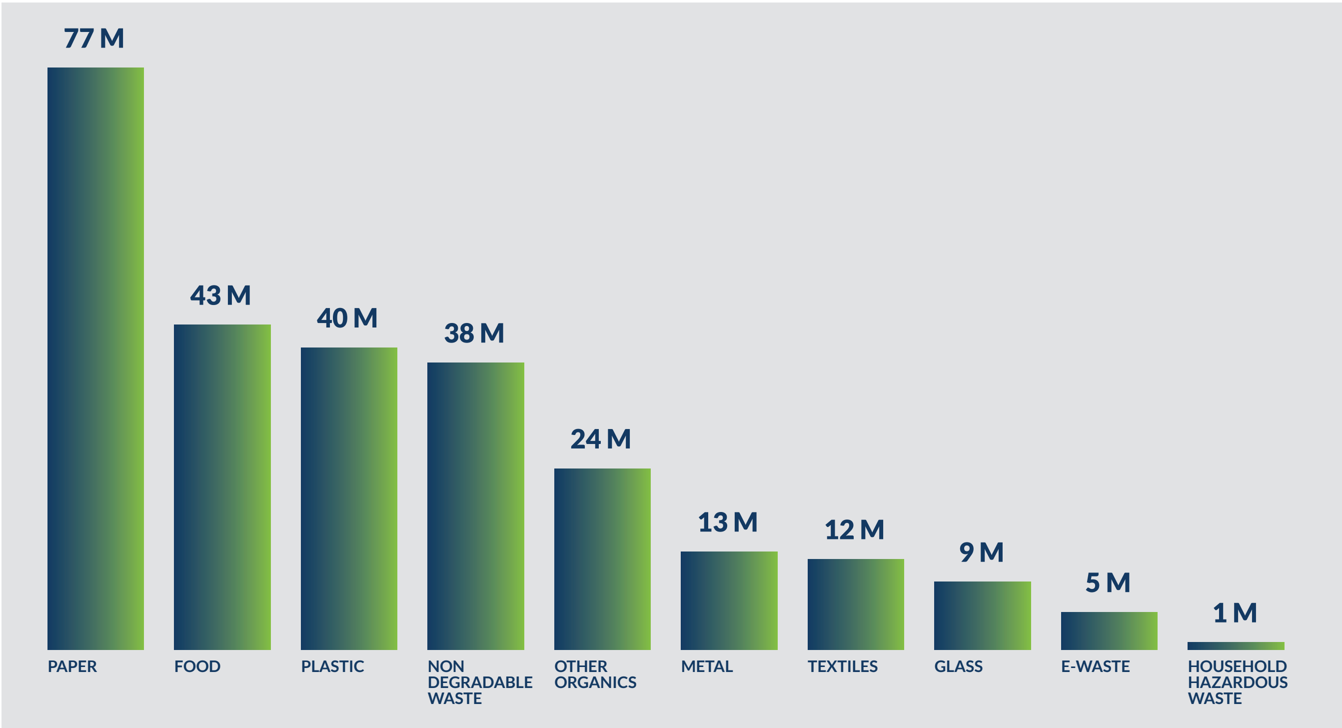
Circular Manufacturing keeps valuable materials out of landfills and in manufacturing supply chains, leading to significant economic opportunities.

Figure 7 illustrates the materials landfilled in the United States in 2018.

Figure 7

Materials Landfilled in the U.S. in 2018

(Source: Closed Loop Partners)



Hence, there is a significant economic opportunity and benefit of circular manufacturing for keeping these valuable materials out of landfills and in manufacturing supply chains.

The circular economy is a new socio-economic paradigm whereby resources and products are used for as long as possible and waste is minimised.

90 billion tonnes of primary materials are extracted and used globally each year, with only 9 percent recycled[20]. It is one of the European Union's key priorities to minimise waste as outlined in the European Green Deal (2019)[21], setting an ambitious roadmap towards a climate-neutral and circular economy, raising opportunities and providing investment directions for a wide range of economic sectors. Eliminating waste from the industrial chain by reusing materials to the maximum extent possible promises production cost savings and less resource dependence.

Circular Manufacturing is gaining momentum as a mechanism to tackle climate change and improve environmental sustainability by treating waste as a resource.

A circular economy model is based on the idea that there is no such thing as waste and aims to design out waste. To that end, products are designed to last and optimised for disassembly and reuse. New business models based on waste prevention and resource efficiency for circularity lead to cost savings, and increased turnover. Global and national strategies are also proving useful as are global agendas such as the 2030 Agenda for Sustainable Development. Such a model reduces greenhouse gas emissions and the use of raw materials, hence making better use of finite resources and decreasing resource dependency.

Increased revenues from new circular activities fosters economic growth.

Decoupling economic growth from resource consumption is key to achieving economic benefits in circular models. Increased revenues from new circular activities, along with a reduced cost of production due to more functional and easily disassembled and reused products and materials, fosters economic growth.

Transitioning to a circular economy could create more and better jobs.

According to a 2018 report by the International Labour Organization concerning world employment and social outlook[22], transitioning to a circular economy could create a net increase of 6 million jobs by 2030. Making the most of this opportunity will require a clear focus on social and environmental justice. Jobs may be lost in more linear businesses; however, new jobs will be created in fields such as recycling, services like repair and rental, or in new enterprises that spring up to make innovative use of secondary materials. Whilst a net increase in jobs is important, another value-add of circularity is the opportunity to provide formal work and improved working conditions for informal labourers.

The circular economy boosts biodiversity and protects human health.

The circular economy is key to halting biodiversity loss as it provides some of the most effective tools for tackling the root causes and getting more value from what is available. Furthermore, reducing the use of primary resources, utilising higher quality materials and products, as well as moving towards a greater use of renewable energy, lead to several positive health implications.

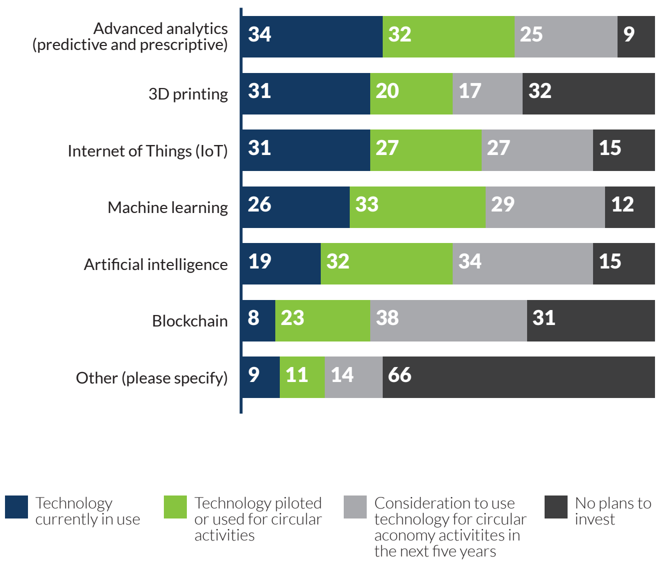
Overview of Enabling Technologies in the Circular Economy

In a digital circular economy, digitalisation supports better coordination and connection of material and information flows via technical solutions such as sensors, automated platforms, the Internet of Things or blockchain applications.[23] The results of a recent Gartner survey[24] highlight four key technologies that advance the circular economy activities of organisations: advanced analytics, 3D printing, the Internet of Things (IoT) and machine learning (ML). Only a few organisations are currently using blockchain but planning to explore the use of blockchain for the circular economy in the next five years (see Figure 8).

Figure 8

Digital Technologies Used to Enable Circular Economy Activities

(Source: Gartner)



% of respondents | n = 786
Source: 2019 Gartner Future of Supply Chain Survey

Internet of Things (IoT)

The manufacturing industry has been using sensors and devices as part of IoT projects in order to improve efficiencies, detect and prevent issues before they occur and maintain products remotely. Remote monitoring is becoming the norm, with manufacturers now seeking to extend this to improve the customer experience to build brand loyalty. IoT platforms collect data from sensors on products and support companies use analytics for the following purposes [25]:

- Understand how their products are being designed and manufactured aligned with more sustainable goals (e.g., using more sustainable and reusable materials as part of the build process)

- Track the provenance of the materials to ensure their sustainable credentials and reduce the impact of counterfeit parts
- Determine which sensors provide the best data and where they should be used to design products with reuse and repair in mind
- Reduce waste by checking water wastage and other materials used in the process
- Track any failures once they are in use with customers and to assess and prevent issues before they arise

Blockchain

Transition to a successful digital circular economy requires transparency and trust, and blockchain has the potential to build that trust. Blockchain's design supports two main uses for the Circular Economy: proving product origins and incentivising positive behavioural change.[26] Blockchain is the foundational technology for building transparent digital supply chains and enables greater transparency of product origins that fosters positive consumption and triggers companies to change their behaviour in terms of how they procure resources.

Blockchain has the potential to tokenise natural resources by giving them a unique digital identity, and this makes the value of resources more apparent, facilitating a new system of pricing and trading natural resources, and incentivising people to adopt circular behaviours. Rewarding circular, consumption or disposal adds motivation beyond the somewhat abstract need to protect our planet.

3D Printing

3D printing disrupts the traditional manufacturing model in a major way, and enables consumers to print products locally, on demand, by downloading design information from online marketplaces. Moreover, additive manufacturing technology is uniquely capable of promoting an essential aspect of the circular economy, i.e., environmentally sustainable product life cycles. 3D printing has proven effective in recent years at enabling companies to embrace distributed production, and this leads to environmental benefits such as less waste, improved process efficiency, and reduced emissions from transportation.

Another important characteristic of 3D printing is the possibility to manufacture products with a lighter structure and also to design different pieces in only one run without assembly. Furthermore, 3D printing minimises the waste in production, since it prints only what is necessary. Other strengths of 3D printing for the CE include the capability to flexibly repair, remanufacture and refurbish parts, and the possibility to use recycled printable materials.

Artificial Intelligence (AI)

The pivotal idea behind AI applications for circular manufacturing is to manage resources efficiently, and in a compliant and sustainable. In that respect, AI can enhance and facilitate circular economy innovation across industries in three main ways[27]:

Circular Product Design: The rapid machine learning-driven prototyping and testing gives rise to the development of new products and materials that fit the purpose of a circular economy.

Circular Business Models: Data-driven AI approaches such as pricing and demand prediction, intelligent inventory management, and predictive maintenance significantly improve product circulation.

Circular Infrastructures: Artificial intelligence approaches are immensely useful for closing the loop on products and materials by establishing the required reverse logistics infrastructure and circular economy processes such as products disassembly, remanufacturing of components, and recycling of materials.

Clean Technologies

Clean technology, also known as cleantech, green technologies, Greentech, eco-innovations, ecotechnologies and Ecotech, are part of a sustainable development outlook that includes new products, services, technologies and processes that significantly reduce negative impacts on the environment (environmentally effective) while offering users superior performance at a lower cost (economically superior) and helping to improve quality of life by optimising resource use (socially responsible). Clean technologies are particularly interesting from a circular manufacturing perspective, since they allow the transformation of residues into resources (water, energy, etc.) that can be reinserted into the manufacturing processes.

Circular Manufacturing 4.0

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Humanity faces dramatic challenges, as humanity is exhausting nature's budget progressively each year. At the same time, waste is growing exponentially; consumption reduction, reusing and recycling are no longer options but vital for sustainable human activities on earth. Hence, recovery and management of end-of-life (EOL) products and pollution reduction are becoming increasingly important for industry and open up new business challenges and opportunities for many industries in the manufacturing supply chain.

The concept of a circular economy aims to address these issues by closing the material loop across the full supply chain towards sustainable economic and environmental development[1], and it will allow the world economy to potentially earn close to a trillion US dollars per year. The circular economy is not limited only to the recycling of raw materials, but it encourages the reuse, remanufacturing and recycling of EOL products, thereby at the same time aiming to contribute to a fairer social economy and an improved quality of life for future generations. Yet, although it emerged decades ago, significant barriers prevent its full adoption in the manufacturing industry. Major impediments are a lack of information on the product life cycles and shortage of technologies for circular manufacturing strategies. Further, due to their ever-shorter lifecycles and planned obsolescence, high technology products become obsolete rapidly making reuse by repair no longer a viable option. The emerging manufacturing paradigm Industry 4.0 – key are smart factories in which flexible manufacturing entities communicate across the supply chain – seems to be an excellent solution.[2] However, research on taking advantage of Industry 4.0 technologies (e.g. Internet-of-Things (IoT)) to unlock the full potential of circular manufacturing is just starting and concrete case studies are lacking.[3]

Besides intelligent approaches for disassembly, remanufacturing, and recycling, the implementation of closed-loop supply chains (CLSCs) needs to be considered by manufacturers to ensure recovery of EOL products. To overcome issues regularly encountered using CLSC approaches, e.g. the large uncertainties in the product flows due to the unpredictable conditions of the EOL products, the use of intelligent IoT strategies would allow the collection of data throughout complete product life cycles to define the most optimal processing to be applied upon product recovery. An academic case study on a real-world product (modular smartphone – Fairphone-2®) was recently developed considering a novel CLSC model based on a prediction of the state of EOL product degradation using different levels of product IoT device implementation.[4]

The proposed models' objective is to maximise the manufacturing company's profits by using the knowledge of the EOL product's condition as provided by the IoT device implemented (e.g. Cloud service connected sensors). It could be shown that significant gains can be made by the manufacturing company when full implementing such IoT devices. In addition, the study presents a flowchart to support managerial decisions on optimal CLSC design policy execution, opening up the possibility of such intelligent CLSC strategies for real business implementation.

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Barriers to Circular Economy and Solutions for Manufacturers

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In the Circular Economy (CE), the concept of waste should no longer exist as it is systematically considered as a resource. Accordingly, circular business models aim to keep products in productive use for longer (durability and repairability) or to recapture waste in "loops" (remanufacturing and recycling) to retain the value embedded in materials. However, circular business models are exceptions rather than an industrial norm and our society is still largely linear.

The number of CE examples is growing fast, but they are often experimental, isolated cases, and difficult to scale up. Besides these inspiring stories, there is also much to be learnt from difficulties encountered in less successful (or failed!) projects. To support manufacturers in their sustainability efforts, we need to better understand the barriers they face in adopting circular and eco-efficient solutions for more responsible production and consumption patterns.

Although CE concepts largely align with resource efficiency and broader sustainability issues, they do not automatically lead to environmental benefits as there can be trade-offs and rebound effects. Furthermore, the social and economic dimensions of sustainability are less directly linked to CE practices. Thus, it is critical to consider carefully the sustainability of circular and service-based business models in a holistic manner. Life cycle methods and composite sustainability indicators can assist in such assessments.

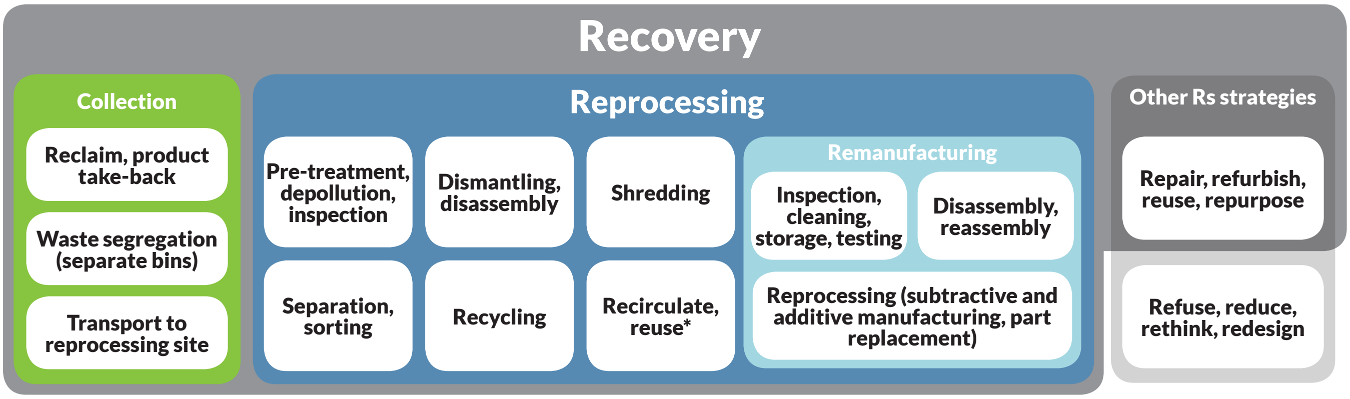
Circular material flows are often considered externally with a strong focus on end-of-life products; i.e., diverting consumer goods away from disposal and bringing them back into productive use. In other cases, the focus is on industrial symbiosis with an exchange of waste and by-products between industrial actors. However, there are eco-efficient and circular opportunities within manufacturing systems which should not be overlooked. For example, increased sourcing of renewable, recyclable, non-toxic and locally abundant materials, waste reduction and valorisation on-site with cascade reuse of resources, wastewater recirculation and reuse, internal material recycling and energy recovery, etc.

Circular strategies and practices (Fig. 1) associated with different loops often target multiple parts of the value chain simultaneously. At a macro level, transitioning towards circular industrial systems requires complex structures, often relying on collaboration between organisational functions and between stakeholders along the value chain. This complexity presents challenges to creating procedures to formalise and coordinate collaborative efforts. This is especially crucial for information sharing between end-of-life (recyclers and remanufacturers) and beginning-of-life stakeholders (designers and manufacturers), which is often missing, thus limiting the ability to develop efficient circular solutions in the future. Relevant stakeholders along the value chain must be connected to feedback information necessary for the development and continuous improvement of recovery processes.

When the recovery processes are handled by the original manufacturer, lack of information is less of an issue, although the product complexity can still present challenges at a micro level for efficient reprocessing. In addition, returning products as well as closed-loop material flows are characterised by higher uncertainty, thereby requiring more flexible manufacturing systems to accommodate input quality and quantity variability.
Remanufacturing tasks also require high levels of skills and knowledge; thus, operator support and training (reskilling and upskilling) are needed. Digital solutions can provide an enabling platform facilitating knowledge transfer and information flows to and from the process to support the continuous improvement of circular processes.
The materials or products can also be difficult to transport and store; for example, in the case of voluminous, time-sensitive, condition-critical materials which may require

Fig. 1

Circular strategies and practices



continuous monitoring. When adequate transport and storage infrastructure are not in place, products may lose some of their value before reaching the stage where it can be recovered. This is especially the case when the benefits of value recovery are distributed in ways that do not incentivise investments in such infrastructure. Collaboration across the supply chain is therefore necessary to promote value retention and share the benefits amongst stakeholders.

At a micro level, products are not always designed to fit in a CE, especially with the trends of miniaturisation and multifunctionality. While these trends have also brought about dematerialisation and a higher value per unit of resource consumed, they often require energy-intensive processes and increase the inherent complexity of products. Thus, the recovery processes can be too inefficient or costly, compared to linear alternatives, to be attractive. Product structure and component assembly can make it difficult to disassemble in a non-destructive manner, limiting the ability to repair and remanufacture, and mixed materials can be difficult to separate, limiting the ability to recycle them. New reprocessing technologies and processes can be developed to overcome such barriers.
However, the ideal approach remains the integration of circular solutions and environmental considerations in the product design and material selection so that they can be reprocessed with minimal mechanical, thermal and chemical treatment. When the material and processes are hazardous with adverse health and environmental effects, standardised procedures must be in place to ensure they are handled adequately and reprocessed safely and efficiently. Automation is often an attractive solution; however, material heterogeneity and product diversity are barriers to technical feasibility and economic viability. Key aspects of material, product and component design should be standardised so that the recovery solutions can be applied industry-wide and benefit from economies of scale.

In some cases, the processes required for closing the loop and the environmental impacts generated may offset in part or completely the benefits compared to traditional processes with linear disposal. There can also be trade-offs between product circularity and quality, such as decreased product longevity when increasing material recycled content. Thus, trade-offs must be evaluated between the benefits and environmental impacts from a life cycle perspective. Alternative solutions must be explored to increase the net benefits of recovery and make them more attractive, both economically and environmentally.

This essay presents lessons learnt from three industrial pilots as part of the collaborative REWIND project (Enabling REuse, REmanufacturing and REcycling Within INDustrial systems). https://produktion2030.se/projekt/enabling-reuse-remanufacturing-and-recycling-within-industrial-systems-rewind-2/

For a fuller version, see *Despeisse M., Chari A., González Chávez C. A., Chen X., Johansson B., Igelmo Garcia V., Syberfeldt A., Abdulfatah T., and Polukeev A. (2021) Achieving Circular and Efficient Production Systems: Emerging Challenges from Industrial Cases. In: Dolgui A., Bernard A., Lemoine D., von Cieminski G., Romero D. (eds) Advances in Production Management Systems. APMS 2021. IFIP Advances in Information and Communication Technology. Springer, Cham.*

2

Digital Technologies for Circular Manufacturing

Digital Technologies for Circular Manufacturing

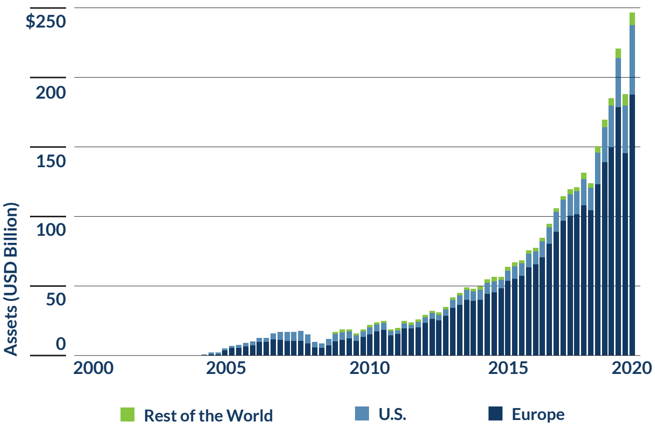
There is a great need for the introduction of new values in our society, where bigger is not necessarily better, where slower can be faster, and where less can be more." – Gaylord Nelson.

The emerging digital era is stimulating the advancement of our society in several dimensions, including the push towards a more sustainable future. Looking at the two paths separately, the last decade has experienced an increasing trend towards the adoption of digital technologies by companies globally to increase their competitive advantage. Large multinational enterprises are investing significant resources in digital transformation and smart technology initiatives as well as growing sustainability programmes. At the same time, small and medium enterprises (SMEs), traditionally more resource-constrained, are exploring innovative ways of adopting new technologies, reimagining their processes, and addressing the sustainability challenge. To provide some quantitative indication of the extent of this movement, the global Industry 4.0 market is expected to reach USD 156.6 billion by 2024 as depicted in Figure 9.[28]

Figure 10

Sustainability-oriented investments

(Source: Morningstar)

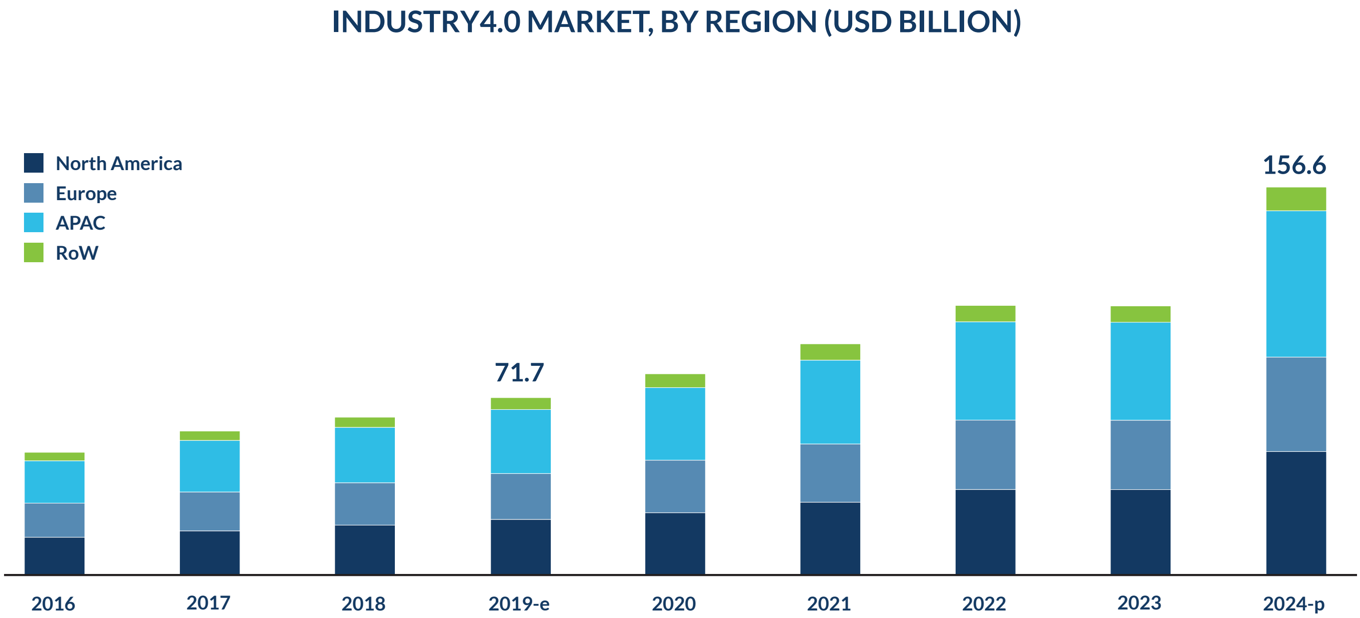


On the other hand, with the same accelerating pace, interest and investments aimed towards sustainability measures are increasing rapidly on a global scale as reported in Figure 10.[29]

Figure 9

Industry 4.0 Worldwide Diffusion

(Source: Market and Markets)



Under the broad umbrella of sustainability, the concept of the circular economy based on the notion of slowing, closing, and narrowing the various resource loops, of particular interest to the manufacturing industry, is gaining momentum. In particular, the circular economy promotes a reduction of resource consumption, waste creation, and greenhouse gas emissions.

For this reason, policymakers worldwide are promoting more sustainable approaches in their respective countries, many particularly focused on establishing circular economy frameworks guiding the manufacturing sector. To report some examples, there is a strong commitment from Europe to Asia to adopting the circular economy.[30]

The European Commission has signed the Circular Economy Action Plan in January 2020[31], promoting the redesign of products allowing for the regeneration of resources, the introduction of circular processes supported by technologies, and the engagement of final consumers, requiring among other things the definition and establishment of new business models, such as product-service systems. In the USA, the EPA (United States Environmental Protection Agency)[32] and the Department of Energy[33] (DoE) are boosting sustainability initiatives in the manufacturing sector holistically and are calling for increased operational efficiency by reducing costs and waste. All these emerging CE initiatives highlight the globally diffused need to be supported by governments to pursue a full transition. Chapter 3: Policy Development and Other Enablers for Circular Manufacturing provides further information about the policies and regulations, including their impact on manufacturers, business models and consumer behaviour.

It can be said that these two apparently separate global movements - technology and sustainability - converge into one main path where technologies become key instruments to achieve sustainability and circularity.[34] Digital technologies become the tools to enhance resource efficiency, to reduce waste, and to minimise the generation of greenhouse gases. These technologies can be employed not only at product, process, and business model levels from a factory perspective but also to coordinate the activities along the supply chain, with the dispersed industrial actors requiring common resources for their industrial activities.

Resource Efficiency

"The immediate goal is to use technologies to extend resource lifecycle as much as possible to fully exploit the value they have".

As just highlighted, one of the major issues in our society is the need to use resources in a more efficient and responsible way. Looking at the most recent data about the Earth Overshoot Day (Figure 11), it is quite evident that consumption is putting a strain on available resources. In particular, the resources that the planet was able to produce in 2020 had already been totally consumed by the worldwide population by August 2020 and none of the countries was able to use the resources available in 2020 efficiently.[35] It is worth analysing how the diffusion of digital technologies, also backed by information systems, can support the reversal of this detrimental trend, especially if we look at the manufacturing sector, which is currently considered to be one of the most resource-intensive sectors.

Firm Perspective - New Business Models

Starting from the review of the current business models of manufacturing companies, it is possible to further engage consumers in embracing this new approach by selling services instead of products, for instance through PSS (product-service systems). In so doing, the role of smart products in extending the resource life cycle is relevant. Indeed, keeping the product ownership with the possibility to monitor the product along the entire life cycle based on IoT (Internet of Things) technologies, makes real-time data tracking and data analytics possible thanks also to the generation of Big Data.

On one hand, product traceability enhances the capability of companies in providing tailored maintenance services aimed at extending the resource life cycle. On the other side, data collection and analysis of consumers behaviours and product conditions could improve the circular characteristics of the next generation of products thanks to the feedback obtained, and support a more structured recovery plan for products.

Furthermore, the data about product characteristics and conditions can facilitate the analysis of the type of treatment required in terms of product refurbishment, remanufacturing or single-component recycling.[36] Giving a new life to the resources opens the way to the creation of various additional revenue streams, for instance by gaining access to secondary markets or entirely new market niches. Above all, products made from recycled materials and remanufactured parts are becoming more and more attractive to consumers with a green mindset, predominantly in developed countries, who are even willing to pay more for 'green products' boosted by the idea of saving the planet. In developing countries, the motivation is driven by a scarcity of resources and the need to optimise processes to increase margins. Aligned with the push towards servitisation, the focus on selling functionality, solutions, and experiences across the whole product life cycle rather than the basic physical product itself represents a major shift and new opportunities for manufacturers, potentially leading to more sustainable revenue streams.

This key aspect turns out to have remarkable implications in optimising overall cash flows and reducing the financial risks in the entire supply chain. In short, thanks to sustainable practices such as remanufacturing supported by digital technologies, the transition to circular manufacturing can be perceived as a competitive asset rather than a burden for companies. Moreover, it can increase the value for customers, such as when product remanufacturing also comes with frequent product updates. In the same way, Additive Manufacturing can become a complementary technology allowing the production of the required spare parts for re-manufacturable products with limited resource usage. It can be used to repair products and to recycle printed materials. Hence, this technology concretely generates the possibility to extend the resource life cycle in an efficient way. In addition, advanced tools for product design and engineering, such as 3D CAD (Computer Aided Design) 3D, can enable the visualisation of product components to think better about circular product design characteristics.

3D CAD can stimulate a life cycle perspective, which can be further supported by the introduction of PLM (Product Lifecycle Management) systems. To be more precise, a circular oriented product design needs to have a long-term perspective to anticipate possible recovery strategies.[37] This approach, also known as Design for X, can facilitate

Figure 11

Country Overshoot Days 2020

(Source: National Footprint and Biocapacity Accounts 2019, published in earthovershootday.org)

product recovery if adopted with a circular orientation by introducing product characteristics, among which the possibility to facilitate product disassembling. Having a circular orientation can anticipate the need arising at the product end of life of disassembling the product to repair it or to recycle the different components. Therefore, with this goal in mind, 3D CAD together with PLM promote the concurrent engineering approach creating the proper synergies among functions based on data sharing, leading to more circular approaches in manufacturing companies.

Still looking at the factory level but moving to the processes to be established within industrial plants, we have just mentioned the refurbishment, remanufacturing and recycling of product and resources. These processes necessitate adequate technologies to be put into practice. These include industrial and collaborative robotics and smart wearables facilitating automation of physical and cognitive tasks. For example, recycling robots enable the easy differentiation of materials from one to another, by recognising the resource composition and therefore being able to select the proper recycling process to be performed to regenerate that specific material. Robots can be used for sorting, disassembling, remanufacturing and reassembling resources. In addition, collaborative robots can help to conduct operations safely and support operators in performing heavy tasks.

Moreover, the traditional manufacturing processes need to be revised to ensure the efficient use of resources. To do that, Cyber-Physical Systems, by ensuring real-time data tracking and subsequent analytics, enable the optimisation of production activities as reduced amounts of water, energy, and materials are consumed.

Supply Network Perspective

The resource efficiency challenge cannot be faced only by a single manufacturing company, but there is also the need for cohesiveness among different companies, even if they do not operate within the same supply-chain. Therefore, networks of companies promoting the same sustainable and circular goals are starting to fulfil prominent roles in our society, and the resource management can be supported either by information systems or by the already mentioned digital technologies allowing data tracking and analytics. Indeed, the concept of traceability becomes increasingly relevant in this context because of the need to share information, among several stakeholders about the condition, location and ownership of resources.

Logistics and Supply chain

Companies operating within the same supply-chain must start thinking about how to reorganise their value chains with additional stakeholders enabling resources recovery, which implicitly guarantees the resources loops. Supply chains operating in this manner can also be called closed-loop supply-chains, enabling the reverse flow of resources once they have been used by consumers. To make this happen, several stakeholders involved must be aligned and IoT technologies embedded in smart products can facilitate data tracking and subsequently Big Data analytics and Artificial Intelligence to support the evaluation of product conditions and the required activities to extend product life cycles.

Therefore, at the end of the product life cycle, with the establishment of well-organised closed-loop supply chains, products can be collected to be repaired or recovered, based on their condition, to be re-introduced in new life cycles. Maintenance activities can be performed on products, by the original manufacturer to extend their life cycles and give them back to the last user, whereas recycling and remanufacturing companies need to be involved too in order to ensure the correct product recovery strategy. To back these networks and satisfy the whole demand, secondary markets can be established to sell the recovered products at special prices. This requires additional efforts to engage consumers and create responsible consumption patterns. This can done through marketing activities, relying on information systems such as customer relationship management (CRM).

Industrial Symbiosis

Companies operating in different supply-chains can start thinking about potential synergies allowing waste, by-products and other resources to be shared as inputs for their operating activities. This can also be done with external industrial actors operating in different sectors. These synergies can take the form of industrial symbiosis to give new life to resources which otherwise would be discarded. Input-Output matching tools or other platforms, such as the one proposed by ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) in Italy[38], can be used to facilitate exchanges among companies. In addition, with the goal of exchanging resources, even non-tangible resources such as capabilities and cloud manufacturing can be adopted.[39]

Waste Reduction

"Reducing waste - in all its variants - along the product lifecycle directly contributes to the sustainability goals of manufacturing."

Reducing waste across the value chain is one of the most important and impactful levers that manufacturing has towards a more sustainable future. While other areas of sustainability face certain reluctance at times, there is a consensus that reducing waste is a worthy endeavour. Waste production impacts both energy consumption (directly and indirectly) and CO2 emissions, in addition to wasting valuable and often scarce financial and manufacturing resources. For each part that is scrapped, the raw materials, including their processing and logistics and the value-adding processing already invested must be accounted for as waste. It comes as no surprise that reducing waste is at the core of lean manufacturing. Recently, with the emergence of digital transformation and smart manufacturing, this established paradigm is extended to also reflect the nature of digital waste.[40]

However, if we truly want to move towards a sustainable industry following the circular economy paradigm, we must think beyond the shop floor and extend our activities to consider the whole life cycle of products. Digital technologies have a tremendous potential to reduce waste, for example, by reducing the scrap rate towards zero-defect manufacturing or increasing uptime of machines via predictive maintenance algorithms. At the same time, digital technologies bring forth their own challenges, including obsolescence and regular replacements leading to large amounts of electronic waste.[41] It is crucial to take on a life cycle perspective and think holistically how the opportunities afforded by digital technologies can be utilised in a sustainable manner.

Designing products with upgradability in mind can be one possible pathway to avoid regular replacements; the right to repair, and advancements of remanufacturing technology can reduce waste at the end of the life cycle, retaining more of the value added of the product's added value than lower cascades of end-of-life processes.[42]

These changes go beyond technological implementations. They affect the business models and impact both manufacturing and business processes throughout the organisation and the whole supply network. In the following sections, we discuss the affordances structured around impact on the business model, as well as a firm's internal and network perspective.

New Business Models

Sustainability has three dimensions following the triple bottom line framework: environmental, social, and financial. Given our economic activity and the need for manufacturers to remain competitive in the marketplace, any change must align with the business model and not adversely affect the company's financial health. With regard to reduction in waste across the life cycle, new paradigms such as non-ownership business models, including product-service systems offerings, aim to address sustained financial success, positive impact on environmental measures, and social improvements, (i.e. through increased access).

Focusing on reducing waste through the use of digital technologies, new and innovative business models play a key role. Digital technologies such as smart and connected machines that enable predictive maintenance and zero-defect manufacturing though machine learning (ML) and artificial intelligence (AI) require an in-depth understanding of the process and access to large amounts of process data, ideally across industries, applications, and organisations. Providing access to such advanced machine tools while maintaining control and access to them is a key driver of non-ownership business models such as pay-per-use or pay-per-outcome in the manufacturing industry, paving the way to new revenue streams. Over time, this enables i) improved design based on real (data-driven) requirements, ii) higher utilisation due to reduced downtime from unplanned maintenance, and iii) better process quality, all impacting the several waste dimensions. It is worth pointing out that the introduction of these digital technologies represents a chance for IT service providers to occupy a focal position since AI or ML solutions, especially for SMEs, could be delivered via cloud-based platforms and subscription-based models with limited initial investments required. Hence, to keep the same level of capital invested (CAPEX) on the waste generator side, AI solution providers could adopt a pay-per-use revenue strategy and exploit the related advantages.

Firm Perspective

Breaking down the impacts of waste reduction from an organisation's internal perspective requires us to look at products (design and development) as well as the manufacturing process.

From a **product** perspective, the design and development phase has a significant impact on the potential reduction of waste along the life cycle. Not only the direct choices such as materials or packaging, but also design considerations around planned obsolescence, repairability, and design for manufacturing assembly (DFMA) factor into the overall picture. Economies of scale and mass customisation or personalisation impact the design decisions and waste produced.

Another area where the design phase can make a significant difference with regard to waste generation is designing products with their repairability and upgradability[43] in mind. Aligned with the product-service systems and servitisation paradigm, this needs to be instilled from the beginning to achieve full effect. This leads directly to the impacts from a **manufacturing** perspective. When considering mass personalized products, additive manufacturing comes into the picture as a digital-first technology. However, we need to consider that additive manufacturing, while capable of reducing the amount of waste (excess material) in many cases can also lead to significant waste for some applications and industries. For example, in some powder bed fusion processes where nano-sized metal powders are used, the excess powder cannot be reused due to certification issues. The excess powder constitutes not only a process waste but might be a safety hazard (nanoscale, toxic, explosive).

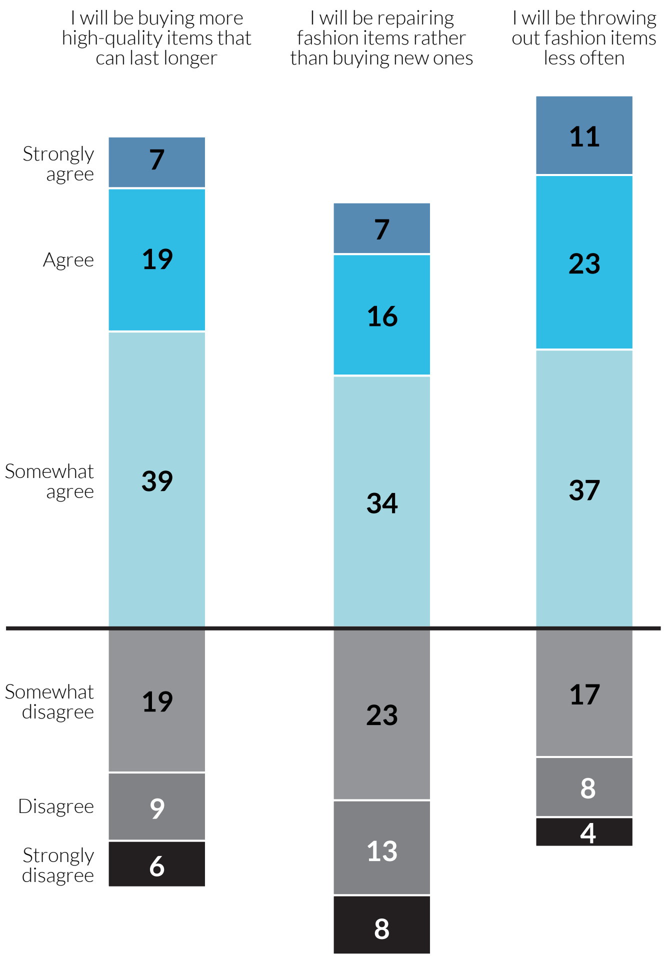
Another AM technology, DED (Directed-energy Deposition), is often used for remanufacturing, which leads to a significant opportunity to reduce waste through advanced manufacturing and digital technology. New remanufacturing processes allow the recovery of end-of-life parts and phase them back into the economy for productive use at a higher cascade use level. Utilising middle-of-life applications such as IoT or smart products helps to predict the remanufacturing potential and improve the yield of the processes, thus again, reducing the waste generated. The right to repair is becoming popular and has already made its way into policies in certain regions. Consumers are willing to retain products longer and repair them instead of discarding and replacing them regularly (see Figure 12).

Figure 12

Changes in purchasing behaviour after COVID-19 crisis

(Source McKinsey) [44]

% of respondents (n=2,004)[1]



[1]Figures may not add up to 100% because of rounding

Supply Network Perspective

Expanding the perspective from the individual organisation towards the supply network is necessary to account for the full effect of today's distributed manufacturing ecosystems. Logistics and shipping materials, parts, and final products around the globe contributes to significant waste beyond the obvious impact on CO2 emissions.

Logistics and Supply Chain

Designing supply networks to facilitate reuse, reduce, and recycle paradigms are crucial for the success of the circular economy paradigm in a competitive market environment. Matching producers/sources of end-of-life components with remanufacturing/recycling facilities and current and new users of the remanufactured/recycled parts and materials is a requirement for a sustainable development and scaling. The establishment of these links inevitably necessitates the traceability of the resources, which is highly facilitated by the adoption of digital technologies and secure data sharing among all stakeholders across the supply network. The integration of large OEMs and SMEs within the network especially poses new challenges when it comes to accessing, sharing, and analysing data.

Reduced Emissions

One of the most urgent topics that policy makers and businesses must face in coming years is related to the need for drastically reducing global greenhouse gas emissions.

Evidence of this urgency can be found in the goals set at the Paris Agreement that were signed by 55 countries worldwide with the objective of reducing their overall emissions. The graph reported in Figure 13 shows how the emissions of CO2 have dramatically increased throughout the decades, reaching unsustainable levels, and they are expected to increase further in the near future. (Figure 13).

However, it is important firstly to understand from where greenhouse gas emissions originate from. At present, most of them are due to energy production, both for industry and consumers (72%). In particular, 31% of global CO2 produced is directly related to the generation of electricity and heat, with the remainder generated by manufacturing processes and transportation. Agriculture is another relevant source of emissions, since it accounts for a further 11%. A detailed overview of the distribution of CO2e emissions by sector is provided in Figure 14.[46] Hence, this section is devoted to the analysis of the role those digital technologies play in the need for drastically cutting greenhouse emissions throughout all products' life cycle: from the supply of raw materials up to the end of life and, in some virtuous cases, its reintroduction into the loop. Firstly, a firm perspective is adopted to provide key findings about how companies are facing such challenges individually.. Finally, the boundaries are extended to the solutions applied at network level, or rather those that affect the interactions among different entities.

Firm Perspective

To reduce greenhouse gas emissions overall and, eventually, to reach complete carbon neutrality is a complex objective. In order to achieve this, companies must think of solutions that encompass both the products offered as well as the necessary processes to produce them. Hence, this section is devoted to these two dimensions.

Product

At product level, great focus is dedicated as early as during the initial new product development (NPD) and design phases. This is translated into many investments aimed at not only

Figure 13

Global Carbon Dioxide Emissions, 1850–2040

(Source: Centre for Climate and Energy Solutions)[45]

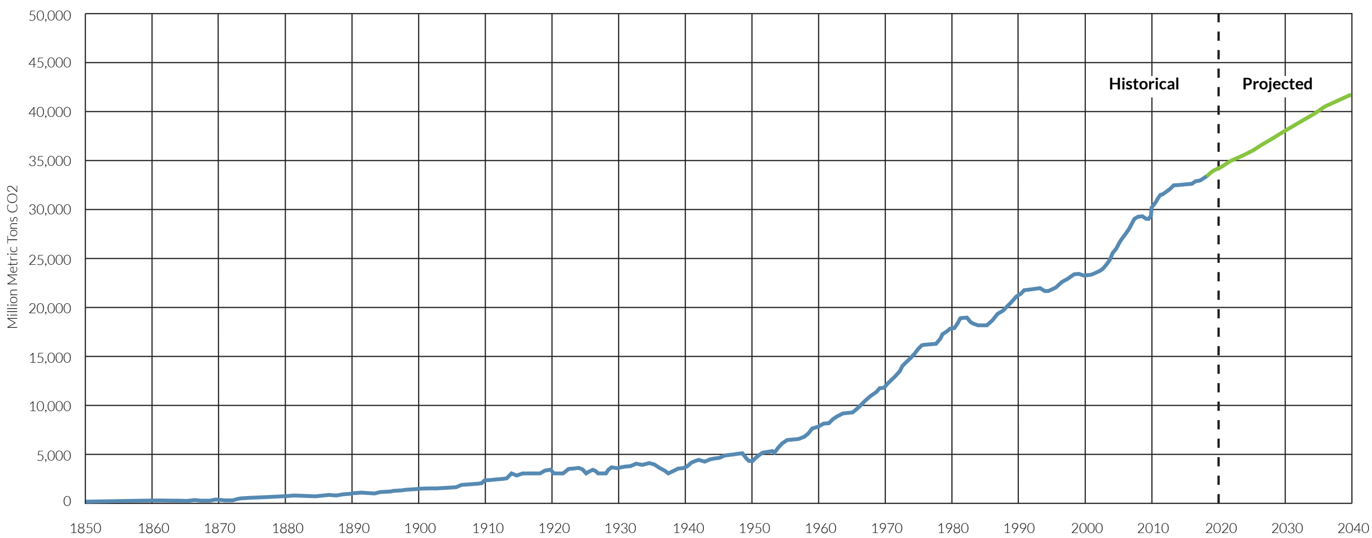
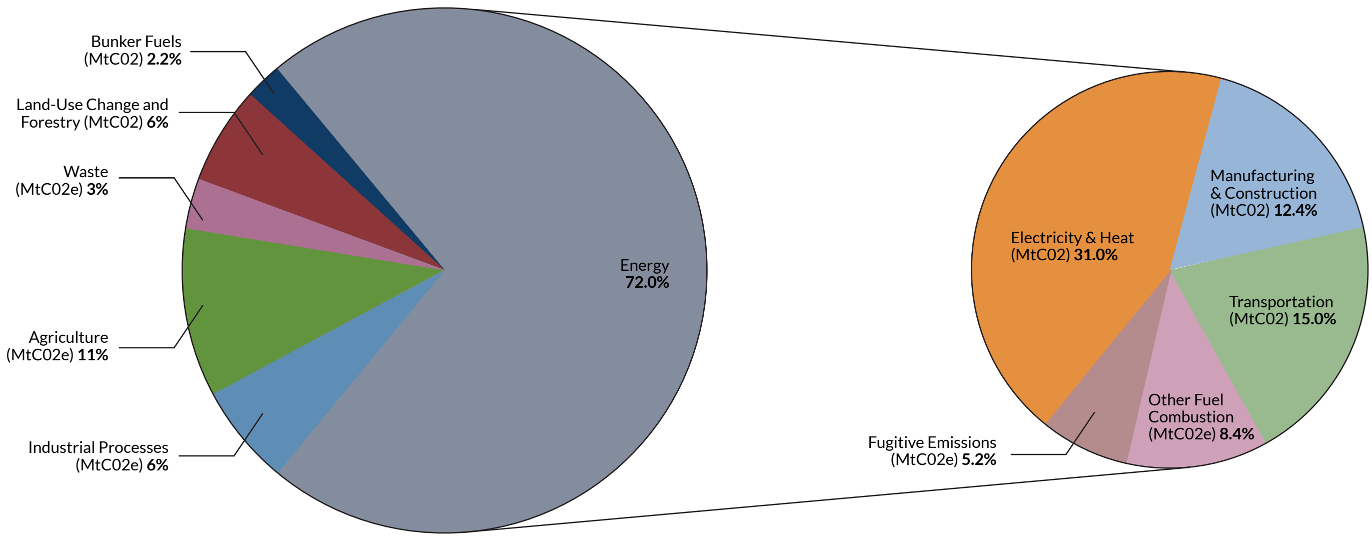


Figure 14

Global Greenhouse Gas Emissions by Sector



making products lighter in order to reduce emissions during their transportation and processing but also increasing the energy efficiency along their entire life cycle.

Additive Manufacturing is increasingly gaining traction in this sense. In fact, not only does it allow manufacturers to reduce the overall material consumed during their operations, but it is also one of the most promising technologies for carrying out NPD activities. While traditional methods are based on extrusive approaches, or rather on the elimination of layers of material to extract the desired shape, additive techniques are based on the continuous deposition of material needed to produce a given object. This technique on the one hand represents an opportunity to generate particularly light geometries without decreasing the technical performances achievable with traditional and heavier designs. The immediate impact, as anticipated above, is a drastic reduction of overall weight during transportation. On the other hand, the adoption of AM would have advantages also in terms of emissions generated from transportation activities of raw materials and components since when these are produced or even extracted on site. The advantage is amplified when dealing with rural areas or inaccessible locations, thus representing an opportunity to boost the economic development of the poorest areas in the world.

Production

As already observed above, energy production accounts for the greatest proportion of greenhouse gas emissions. Hence, the optimisation of energy management represents a priority for businesses, especially for manufacturers. In this sense, there are plenty of solutions that can support firms in making their processes constantly less energy intensive. However, before implementing such solutions, it is crucial to monitor the energy needs of the processes themselves.

The Internet of Things (IoT) can provide a practical support in this field. In fact, IoT technologies are devices able to collect, store and transfer valuable data, thus representing a fundamental element for undertaking analysis, even real-time, aimed at monitoring processes and reducing, among other things, waste and inefficiencies. Smart sensors able to monitor the energy requirements of the machine would be the first step for a carbon reduction transition.

Also, AI and ML fulfil an important role in reducing energy consumption. Indeed, AI-based solutions devoted to the heuristic optimisation of energy consumption already exist on the market. For instance, Google has successfully cut its energy-related costs and consumption for cooling its data centres by 40% through the ML algorithms developed in DeepMind as shown in Figure 15.[47]

In a similar direction, Microsoft, with its Project Natick, has cut down emissions for cooling systems by locating data centres underwater and monitoring their status remotely. The process industry, traditionally with a significant energy impact, is utilising smart manufacturing technologies such as IoT, AI, and automation to optimise its energy footprint.

Supply Network Perspective

As previously stated, greenhouse gas emissions reduction is not only an issue to be solved at company level. A large part of pollution (15%) is generated from transportation, for instance. Hence, to address the problem in a comprehensive way, it is worth broadening the horizon of analysis to the supply chains or, more in general, to the more complex network of entities around each firm.

For this reason, the next section is dedicated to the analysis of the issues to be faced at single supply chain level and consequently to the analysis of how the network of companies could interact to achieve so-called industrial symbiosis.

Supply Chain

Similarly, to product management, there are two main pathways that can be followed to reduce emissions at the supply chain level. The first is to reduce polluting activities and the second and more effective is to substitute them with virtualised services, or to eliminate them. An example of the second strategy is already reported in the section dedicated to product. By means of additive manufacturing, it is possible to conduct the production processes nearshore, thus drastically reducing transportation needs for raw materials or finished goods. This represents an opportunity for companies either to produce what they need, almost real-time, based on additive manufacturing, or to establish stronger relationships with nearshore companies.

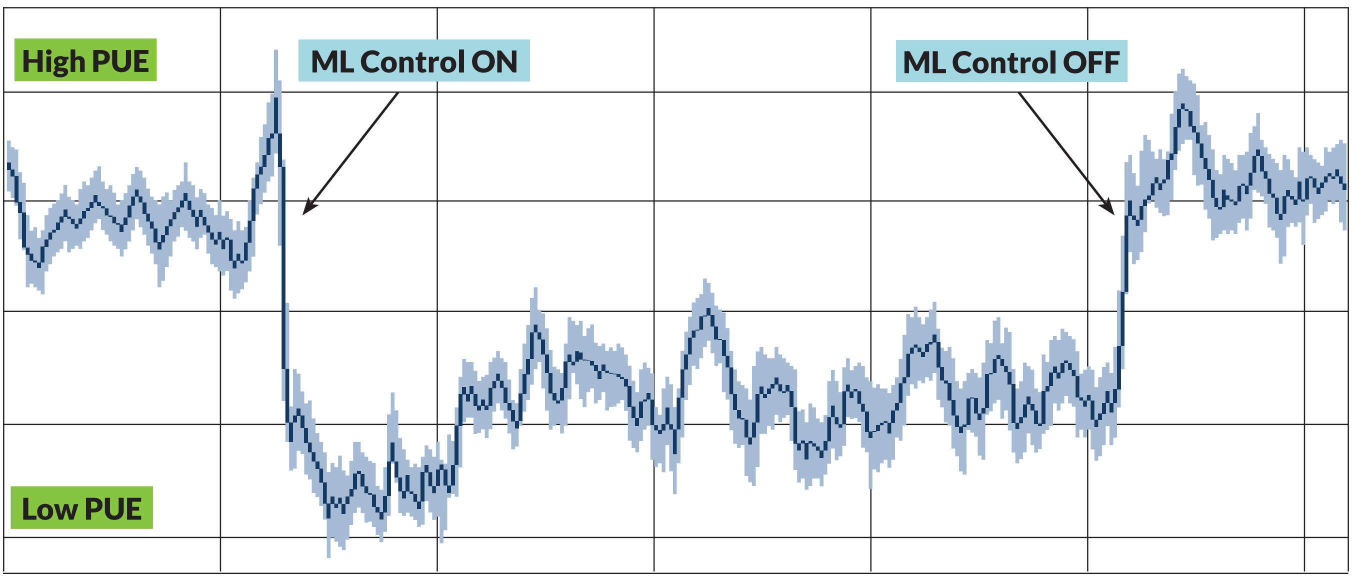
In terms of reduction of emissions, optimisation of transportation needs also plays a remarkable role. In this sense, many Cloud-based logistics can aggregate different companies' needs and optimise transportation of goods. Then, once the aggregated requirements have been collected, the actual optimisation process is delegated to other technologies like AI and Big Data analytics to dynamically manage and define the optimal transportation plan. The need for a reliable and scalable track & trace system, enabled by IoT devices, is clearly evident in this scenario. In fact, the applicability of such heuristically optimised solutions depends on real-time awareness of both the products to be transported and transportation means.

Finally, in parallel with the virtualisation of the product, different services among supply chain actors could be virtualised too, thus directly eliminating the source of emission. In this sense, augmented reality (AR) and virtual reality (VR) are valuable, and other essential technologies could prove useful. Indeed, they are key enablers for activities like remote maintenance or remote monitoring of tools and facilities, especially when such a service is provided by the OEM itself. This, together with the solutions reported above, will further contribute to drastically reducing the emissions generated from transportation.

Figure 15

Power Usage variation of Google Data Centres while running ML control

(Source: DeepMind)



Mallinda's Vitrimer Composites for the Circular Economy

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Plastics can be divided into two basic categories: thermoplastic and thermoset. Both types represent an enormous challenge to the circular economy. Some thermoplastics (such as the PET that constitutes water bottles) can be melt-processed and reused or moderately downcycled, typically resulting in loss of mechanical performance due to reduced polymer chain length through each recycling process. Thermosets, which make up most adhesives and durable goods such as composite structures (wind blades, electronics, marine craft, aircraft, etc.) are not melt-processable.

This means thermoset-containing products are refractory to recycling, thus becoming either landfill fodder, or worse, at end-of-life. They can be degraded by either pyrolysis (burning the plastic to release energy, and gaseous pollutants) or solvolysis (using extremely corrosive chemical baths). These harmful processing steps are sometimes applied when something of high value is encapsulated in the thermoset plastic such as valuable metals in electronics, or carbon fibre in scraps from aircraft production.

But it doesn't have to be this way. Thermosets were originally invented to replace ivory[1], and were designed to be irreversibly permanent and mechanically robust polymeric materials. Vitrimers represent a 21st century re-design of thermoset plastics. Vitrimers incorporate infinitely reversible chemical bonds into the chemical network of a thermoset plastic. Thus, a simple route to circular recyclability is built into a vitrimer system. Like thermosets, vitrimers are network polymers, meaning they can achieve the strength required for structural applications in composites and elsewhere. The reversibility and re-workability of the underlying chemical bonds in vitrimers can lead to economic and cycle time improvements for production. In addition, these novel materials enable repair, which is extremely difficult for traditional thermoset materials.

Mallinda Inc. is the leading commercial developer of vitrimer polymers and vitrimer matrix composites. Since spinning out of the University of Colorado in 2014, the company has developed and matured a vitrimer resin system based on reversible imine chemistry.[2] The key innovation leading to Mallinda's success is built-in to the imine bond itself, which is a double bond between carbon and nitrogen atoms. Imine chemistry has been known to organic chemists for decades, and the reversible bond exchange of imines was highlighted by Nobel laureate Jean-Marie Lehn[3], but these materials were not very stable, and would easily degrade. During his Ph.D. work at the University of Colorado, Mallinda co-founder Philip Taynton worked to improve the environmental and thermal stability of imine chemistry. He used that chemistry to demonstrate the first imine-linked vitrimer materials. Since then, the Mallinda team has been

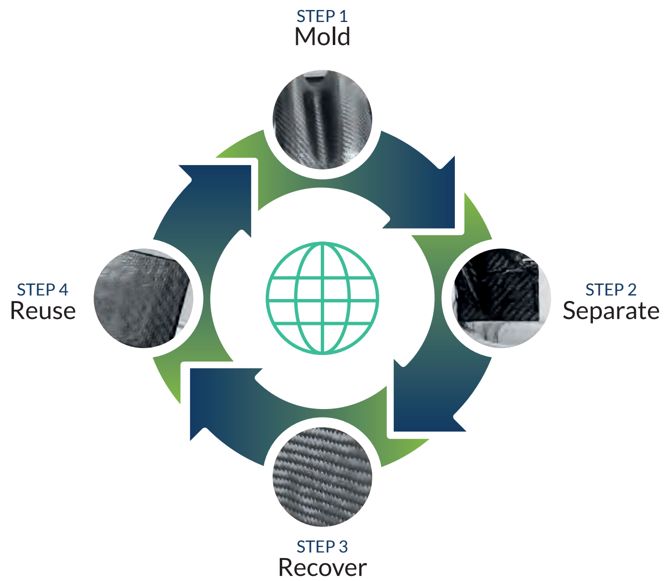

Figure 1: Chemical recycling of vitrimer-based composites for circular recovery and reuse of both fibre and resin.

continuously improving this technology to the point where it is now competitive with epoxy resins in stability and performance and can even be used as a drop-in for epoxy-based manufacturing processes. To date, the company has focused on the development of vitrimer resins to replace epoxy resins in structural composites applications.

Mallinda's vitrimers are doubly recyclable - both chemically and mechanically. To chemically recycle the material, it is introduced to a solution containing select chemical precursors to the resin itself. These precursors undergo chemical bond exchange with the cured vitrimer material, effectively breaking it down into smaller molecular pieces until it all becomes soluble. This reaction takes place under mild conditions (20-80C), and the entire resulting solution can be used directly to make more of the same vitrimer resin, meaning there is no chemical waste generated. Alternatively, mechanical recycling can be used to pulverise the cured material for reuse in secondary applications. Unlike thermoplastics, mechanical processing of vitrimers does not shorten the polymer chain length, and thus, does not result in degraded mechanical performance.

Mallinda's first products are imine-linked vitrimer resins for pre-impregnated carbon fibre composites (prepregs). This is one of the most common formats for composite material production and offers superior quality and consistency when compared with resin infusion processes. The problem with traditional thermosetting prepregs is that they must be kept frozen or "B-staged" until they are used to produce a product. Once a traditional prepreg is thawed, it must immediately be utilised to produce a part, before the prepreg fully cures. One advantage of vitrimers is that they can be reprocessed even after cure. Mallinda's vitrimer resins enable prepregs that can be pre-cured, meaning no refrigerated storage or transport is needed, shipping becomes non-hazardous, ambient shelf life becomes indefinite, and shorter in-mould times for production (between 20 seconds to 5 minutes) are possible for improved production efficiencies. All of these factors combined can reduce the production costs of a traditional prepreg-based part by 50%, while enabling a 4x improvement in throughput. It also enables new high-throughput production schemes for the automotive industry, where vitrimer materials represent an opportunity to produce lightweight composite parts with similar processes and economics to sheet-metal stamping. In Q1 of 2021, the company conducted its first commercial-scale production trials, producing volumes at the metric ton scale, and is planning to publicly launch its first products in early 2022. The company is currently working on an aerospace-grade resin and has validated that the chemistry can be adapted to the other common thermoset composite production processes of pultrusion, tow-pregging, and infusion/resin transfer moulding. Beyond structural composites, Mallinda sees vitrimers impacting electronics, adhesives, and eventually commodity plastics applications.

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Case Study

Augmented Reality Takes Centre Stage in Steel Industry Program

Jacqui Cook
Senior Manager, Corporate Communications Department, PTC

The power of Augmented Reality (AR) is set to be used to optimise processes in the steel and metals industry and retain crucial skills that could be lost forever as an ageing workforce retires.

PTC has joined forces with the Materials Processing Institute, a research and innovation centre serving global steel and materials organisations, to explore the potential of AR at its Normanton Plant in Teesside, UK.

The project will initially use Vuforia Studio technology to overlay live data – taken from the ThingWorx industrial IoT platform – to various points of the facility, so that operators moving around will be able to make informed decisions on changes to casting and melting lines or troubleshoot issues before they happen.

It is anticipated that augmented reality will make it easier for staff to have the right information at exactly the right point they need it, while the use of smart glasses will mean the individual has both hands free to complete tasks.

This project will contribute to the sector's longer-term desire to move toward a net-zero steelworks by 2050 and is part of the £22 million PRISM steel and metals sector research and innovation programme being delivered by the Materials Processing Institute with funding provided through Innovate UK, part of UK Research and Innovation. "The successful implementation of digital technologies has the potential to save tens of millions every year," explained Chris Oswin, Group Manager of Digital Technologies at the Materials Processing Institute. "We are taking responsibility for exploring IIoT platforms and AR and working out how we can get the most out of them in a live steel plant, learning from testing and trials to identify best use cases."

He continued: "This means we absorb a lot of the time and remove the initial expenditure that could act as a barrier to entry for companies in our industry, hopefully encouraging digital adoption as we will have proved it works and how it can be applied to businesses.

PRISM is guided by a team of industry leaders on our Industrial Advisory Board, including the Aluminium Federation, British Manufacturing Plant Constructors' Association, British Steel, Celsa Steel, Liberty Steel, Outokumpu Stainless Steel, Sheffield Forgemasters, Swansea University, Tata Steel and the UK Metals Council. The Materials Processing Institute has a long-term relationship with PTC, with the latest project following on from the introduction of ThingWorx as part of the £10 million programme to explore how digital technologies can be implemented in brownfield manufacturing sites.

In addition to optimising processes and introducing new efficiency improvements, Augmented reality will also be used to capture some of the traditional skills in the sector that could be lost if the knowledge of older workers is not retained before they retire.

With Vuforia Expert Capture, operators and technicians can film their daily tasks in step-by-step instructions, in-situ when and where they do their work.

This will be uploaded to the cloud, which can then be accessed by new starters or people switching roles, using smart glasses to get a real hands-on experience, or other devices such as mobiles, tablets or on desktop computers. Furthermore, for problem resolution and live 'on the job' support, there is Vuforia Chalk. Using mobile devices, digital eyewear or seated at a desk - experts can connect with on and off-site employees and customers and collaborate in real-time. It combines live video, audio and the ability for remote and local participants to annotate their live shared view and mark-up the real-world environment.

"If we don't act soon, we stand to lose so much knowledge

from the industry and AR gives us a cost effective and easy way to retain skills and experience in a virtual library for generations to come," added Oswin.
"Working closely with PTC's experts, we can tailor how we capture information, footage and skills in what is a very demanding and intense environment. We believe we've got the initial framework to start the roll-out and will continue to adapt the processes as we understand more about how digital technologies can play a role."

David Grammer, general manager for UKI for PTC, went on to add: "Covid-19 has definitely thrust the digital thread into the spotlight, but there is still a resistance to adoption due to a lack of awareness of how it will deliver a genuine business benefit."

This project with the Materials Processing Institute gives an entire sector the opportunity to explore how AR can be applied and developed in a real live steel plant without the potential disruption and cost of trying it in their own facilities.

"Businesses will be involved in the roll-out and informing some of the test cases and our team will be on hand to support experts at the Institute to get the most out of our technology and software," said Grammer. "The end goal is that we will have proven business cases on how steel and metals companies can optimise processes using augmented reality and live data, not to mention protecting vital skills for the steel workers of the future."

3

Policy Developments and Enablers for Circular Manufacturing

Policy Developments and Enablers for Circular Manufacturing

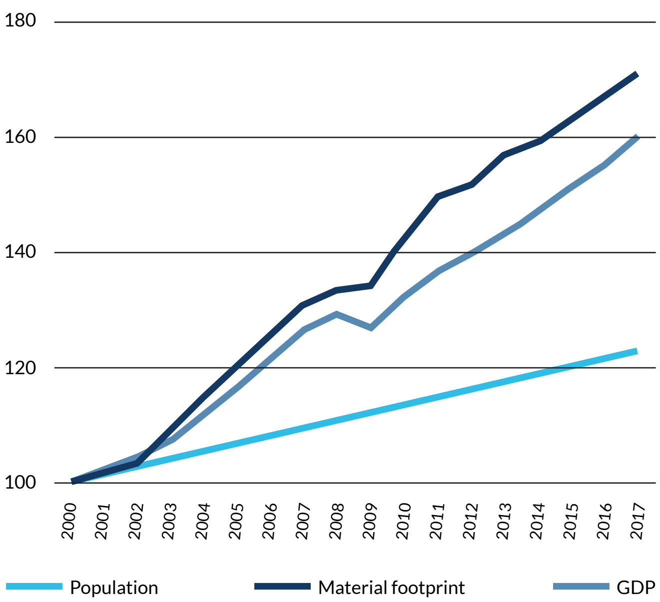
Linear production models are unfit to deliver social, environmental, and economic sustainability.

The 'take-make-waste' linear production model that powers the global economy is taking a toll on Planet Earth's carrying capacity.
Over the last twenty years, the world material footprint (i.e., the amount of raw material extracted to meet final consumption demand) has increased by more than 70 percent (from 54 billion metric tons in 2000 to 92 billion metric tons in 2017), outpacing both global population growth and GDP growth (Figure 16).[48]

Figure 16

Population, material footprint and GDP growth index, 2000-2017 (baseline 2000=100)

(Source: United Nations)

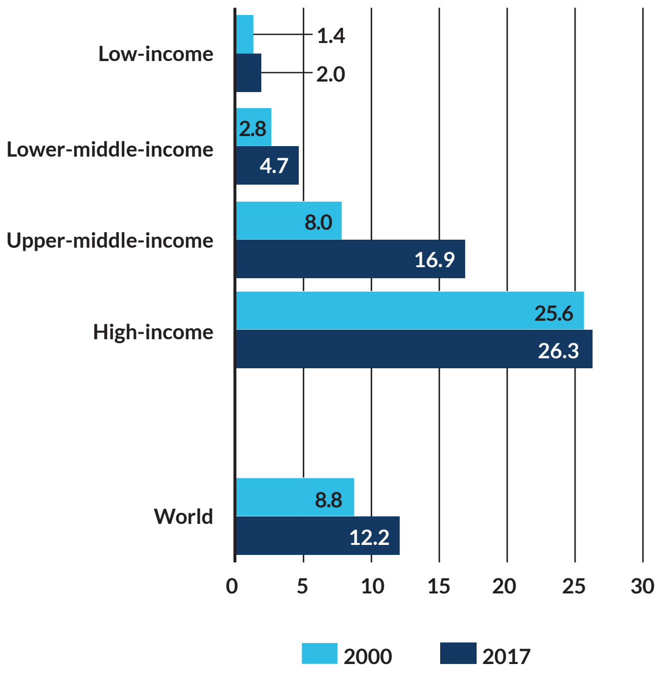


Most of the demand for raw materials comes from high-income countries. Their per capita material footprint is considerably above the world average and approximately 13 times bigger than in low-income countries, with 26.3 metric tons compared to 2 metric tons based on 2017 data (Figure 17). Furthermore, more than a third of primary materials used in the richest nations comes from elsewhere in the world. [49]

Figure 17

Material footprint per capita, 2000 and 2017 (metric tons per person)

(Source: United Nations)



Taken together, these numbers paint a picture of a production system inherently unfit to deliver social, environmental, and economic sustainability.

The decoupling of growth and material usage is necessary to deliver global and intergenerational equity.

Consumption patterns in high-income countries depend largely on resources extracted in poorer countries, contributing to global and intergenerational inequality. Furthermore, the linear economy reliance on environmental degradation and resource depletion is endangering the systems on which our economic development depends.[50]

Without decoupling economic growth from the material footprint (Figure 16), it will be inherently difficult to meet the rising demands of a growing global middle class, projected to reach 5.3 billion people by 2030.[51]

Circular Manufacturing in the Context of the UN 2030 Agenda and the Paris Agreement

The transition to circular manufacturing can help countries meet the UN Sustainable Development Goals and those of the Paris climate agreement.

The United Nations (UN) General Assembly identified the transition towards sustainable consumption and production patterns as one of the key goals of its 2030 Agenda for Sustainable Development (from now on "Sustainable Development Goal 12", or "SDG 12").[52] This goal is also accompanied by 11 targets that focus on, among other dimensions, the efficiency of natural resources, food waste, chemical waste, waste generation, scientific and technological capacity, tourism, and market distortions (e.g., subsidies to fossil-fuel, taxation systems).

Although the concept of a "circular economy" (CE) is not explicitly mentioned in the 2030 Agenda, this paradigm shift has long been considered to be able to fulfil all four requirements of "sustainable production and consumption", as identified by the UN[53], namely:

Figure 18

Linkages between SDG 12 and other SDGs[54]

(Source: United Nations)

- Improving the quality of life without increasing environmental degradation or compromising the resource needs of future generations
- Decoupling economic growth from environmental degradation by reducing material and energy intensity of current economic activities, as well as emissions and waste.
- Applying life cycle thinking
- Guarding against the "rebound effect," where efficiency gains are offset by resulting increases in consumption.

In addition to achieving SDG 12, the circular economy and the application of its principles to manufacturing can help deliver other goals of the 2030 Agenda (Figure 18), such as: sustainable management of water and sanitation (i.e., SDG 6); affordable and clean energy (i.e., SDG 7); sustained, inclusive and sustainable economic growth (i.e., SDG 8); resilient infrastructure, inclusive and sustainable industrialisation, and innovation (i.e., SDG 9); resilient and sustainable cities and human settlements (i.e., SDG 11); climate action (i.e., SDG 13); conservation and sustainable use of our marine and coastal legacy (i.e., SDG 14); and protection and restoration of terrestrial biodiversity and ecosystems (i.e., SDG 15).[55]

The circular transformation can also play a role in tackling climate change and meeting the Paris Agreement goal of limiting global warming to 1.5 degrees Celsius compared to pre-industrial levels.[56]

According to the Ellen MacArthur Foundation, improvements in energy efficiency and the transition to renewable energy sources—the current focus of national climate and energy frameworks—"would only address 55 percent of global greenhouse gas emissions," with the remaining 45 percent being "a consequence of the way we make and use materials and products, including our food".[57] The transition to a circular economy, then, can help cut down part of these "hard-to-abate emissions" by changing the way we produce, use, and dispose of products (Figure 19).[58]

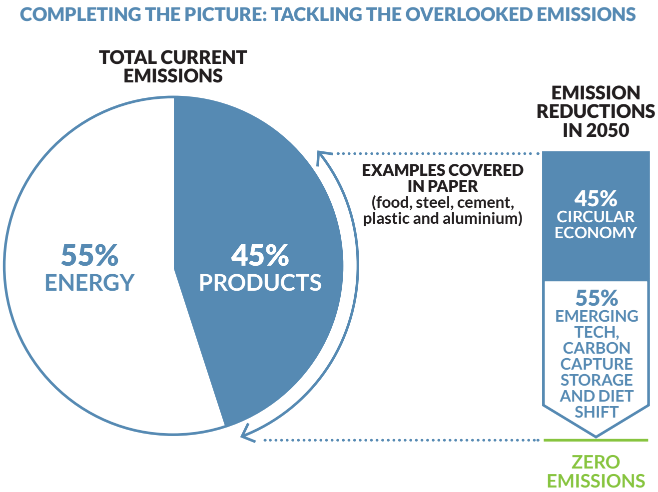
The complexities of integrating circular principles into the manufacturing process have so far held back meaningful progress.

Despite the relevance of the circular economy in achieving global policy goals, progress in integrating "circular" principles into the manufacturing process has so far been limited to a small number of global companies able to overcome barriers such as geographically dispersed value chains and "the complexity of materials and deconstructing products".[60]

Figure 19

Tackling the overlooked emissions[59]

(Source: Ellen MacArthur Foundation)



Go Digital to Go Circular: 'Building Back Better' Post COVID-19

With the pandemic highlighting both the vulnerabilities of the 'take-make-waste' linear production model and the potential of digital technologies to build resilience, a growing number of policymakers are betting on the circular and digital transformations to build sustainable and resilient economies.

The COVID-19 pandemic has exposed the vulnerabilities of production models that rely on the continuous availability of cheap and unlimited natural resources, and revamped governments' interest in the circular economy as a strategy to deliver durable and resilient recovery.

At the same time, the pandemic has also accelerated the adoption of digital technologies by companies trying to ensure continuity and connectivity, permanently changing the way they interact with customers, manage their supply chains, and handle internal operations.[61]

Considering these two trends, policymakers around the world are increasingly emphasising the circular and digital transitions as transformative strategies to "build back better" post COVID-19. According to the World Bank, national governments have already committed to more than USD 1.5 trillion to digital measures within their COVID-19 recovery packages[62], and OECD countries and key partner economies have allocated an additional USD 336 billion to environmental measures.[63]

Bringing both transitions together in one coherent policy can allow the identification of opportunities, trade-offs and compromises, and help manufacturers embrace circularity.

Despite the enabling role of digital technologies to facilitate the circular transitions, only a few countries are bringing digital and circular objectives together in one coherent policy allowing the identification of opportunities, trade-offs, and compromises (e.g., the EU and its Member States). Nonetheless, many others are taking note and actively seeking guidance on how they could mobilise finance, technology and capacity-building to enable the transition to a circular economy (Box 1).

Although each national strategy will have to take into account country-specific contexts (e.g., fiscal capacity, the presence of existing infrastructure, the extent of the digital divide), aligning the circular and digital strategies and allocating part of the COVID-19 recovery packages to this twin transition can help manufacturers overcome those barriers that currently hinder the adoption of greener, more circular, and more resource-efficient production models.

Box 1

United Nations Industrial Development Organization (UNIDO)'s Global Consultations on Circular Economy.

In 2020, in response to a request from its Member States, the United Nations Industrial Development Organization (UNIDO) organized a series of global consultations on the circular economy. The consultations facilitated exchanges on best practices, and emerging innovations and the promotion and adoption of circular economy principles and practices by industries, particularly in developing countries. The consultative sessions were attended by representatives of 70 countries, including national governments, United Nations entities, intergovernmental and non-governmental organizations, the private sector, and academia.

The consultations revolved around two main topics:

- Topic 1: Circular economy as a substantial contribution to addressing the climate crisis and advancing the achievement of the Sustainable Development Goals (SDGs).
- Topic 2: Mobilizing finance, technology and capacity-building to promote circular economy principles and practices in developing countries.

Several policy messages were distilled from the discussion:

- The scarcity of resources, in particular in developing countries, emphasises the need for efficient resource use as an economically driven goal.
- To date, efforts to tackle the climate crisis have mostly focused on energy transition, that can reduce about 55 per cent of global greenhouse gas emissions. The remaining 45 per cent of emissions come from extraction and manufacturing industries and lifestyle choices. It is therefore imperative to integrate the circular economy into climate change strategies and intergovernmental processes.
- It is necessary to enhance action on circular economy and strengthen the engagement of communities in this action to advance a sustainable and resilient COVID-19 recovery.

Moreover, the key takeaways envisaged potential actions to be taken at policy, institutional and business sector level to support the transition towards a circular economy:

- Set adequate regulatory frameworks to allow enterprises to embark on the transition to a circular economy on their own
- Promote mandatory producer responsibility to increase enterprise accountability relating to pollution and increase green investments
- Develop standardised indicators of a circular economy to track improvements at the regional, national and international levels
- Mainstream environmental and social responsibility in business strategies
- Develop circular economic models integrated with the SDGs.

Regional Approaches to Circularity

Regional and national strategies to promote circularity vary in ambition, approach, and the emphasis put on the enabling role of digital technologies.

As discussed in the previous section, a vast majority of countries have not yet developed a consistent policy framework that aligns digital and circular objectives, leaving an important opportunity to accelerate the circular transformation untapped.

Furthermore, lawmakers in different countries have been prioritising different instruments and objectives, creating gaps and inconsistencies that risk undermining progress and hinder the circularity of global value chains. For example, while some countries have focused on capturing the value of resources downstream through recycling and recovery (e.g., Canada), others have adopted a more proactive waste prevention approach focused on product design (e.g., Japan, China, the EU).[64]

While these differences partly reflect country-specific contextual factors, they also point to the lack of global policy framework for the circular economy underpinned by common definitions, targets, standards, and metrics of success.

To some extent, these differences reflect the state of the debate over digital technologies, the role each country plays in global value chains, economic aspirations (e.g., to diversify the economy, to move to higher-value-added activities), priorities at the time of adoption (e.g., industrial competitiveness, equity), and the intellectual foundations of the economic system. But they also result from the lack of a consistent global framework for achieving circular production systems, underpinned by common definitions, targets, standards, and success metrics.

Considering the cross-cutting nature of sustainable production models and their reliance on the collaboration among several suppliers at different levels of the value chain, a piecemeal approach to the circular economy may fail to deliver results.

Learning about regional and national circular strategies, highlighting best practices, and understanding the role that each country plays in global value chains are key to developing effective and integrated policy frameworks that take a life cycle perspective to digitally enabled circular manufacturing.

Europe and Central Asia

The Europe and Central Asia region is extremely diversified in terms of economic structure. It comprises economies dominated by extractive industries (e.g., in Central Asia), economies that are making strides towards technology-intensive manufacturing sectors (e.g., new EU Member States and some South-East European countries), and high-income countries with a shrinking manufacturing base and a growing services sector (i.e., Western Europe).[65] While some parts of the region are at the forefront of the circular revolution and have already started looking at digital technology as a key enabler (e.g., the EU), others are moving more slowly (e.g., the Russian Federation).

European Union

The European Union has been at the forefront of the transition towards a sustainable economy for more than 20 years. Already in 1997, sustainable development was included in the Treaty of Amsterdam as a fundamental objective of the EU,[66] with the first strategy having been launched at the Gothenburg Summit in 2001.[67]

The EU's latest effort in this area is the 2020 Circular Economy Action Plan[68] to accelerate the transition to a more circular economy, which builds on the actions implemented since 2015 and represents one of the building blocks of Europe's roadmap towards the climate-neutrality target by 2050 (i.e., the European Green Deal).[69] This comprehensive plan outlines actions to establish a sustainable product policy framework, empower consumers and public buyers to play a more active role in the circular economy, promote circularity in key sectors (i.e., electronic and ICT, textiles, plastics, construction and buildings, packaging, batteries and vehicles, food), reduce waste, promote synergies with EU climate policies, and foster the circular economy at international level. The plan also includes measures to mobilise EU funds and private financing.[70]

The EU circular economy transition is also supported by the 2020 New Industrial Strategy[71], which lays out a plan to help EU industry and SMEs lead the twin transition towards climate neutrality and digital leadership. This strategy, which emphasises the role of digital technologies in enabling the adoption of circular business models, builds upon the work carried out by the Task Force on the Digital Roadmap for a Circular Economy. Convened by the European Policy Centre (EPC) between 2017 and 2019, the Task Force highlighted the need to systematically align the circular and digital agendas to achieve a sustainable and competitive Europe (Figure 20).[72]

EU Heads of States and Governments recently reaffirmed the centrality of the transition towards a circular economy and the digital transformation to recover from the impact of the COVID-19 pandemic and build a more resilient and less dependent economy to deal with unforeseen events.[74] In February, the European Commission also launched a Global Alliance on Circular Economy and Resource Efficiency (GACERE)[75] to help advance the circular economy transition at the global level.

United Kingdom

The UK is one of the countries in Europe that has achieved the most progress in terms of waste reduction, recycling, and reuse[79], and it was the first major economy to set a target to bring all greenhouse gas emissions to net-zero by 2050.[80] Following Brexit, the country renewed its commitment to leadind the new green industrial revolution with the Circular Economy Package (CEP).

Box 2

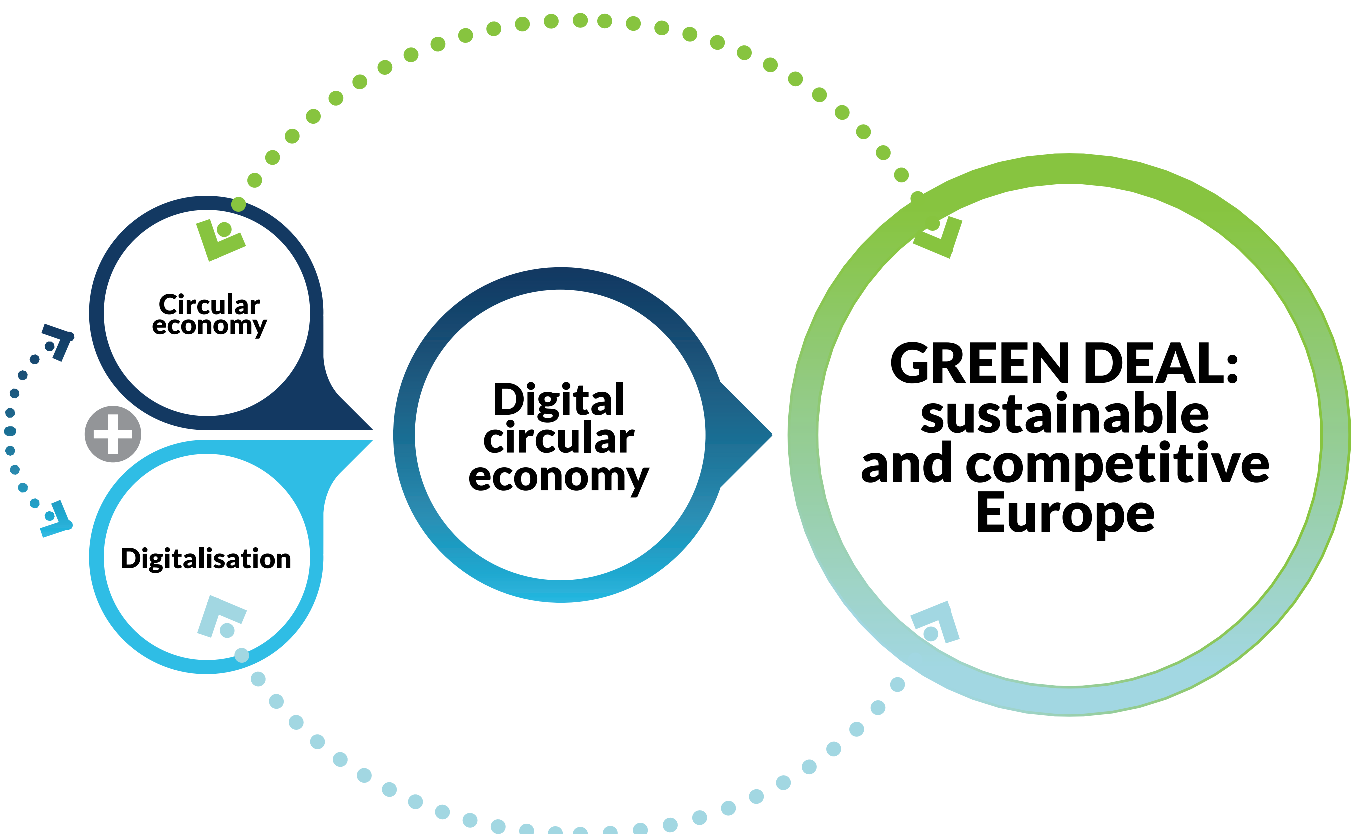
Tracking progress across EU Member States

In addition to being responsible for implementing European policies, EU countries—and, in some cases, even regions and cities—have adopted their own regulations to promote a circular economy[76], with uneven results in waste reduction, recycling, and reuse. A comprehensive list of these initiatives can be found on the European Circular Economy Stakeholder Platform.[77] The European Commission also tracks national progress on achieving CE goals by compiling ten indicators divided into four thematic areas: production and consumption; waste management; secondary raw materials; competitiveness and innovation.[78]

Figure 20

Interactions between a circular economy, digitalisation, and the European Green Deal[73]

(Source: European Policy Centre)



The CEP is an overarching legislative framework that identifies steps to reduce waste and establishes a "long-term path for waste management and recycling.[81]

In addition, the Government adopted a Ten Point Plan to increase the level of ambition in ten key areas (i.e., offshore wind; carbon-hydrogen; nuclear power; zero-emission vehicles; public transport; "jet zero" and green shipping; carbon capture, usage, and storage; natural environment; finance), thanks to the mobilisation of GBP 12 billion of government investment.[82] The UK Government also announced the creation of five interdisciplinary economy centres tasked with exploring the potential of the circular economy in the textiles, construction, chemical, and metal industries.[83]

Turkey

The transition towards a circular economy in Turkey was kickstarted by the EBRD with the launch of the Near Zero Waste Programme (NØW) in 2015, as part of its Green Economy Transition (GET) approach[84] to increase green financing.

NØW is a strategic initiative developed in partnership with the Clean Technology Fund and the EU to promote waste minimisation and pollution prevention projects across different economic sectors. The initiative is based on four pillars: investments, technical assistance, policy dialogue, and awareness raising and knowledge sharing.[85] One year later, the EBRD also launched the Turkey Materials Marketplace (TMM) in partnership with the Business Council for Sustainable Development Turkey (BCSD Turkey). TMM is a cloud-based platform designed to facilitate cross-industry materials (waste, by-products and unused raw materials from production processes) re-use among Turkish companies.

Russian Federation

Despite having signed all UN agreements on climate, the Russian Federation's efforts towards greening the economy have been lagging behind.

According to some critics, the lack of progress is due to poor political leadership, pressure by energy lobbies, and scientists willing to downplay the climate threat to appease the government.[86] For example, the Russian Union of Industrialists and Entrepreneurs was able to water down a climate legislation that would have imposed emissions quotas, and the country's recent Energy Strategy 2035 prioritises the development of fossil fuel industries to the detriment of renewable energy sources.[87]

The COVID-19 pandemic has now increased the need for urgent action on climate, biodiversity and waste, forcing countries around the world -including Russia- to rethink their socioeconomic and sociocultural systems.[88] In this context, the country recently passed a law on waste management[89], and the Prime Minister, Mikhail Mishustin, announced the government's intention to develop a circular economy, increase the share of eco-packaging, and halve waste disposal.[90]

North America

Due to its influence and economic relevance, North America has an important role to play in the global transition towards sustainable production and consumption.[91] The United States and Canada combined account for more than 17 percent of global GDP based on purchasing power parity (PPP)[92], and generate a record amount of waste (2.58 kilograms and 2.33 kilograms of daily municipal solid waste per capita respectively).[93] Furthermore, both countries have developed and diversified economies and are rich in natural resources.

The region is also home to some of the largest and most innovative technology companies (e.g., Google, Amazon, Cisco). Thanks to their digital capabilities, these companies can play a pivotal role in overcoming key barriers that currently prevent the uptake of circular business models.[94] Many of these companies have already established circular economy strategies and are members of the Ellen MacArthur Foundation's community.[95]

United States

After four years of relative inaction, President Joe Biden has made the transition to a greener economy a core priority of his political agenda. As part of this push, in April 2021 the Biden-Harris administration announced that the country aims to achieve a 50-52% reduction in greenhouse gas emissions by 2030 compared to 2005 levels[96], and it is now proposing that Congress approve a USD 14 billion hike in the 2022 budget to be spent on initiatives to fight climate change. The proposal includes USD 11.1 billion in additional funding for the U.S. Environmental Protection Agency (EPA) and USD 10.2 billion for the National Science Foundation.[97] Meanwhile, the EPA has already put forward a national strategy to increase the domestic recycling rate from 32.1% to 50% by 2030.[98]

In the US, the transition towards a circular economy is also facilitated by The REMADE Institute (i.e., Reducing EMbodied-energy And Decreasing Emissions)[99], a public-private partnership established by the US Department of Energy in the context of Manufacturing USA, a network of institutes operated by the interagency Advance Manufacturing National Program Office in the Department of Commerce to secure US global leadership in advanced manufacturing.[100] The partnership, which involves industry and independent researchers, pursues efforts to drive down the cost of key technologies needed to reuse, recycle and remanufacture materials such as metals, fibres, polymers, and electronic waste.[101]

Canada

Canada's commitment to a circular economy has progressed at a much slower rate compared to the rest of the world. Furthermore, initiatives to foster a circular economy have been focused on recycling and resource recovery, with minimal emphasis on waste reduction.[102] This has been changing in recent years. For example, the Canadian Government recently formulated a comprehensive plan to achieve zero plastic waste by 2030, including a ban on harmful single-use plastic items (e.g., bags, straws).[103]

The Government's efforts to reduce plastic waste are also supported by circular economy stakeholders thanks to various private-led initiatives. Among them, the Canada Plastic Pact[104], a "multi-stakeholder, industry-led, cross-value chain collaboration platform" created within the framework of the Ellen MacArthur Foundation's Plastics Pact network, a global effort to tackle plastic waste and pollution.[105] In September, Canada will also host the 2021 edition of the World Circular Economy Forum (WCEF).[106]

Asia and the Pacific Region

Asia and the Pacific Region comprises a diverse group of countries experiencing growth in population, economic development, urbanisation, and migration. These trends put enormous pressure on the global demand for energy and natural resources[107], making the adoption of sustainable business models even more salient than in other regions.

As several Asian-Pacific countries already have circular strategies in place and are digital leaders[108] (e.g., China, Japan, India, Republic of Korea), the region presents significant opportunities to rapidly accelerate the transition towards a circular economy.

China

The country outlined its latest circular economy strategy in the 14th Five-Year Plan (2021-2025) approved by the National People's Congress in March.[109] The plan, which builds on the successes of the 13th Five-Year Plan[110], is the first since President Xi's commitment to achieve carbon neutrality before 2060.[111]

Although the plan has already been criticised for failing to establish clear climate and environmental targets[112], it sets some important priorities directly relevant to the promotion of a circular economy: improving energy and resource efficiency both in traditional sectors (e.g., manufacturing, buildings, transportation) and emerging fields (e.g., 5G, big data centres); building a multi-level resource-efficient recycling system; actively promoting the green economy; strengthening legal and policy guarantees for green development (e.g., tax policies conducive to energy conservation and environmental protection, green finance, measures to improve the price formation mechanism for natural resources and energy use).[113] More detailed measures are expected to be formulated later this year or by early 2022.

So far, China's circular economy goals have been pursued thanks to a combination of policies, binding targets, legislation, and financial instruments.[114]

Japan

Japan launched its first Circular Economy Vision based on the "3RS" (i.e., reduce, reuse, recycle) back in 1999, to depart from a growth model based on mass production, consumption, and disposal in favour of a model that integrates environmental and economic considerations.[115] Although the 3Rs still underpin the country's efforts to achieve a circular economy, the recent development of digital technologies and growing demand for environmental action have changed the framework conditions, making the transition towards the circular economy a profitable business strategy.

In response to these changes, Japan's focus has shifted towards the need to encourage companies' voluntary adoption of circular business models, "with minimal introduction of regulatory measures".[116] Japan's Circular Economy Vision 2020 is part of the country's green growth strategy, which also includes a roadmap to triple the renewables' share of power generation to at least 50% and achieve net-zero greenhouse gas emissions by 2050.[117]

India

Although India has put in place several policies to promote resource efficiency throughout the life cycle, results have been limited due to the lack of an overarching strategy and a supportive ecosystem.[118]

To overcome these challenges, the Indian Ministry of Environment, Forest and Climate Change (MoEFCC) created a Resource Efficiency Cell tasked with developing a whole-of-government approach to resource efficiency based on materials, products, and processes.[119] The work of the Cell is guided by a steering committee composed of experts from academia, civil society, think tanks, and international and multilateral institutions.[120]
Also, the country's digital backbone can play a key role in supporting the transition to a circular economy and serve as an example to other developing countries.[121]

Republic of Korea

South Korea's approach to the circular economy has gradually shifted from the "safe disposal of wastes" to "waste reduction at source and recycling".[122] This shift in focus led to the adoption of the Framework Act on Resource Circulation (FARC) in 2018, comprehensive legislation that aims to establish a "resource-circulating society".[123] To this end, the FARC introduces provisions to establish a basis for resource circulation, promote resource circulation and support recycling industries. These measures are summarised in Figure 21. South Korea recently adopted a strategy to achieve carbon neutrality by 2050[125] that identifies in the transition to a circular economy a key goal to help reduce GHG emissions while conserving the ecosystems.

Latin America and the Caribbean

Countries in the Latin America and Caribbean (LAC) region range from large, rapidly growing high/middle-income economies (e.g., Brazil, Mexico, and Argentina) to small, vulnerable states (e.g., Haiti).[126]

LAC's specialisation in low-technology sectors and dependency on commodities act as a constraint on growth and intraregional trade[127] and leave the region more vulnerable to systemic shocks.[128] LAC countries tend to also be vulnerable to climate-related natural disasters.[129] Read in aggregate, these regional features add to the relevance of the circular economy as an opportunity for sectoral diversification able to generate added value.[130]

Most recently, the circular economy and Industry 4.0 have also become central topics in the policy debate on how to build economic resilience in the region and recover from the crisis triggered by the COVID-19 pandemic.[131] According to a Chatham House report, circular economy frontrunners in LAC include Colombia, Chile, and Uruguay.[132]

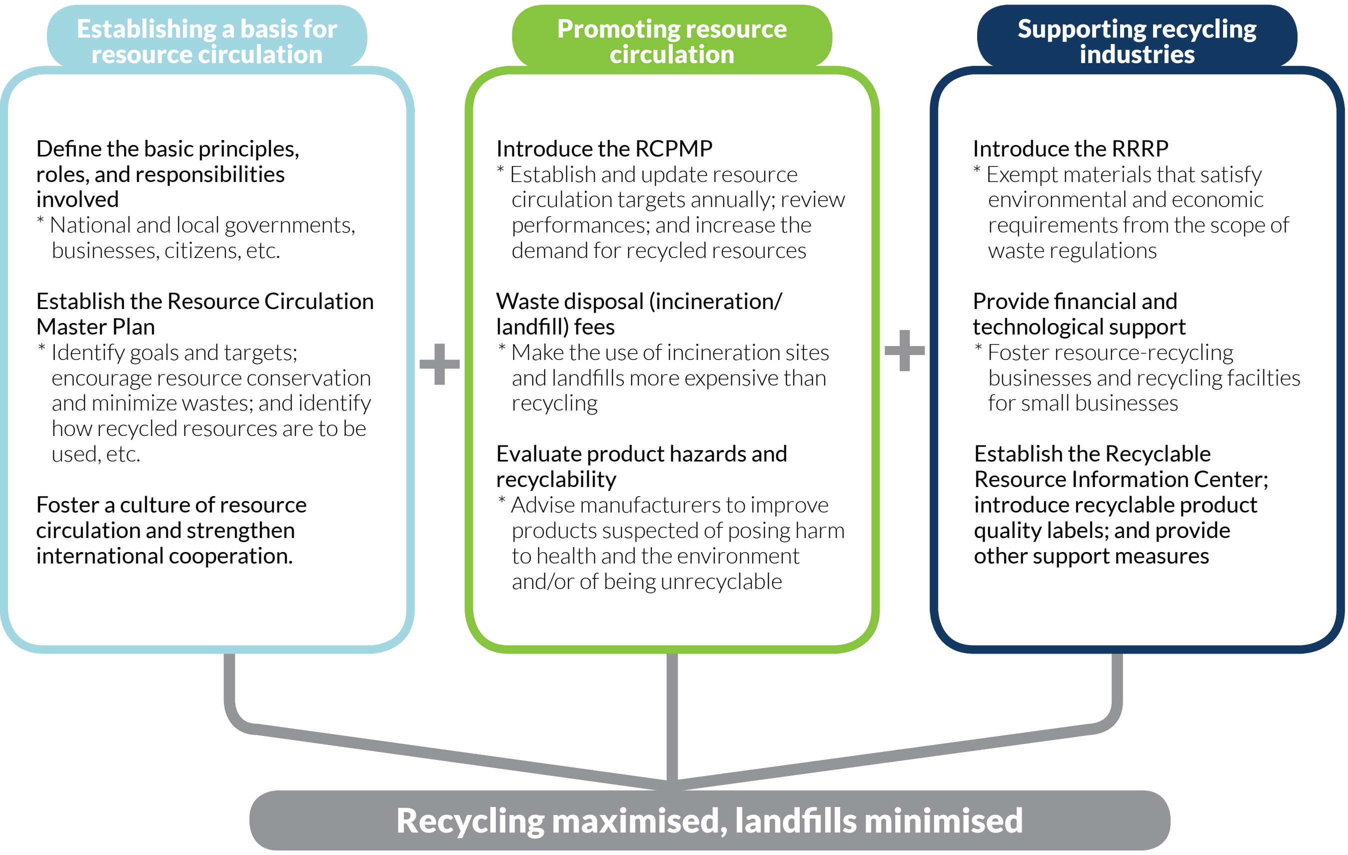
Colombia

Colombia was among the first countries in the region to adopt a National Strategy for the Circular Economy in 2019. This strategy seeks to promote the continuous valorisation of resources and increase the efficiency of production processes. It also sets a quantitative goal to increase the rate of recycling and reuse of waste materials from 8.7% to 17.9% by 2030.[133]

Figure 21

FARC provisions by category [124]

(Source: Korea Environmental Policy Bulletin Vol. XIV Issue 2)



Chile

Chile has been a pioneer in introducing a circular economy component in its nationally determined contribution (NDC) to reduce global emissions and address the impacts of climate change.

Other initiatives adopted by the country to promote a circular economy include a national roadmap to achieve a zero-waste economy[134], a programme to finance innovative circular opportunities[135], and a pact with the UK and France to ban single-use plastics.[136] Chile also plans to combine Industry 4.0 and circular economy technologies to become a global supplier of lithium batteries for electric cars.[137]

Uruguay

Several international organisations have long identified Uruguay as a "green energy leader".[138]
As early as 2004, the country established a law to promote the reuse, recycling, and recovery of packaging, and the promotion of the circular economy is included in Uruguay's national development plan. Most recently, the Uruguayan Government created the National System for Productive Transformation and Competitiveness, a multi-stakeholder initiative that led to the creation of a Circular Economy National Action Plan in 2019.[139]

Box 3

The LAC Circular Economy Coalition

The circular economy model recently gained traction in the region as a strategy to fulfil global commitments (i.e., sustainable development and GHG emissions reduction targets) and build resilient economies and societies post-COVID-19.[140]
One outcome of this focus was the Latin-American and the Caribbean Circular Economy Coalition launch[141] in February 2021. Coordinated by the United Nations Environmental Programme (UNEP) and supported by eight strategic partners (e.g., Ellen MacArthur Foundation, Inter-American Development Bank, Konrad Adenauer Foundation, Platform for Accelerating the Circular Economy Coalition, United Nations Industrial Development Organization, World Economic Forum, Climate Technology Centre & Network), the Coalition aims to facilitate the exchange best practices and cross-sectoral collaboration to accelerate the CE transition.[142]

Box 4

The African Circular Economy Alliance

Conceived in 2016 at the World Economic Forum on Africa in Kigali and formally launched at COP 23 in Bonn by Rwanda, Nigeria, and South Africa, the African Circular Economy Alliance (ACEA) is a government-led coalition of African nations that aims "to spur Africa's transformation to a circular economy".[146] This objective is pursued by sharing best practices, facilitating circular economy projects, raising awareness, and bringing about partnerships among member countries.
The Alliance also identified five industries that offer immediate opportunities for increased circularity (i.e., food systems, packaging, the built environment, electronics, and fashion and textiles), and some key enablers to support a transition towards digital production systems in these sectors (i.e., supportive policy, business development services, relevant data and information, access to technology and financial services, and infrastructure solutions).[147]
The ACEA's secretariat is hosted at the African Development Bank (AfDB), with support from the World Economic Forum, which supports the alliance's mission more broadly on the continent.
Despite ACEA's efforts, in Africa, the shift towards a circular economy is still largely driven by the private sector.[148]

Africa Region

The Africa region comprises diverse sub-Saharan countries facing common challenges, such as poverty, inadequate infrastructure, skills shortage, and limited development opportunities for companies and especially SMEs.[143]

Although Africa's economic prospects looked promising at the beginning of 2020[144], they were severely compromised by the COVID-19 pandemic. In particular, "the steady increase in manufacturing production since 1986 was reversed and dropped below the 1.3 percent recorded in 2019, while many companies transitioned to producing essential medical supplies to make up for the lower levels of international demand for other products".[145]

A shift towards a digital-enabled circular economy can help African countries regain industrial capacity, adapt to new global conditions, and leapfrog to a low-emission, climate-resilient, and sustainable development model.

Middle East and North Africa Region

Countries in the Middle East and North Africa (MENA) region range from rich oil producers (e.g., Saudi Arabia, the United Arab Emirates) to least developed countries focused on agriculture production (e.g., Sudan, Yemen).[149]

Although each country has its own challenges, common issues include currency devaluation and rising inflation; import reliance; high unemployment, further exacerbated by the COVID-19 pandemic; corruption and public mismanagement; a general disregard for natural resources and environmental impact.[150]

Although the circular economy can be a pathway to alleviate most of MENA's challenges, from extreme inequality to environmental degradation, only a few countries have already adopted initiatives to promote sustainable production and consumption patterns (e.g., Saudi Arabia, the United Arab Emirates).[151]

Key Enablers of the Circular Manufacturing Transition

Our analysis suggests that achieving a circular economy is within reach: people across the world support climate and environmental action, giving politicians a clear mandate[152]; a growing number of countries are looking at the circular economy as a key strategy to build sustainable and resilient economies post COVID-19, and emerging technologies have the potential to improve resource efficiency, reduce waste, and cost-effectively cut emissions.

Yet, companies—especially SMEs—are delaying the adoption of circular business models. While corporate inertia might have a role to play, this transition also requires an enabling environment that promotes digital technologies and innovation at the company level, supports coordination and collaboration across the whole value chain and incentivises the demand for circular products. The rest of the chapter looks at the key enablers of the circular manufacturing transition within three dimensions: at consumer level, company level, and value chain level.

Circular Economy Enablers at Consumer Level

Despite often being disregarded, circular manufacturing critically depends on policymakers' ability to support changes in consumption patterns. There are at least two reasons for this. First, promoting sustainable consumption would directly address the root causes of environmental degradation. Second, it would drive the implementation of circular business models as a strategy to conquer new and growing markets.[153]

Although there is limited research about the factors affecting consumers' acceptance of sustainable consumption models, four factors are likely to play a key enabling role: environmental awareness, trust and transparency, convenience, and digital literacy.

Environmental awareness
A thorough understanding of environmental issues and the impact of our consumption choices on the planet, the people living in waste-importing countries[154], and future generations, can help direct consumer demand towards circular/sustainable products. According to a BCG survey[155] , the COVID-19 pandemic has heightened environmental awareness and increased the commitment towards sustainability. In particular, 87 percent of respondents said that "companies should integrate environmental concerns into their products, services, and operations to a greater extent than they have in the past".[156] This trend is particularly strong among younger people, with major demographic implications on governments and companies.

Trust and transparency
The last decade has seen the emergence of an "access-based" consumption model as an alternative to the "ownership-based" model. Popular examples include the car-sharing

service, ZipCar, and the short-stay accommodation service, Airbnb. This new paradigm that underpins the "sharing economy" can play a key role in fostering sustainable consumption patterns by increasing the utilisation rate of a product and/or "ensuring the return of products and their resource management throughout multiple lifetimes".[157]

Although "the value created by sharing these goods is not, for the most part, being captured by product manufacturers," the sharing economy can represent an "opportunity for manufacturers to reconfigure their own business models, re-envisioning the nature of their products in a way that helps them take advantage of the product-as-a-service concept".[158]

One challenge of access-based consumption is fostering consumers' trust in the service provider, its reliability, and product availability.[159] Regulation that empowers consumers by clarifying the company's responsibilities may help support it.

Convenience

As discussed, consumers are increasingly concerned about the environment. Nonetheless, to translate these concerns into buying decisions, consumers should have access to sustainable products that are both affordable and comparable in terms of performance.[160]

Digital Literacy

As consumers' ability to use digital innovations will be key to realising circular economy opportunities, these should be made accessible to communities at all socio-economic levels by investing in both digital infrastructure and digital literacy.[161]

Circular Economy Enablers at Company Level

Many companies are already making headway in the circular economy, and others are increasingly interested in its potential to shrink their environmental footprint, trim operational waste, and improve resource efficiency.[162] Nonetheless, the adoption of a circular business model is a complex task, and failure can be costly.[163]

For companies to embark on this risky journey requires policymakers to pay greater attention to some key enablers that would either remove existing barriers or increase the expected profitability of circular investments: robust demand for sustainable products, the availability of digital technologies and circular skills, top-management commitment and purpose, resource prices that incentivise the use of secondary resources, a supportive policy framework, and access to financial services.

Demand for Sustainable Products

The presence of robust demand for sustainable products can provide a strong incentive for manufacturers to develop new value propositions that align with the aspirations of environmentally aware consumers.

Sustainability has already become a big trend in the packaged goods and fashion industry, representing one key driver of consumers' purchasing decisions.[164] Furthermore, according to a survey conducted by IBM[165], three out of five consumers around the globe "are willing to change their shopping habits to reduce environmental impact," and four out of five consider sustainability to be "important for them." For those who say it is very/extremely important, "over 70 percent would pay a premium of 35 percent, on average, for brands that are sustainable and environmentally responsible".[166]

Digital Technologies

As discussed in previous chapters, emerging digital technologies such as AI/ML, IoT, 3D printing, and Blockchain can accelerate the transition towards circular manufacturing. Ensuring their uptake by companies—especially SMEs—is essential to enable their integration in value chains that apply circular economy principles.

Circular Skills

The availability of skills will also play a crucial role in enabling the circular economy manufacturing transition. Although it is impossible to forecast what specific skills will be needed to meet the needs of circular business models, these will entail a combination of "green skills" (i.e., defined by the UNIDO as "the knowledge, abilities, values, and attitudes needed to live in, develop and support a sustainable and resource-efficient society")[167], and "digital skills" (see the WMF's Top Ten Skills for the Future of Manufacturing[168]—i.e., digital literacy, AI and data analytics, creative problem solving, entrepreneurial mindset, ability to collaborate with new technology, an inter-cultural and -disciplinary, inclusive, and diversity-oriented mindset, privacy and data/information mindfulness, ability to handle complexity, communication skills, ability to handle change).

Furthermore, as manufacturers start adopting a product-as-a-service business model, all workers—from white collars in executive positions to blue collars on the shop floor—will need to "understand and take ownership of their roles in a wider regenerative system".[169]

As stressed by the Circular Jobs Initiative, a knowledge centre that aims to ensure a positive transition to the circular economy for work and workers, the transition from product to service "will be a particular challenge in sectors that traditionally have a risk-averse mindset and tend not to hold responsibility for products past the point of delivery".[170]

Top-Management Commitment & Purpose

According to a survey conducted by the R2π project[171], circularity can only be achieved if the top management considers the implementation of circular economy business models an economic opportunity to be pursued over the long term. Furthermore, circular economy business models need to be supported by a company culture that ties circularity in with social and ethical goals. As stressed by R2π, purpose-driven approaches can be "motivating for employees," enhance productivity and facilitate the attraction and retention of talent within the company.[172]

Resource Prices

For circularity to be considered a viable business strategy, three things need to happen regarding resource prices. First, manufacturers need to be able to access "abundant, cheap, green energy to support secondary raw material use".[173] Second, the price of fossil fuels should reflect its true cost (i.e., it should internalise their negative impact on public health and the environment). Third, companies should be able to sell their waste to other companies that can use it as input. [174]

Supportive Policy Framework

Whenever possible, policymakers should favour market-based incentives over prescriptive regulations. For example, governments could promote the use of secondary material by modernising their taxation systems rather than setting resource efficiency targets. Or, again, they could embed environmental considerations in their public procurement decisions to incentivise the adoption of circular business models.

Access to Financial Services

As highlighted in Chapter 1, the lack of financial resources is considered a "major" obstacle towards building a circular economy and bringing it to scale.[175] This barrier, if properly addressed, could be transformed into an enabler. Options include a temporary system of direct subsidies to overcome market failures; regulations that increase investors, banks, and financial services firms' incentives to support circular economy projects; and blended finance solutions that combine public and private resources.[176]

Circular Economy Enablers at Value Chain Level

Achieving a circular economy requires more than promoting the demand and supply of sustainable products. To close the production loop and retain value across the whole circular production cycle, policymakers need to take a value-chain approach to support communication and collaboration among people, materials, and processes.
Against this background, an effective circular economy strategy should incorporate three key enablers of circular economy business models at the value chain level: data sharing, infrastructure and networks, and the standardisation of requirements.

Data Sharing

As stressed by the Boston Consulting Group, "data sharing can facilitate coordination and foster trust among multiple parties in a supply chain, enabling new business models in a circular economy".[177]
For example, the adoption of circular economy business models implies the ability to recycle materials. But due to their complexity, recycling them properly requires precise knowledge of their composition and content, which can be acquired only by sharing data between manufacturers and recyclers.

Data-sharing is also essential in the product-as-a-service business model. In this case, manufacturers may need to acquire data from the customer to control machinery and exercise predictive maintenance remotely.
Unfortunately, data sharing is complex and full of obstacles. As observed last year in the 2020 World Manufacturing Report, data sharing may raise several challenges, including the need to comply with privacy laws, cybersecurity threats, data quality, and the lack of standardisation in data collection practices.[178]

Infrastructure, Networks

According to a recent stakeholder survey, existing infrastructure is insufficient to support the transition to a circular economy.[179] Suitable recycling and product recovery infrastructure, as well as infrastructure to support data sharing, are fundamental for this transformation to succeed.[180]

Standardisation of Requirements

Consumers and suppliers along the whole value chain should have access to objective, standardised, and reliable information about the sustainability of a product.
Among other reasons, standards can help manufacturers identify environmentally conscious suppliers, prevent "greenwashing" (i.e., the practice of making false/misleading claims about the environmental qualities of a product or service)[181], help assess how goods can be disposed of, and promote trust.

One popular methodology to quantify sustainability is the Life Cycle Assessments (LCA), "a technique to assess the environmental aspects and potential impacts associated with a product, process, or service".[182]
In the case of digitally enabled circular manufacturing, the standardisation of technical requirements can also promote interoperability, data sharing, and technology transfers, which are essential to foster AI adoption and allow new applications to emerge.[183]

Fostering Engagement in a Place-based Circular Economy

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Introduction

The need for sustainable practice has grown rapidly in global corporate language given the acceptance of the impact of climate change. The latest UN IPCC report[1] has emphasised the urgency for action; it is no longer a matter of if or why we should adopt sustainability measures, but how and when. The circular economy (CE) is recognised as one means of reducing impact and engaging manufacturers in exploring new opportunities for circularity. Businesses and their supply chains will benefit from improved operations through industrial symbiosis, re-designing products and packaging, and resource sharing.

Circular economy principles are well illustrated through both the Ricoh comet circle[2] and the Ellen MacArthur butterfly diagram[3], which demonstrate many circularity opportunities available. CE prioritises retaining the maximum value by focusing on the shortest product journey (or 'loop') within the supply chain. Importantly, CE offers opportunities beyond supply chains to benefit the communities around each business. Place-based solutions can take a variety of forms outside traditional supply chains, from neighbouring companies on a business park or city centre, to community groups and businesses collaborating to create new local opportunities. Importantly, Small and Medium-sized Enterprises (SMEs) which may not have staff availability or a sufficient volume of 'waste' to consider traditional supply chain routes to reuse, can collaborate locally with other businesses and stakeholders to make the best use of resources.

Place-based circularity is mutually beneficial to businesses, the environment, and society. It can engage more businesses as well as be more visible to the customers and communities around those businesses – SMEs form part of the local fabric of their communities, and therefore driving change within them can trigger further change. Yorkshire, a region towards the northeast of England, has one such example.

The case of Circular Malton

The Circular Malton initiative was launched in 2019 by a group of UK stakeholders, led by Sue Jefferson, a Malton resident and one of York and North Yorkshire (YNY) Local Enterprise Partnership's (LEP)[4] (regional development agency) Board Members.

Malton (market town, population c.10,000) has a variety of businesses embracing CE. New start-ups and established businesses are taking advantage of CE to reduce costs, reduce carbon and be distinctive. The Circular Malton[5] team have led the campaign to showcase innovative circular practices through events and directing businesses to funding support. Essentially, educating and inspiring people to change. New value opportunities have been develop ed, such as an anaerobic digester to produce energy from local food waste. Encouraging collaboration between businesses has been an important factor in Circular Malton's success. Businesses are moving resources locally and new business created.

Bringing CE into the community helps make opportunities visible and achievable; businesses and residents can see initial changes, creating a desire to achieve more. Research commissioned by the Circular Malton team evidences the community cultural change with 62% of respondents aware and 88% supporting further change. In striving to become Yorkshire's first Circular Market Town, Malton has provided inspiration for others to follow.

The role of the region

Circular Malton is part of YNY LEP's larger campaign, Circular Yorkshire[5], which aims to educate, engage, and inspire residents, communities, and businesses in terms of what CE is, how it relates to their day-to-day lives and how they can participate. "There is a critical role for regional development bodies to coordinate local, place-

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based circular economy action," said Katie Thomas, Senior Strategy Manager for the Low Carbon and Environment Team at the LEP. "We understand local business challenges and have the capability to build partnerships between diverse stakeholders to close the loop on resource flows."

Circular Yorkshire has supported SMEs across sectors (including in Malton) to implement CE. "Flexibility is key," said Erin Wheeler, Circular Economy Officer in the Low Carbon and Environment Team. "We can support businesses of all sizes and sectors; how they engage in circularity to find opportunities will look very different."

Circular Yorkshire's work has led to their Circular Towns Guide, which introduces CE and provides a ten-step framework for communities to start their CE initiatives. Businesses will be encouraged to become 'circular champions' for place-based solutions – embodying sustainable principles and demonstrating CE in action. The guide complements LEP resources such as the Circular Economy Guide, Demonstrator Projects and Business Case Studies[5].

Lessons for manufacturers

Circular Malton demonstrates the appetite for circularity practices at community scale. A place-based approach offers the opportunity to foster enthusiasm and share expertise. By recognising businesses as one element of a larger landscape, we can move CE beyond the confines of those existing businesses.

The Six Capitals[5] concept allows a more granular distinction of the foundations of sustainability. We already recognise the importance of financial and manufacturing capitals (economic pillar) and natural capital (environmental pillar). Importantly, we must emphasise the worth in the human, social and knowledge capitals (social pillar) more. This places greater value on people, what knowledge they have and their networks that bring different stakeholders together, enriching communities and providing new opportunities for knowledge and skill sharing.

Manufacturers can use CE to extend and reinforce their purposefulness. Working locally, businesses and communities can mutually benefit from collaboration that bring new income streams and resilience. Taking part in a place-based initiative can also support employee well-being and create a sense of belonging as the company invests and supports the landscape it sits within.

Taking the role of 'circular champions', businesses can foster sustainability ambitions locally, share expertise and create local benefit. Collaboration is essential. Using processes such as the Cambridge Value Mapping Tool[6], manufacturers can identify opportunities and prompt dialogue with others to seek sustainable pathways.

CE provides opportunities to view our resources differently and create a system for businesses and the environment to thrive. The example of Circular Malton demonstrates place-based solutions to the climate crisis and offers SMEs the chance to prosper locally in terms of change. By recognising existing businesses as being part of a larger landscape, we can create new business opportunities and ensure those opportunities benefit our local businesses, communities and environment.

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How Decentralised Manufacturing can Lead to Efficiency and have Positive Environmental Impacts on the Process

by Joel Neidig
CEO SIMBA Chain

Long before the Covid-19 outbreak, it was my belief that manufacturing would become decentralised and distributed. With all that has taken place since 2020, that view has only been cemented in my mind, and SIMBA Chain offers a pathway to that future.

SIMBA Chain is a cloud-based, smart-contract-as-a-service (SCaaS) platform, enabling users across a variety of skill sets to implement dapps (decentralised applications). These apps allow secure, direct connections between users and providers, eliminating third parties. The easy-to-use platform is tailored for users, developers, government, and enterprises to quickly deploy blockchain dapps for their enterprise.

The future of manufacturing is not an urban centralised industrial complex, but rather one where manufacturing takes place at the point of use for the consumer. With the advent and democratisation of 3D printing in combination with a distributed decentralised digital thread using Blockchain, the sharing of ideas, designs, and products can be consumed at the point of use while still maintaining intellectual property and providing the best price model for the seller and consumer.

Imagine that a farmer in Indiana has a tractor that recently broke a pulley on the engine. Instead of the local supply store having to stock hundreds of thousands of dollars of inventory or ordering the part from the manufacturer and waiting for delivery, they have one metal 3D printer that they can use to print any part on-demand from the OEMs catalogue and provide it within the same day to the farmer, thus reducing the local farm supply store's overheads and providing the most competitively priced component to the farmer. Additionally, this approach to manufacturing leads to more efficiencies in material use and expands savings beyond the manufacturing process to the supply chain with less of an emphasis put on the transportation of finished goods by the various suppliers who would need to be traditionally stocked, positively affecting the environment.

Now, how do we protect the intellectual property and everyone in between? Enter the Blockchain. The blockchain is a chain of blocks that form a database. Devices that store these distributed data are not shared servers. Each block is an ordered record that contains a reference to the previous block and the time stamp. The list of blocks inside the database is constantly growing. The principle of the blockchain is to combine digital records into blocks. Complex mathematical algorithms link these blocks together in a chronological cryptographic chain, then new units are added at the end of this chain. To rearrange the blocks in some places is impossible - the system will reject such action on the basis of the timestamp and structure. The digital thread of models to 3D print various products from OEM catalogues can be secured in these digital blocks and only be accessed if payment is made, subsequently releasing the file to be used once for printing on the machine through which the payment is made. It's almost like an on-demand manufacturing vending machine.

A great physical example of this is Coca-Cola. They set up a business model in which everybody makes money. Within very short order, they had worked out a model in which the bottlers, transporters, servers, and soda fountains were all making money. There was also a big push during World War II. Coca-Cola made a deal with the Army to provide a Coke to any soldier anywhere in the world at a nickel a piece, and they got the Army to support this. This meant that the Army did all the transportation and helped build bottling plants. At the end of the war, the infrastructure was in place in practically any country in the world and there was a whole generation totally devoted to Coke.

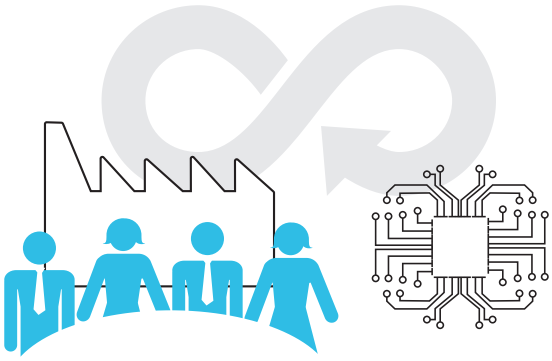
Bringing manufacturing to the source of use is the future: large warehouses and storage facilities like Amazon distribution centres will be a thing of the past in 20 years' time. Everything from consumer products to electronics to industrial components will be printed on-demand via Distributed Decentralised Rural Agile Manufacturing.

4

Key Recommendations

The World Manufacturing Foundation, in collaboration with experts globally, is pleased to present the Ten Key Recommendations of the 2021 World Manufacturing Report. We hope our readers can embrace these recommendations and work together towards a successful transition to circular manufacturing, enabled by digital technologies.

1. PROMOTE A CIRCULAR COMPANY MINDSET THAT EMBRACES THE OPPORTUNITIES OF THE CIRCULAR ECONOMY AND THE ENABLING ROLE OF DIGITAL TECHNOLOGIES



- **Acknowledge that the circular transition is a must**
- **Define new key performance indicators related to circularity**
- **Educate citizens on sustainable consumption**

Companies must understand that the transition to the circular economy is not optional but a must. With more and more customers demanding sustainable products and a global regulatory landscape driving companies towards circularity, it has become more urgent than ever before for manufacturers to rethink how their products are designed and produced. In addition, they should take responsibility for what happens to their products past the point of delivery to customers.

A circular mindset acknowledges that resources are finite and adopts a broader view of the product lifecycle. This places importance on analysing the environmental impact of producing a product from the early stages of designing and sourcing raw materials, to when it is manufactured, used by consumers, and reaches its end of life. To achieve this, companies must think "out-of-the-box" in designing products with circularity in mind, experimenting on sustainable materials, exploring new ways of production that minimises waste, and adopting more sophisticated life extension and recovery processes that give additional and new life to materials.

As discussed throughout this Report, digital technologies have an immense potential in enabling companies in the transition towards the circular economy, and companies must understand and exploit this potential. Companies should therefore inform themselves about the available digital solutions and what impact they could make to achieve their objectives related to circularity. Companies should not think of sustainability as a constraint but rather an opportunity or potential source of competitive advantage. In fostering this circular mindset throughout the organisation, commitment from top management is necessary. Circularity should be kept in mind in every major company decision which includes designing business models. In addition, circularity goals should be aligned with other company objectives, such as profitability. For example, companies should make environmentally-friendly products more accessible to consumers, both in terms of choice and price. Today, consumers are still paying a higher premium for such sustainable products and making them more accessible can increase their adoption. When assessing operational performance, more metrics should be used such as "resource productivity" and "carbon footprint" in addition to traditional operational excellence measures. This gives a more holistic assessment of a company's impact on the environment and society.

It is equally important to educate citizens on the importance of sustainable production and consumption. Different actors such as governments, schools, and companies have a role to play by providing information that allows consumers to make environmentally conscious decisions. This includes educating them on the proper disposal of products or developing schemes that incentivise recycling and reuse. For example, through (eco-) labelling, many companies can provide more information on the products such as material composition, how they are sourced, and the correct way to dispose of them. Quantifying the waste generated or using a meaningful measure such as the carbon footprint, can help consumers make conscious decisions with regard to the purchase and use of products. As evidenced in Recommendation 2, consumers also have an active role to play in the transition to circular manufacturing, highlighting the dual responsibility of companies and consumers.

2. DRIVE CIRCULARITY THROUGH CONSUMER RESPONSIBILITY, PROACTIVITY, AND CONSCIOUS DECISION-MAKING

- **Inform oneself on circularity and the environmental impact of consumption**
- **Demand sustainable products from companies**
- **Take advantage of the sharing economy to increase utilisation of products**

Every individual has a role to play in the transition to the circular economy. Manufacturers develop products and services for society, which then consumes or uses those products. In the same way, manufacturers are also considered consumers as they source the inputs used in their production from someone else. Hence, their actions have a big impact on the transition towards circularity.

Consumers must understand what circularity means and how their actions impact circularity. This extends to making informed decisions when purchasing new products and being mindful of how they are used and eventually disposed of in an environmentally safe manner. Consumers must realise that they are part of a bigger community, which is impacted by their individual choices and actions.

Consumers must also be proactive and demand sustainable products from companies. The new breed of consumer activism, centred on circularity, must favour companies that produce and sustainably dispose of products. With the advent of the Internet and social media, there are now many channels and sources from where information can be obtained about how products are manufactured, as well as the environmental track record of their producers. As mentioned in Recommendation 1, companies can provide more information such as material composition, certifications, and other relevant evidence of their products' environmental performance, ideally available at the point of sale to inform consumers before they purchase a product. It is the responsibility of consumers to read such information. In the same way, social media now allow individuals to interact with others and advocate or support companies that produce "green" products or call on other consumers to boycott companies with unsustainable production practices.

Consumers must adopt a "circular" behaviour, which favours the recycling and reuse of products. Before deciding whether to buy a new product, consumers should ask themselves whether a purchase is necessary and evaluate the total cost of ownership of that product over its lifespan. In this regard, it may be imperative to evaluate sharing economy models (i.e. car sharing), which are not only often cheaper but also increase the utilisation rate of those products, resulting in fewer products being disposed of. In the same way, when buying a new product, some products may appear more costly but are more cost-effective in the long term. For example, electric cars have higher upfront costs but may be more viable economically in the long term, with a less negative impact on the environment.

In summary, each individual should play an active role and be a major driver in the shift to circularity by making consciously informed decisions on the purchase and use of products. This more conscious consumerism decides who is successful in the market and drives companies to deliver sustainably sourced and produced products to gain competitive advantage.

3. ENABLE COOPERATION AMONG RELEVANT STAKEHOLDERS IN BUILDING CIRCULAR VALUE CHAINS

- **Facilitate information sharing in the value chain**
- **Promote shared standards, certifications, and common sustainability metrics**
- **Engage all relevant stakeholders in technology implementation**

Due to the sheer complexity of transitioning to circular manufacturing, promoting trust and collaboration among different relevant actors in the value chain is becoming more important than ever. In circular value chains, stakeholders must have access to reliable information about the sustainability of a product. For example, manufacturers and recyclers should collaborate closely to ensure that the latter have the information about what comprises the product and how it is produced to facilitate recycling. In the same way, manufacturers should understand the best configuration when designing a product to make recovery and recycling at the end of its life easier.

To support information sharing, seamless connectivity and data exchange in the supply chain should be guaranteed. To achieve this, it is essential to create the necessary digital infrastructure and engage different actors around these (digital) platforms. The use of common shared standards (i.e. for data capture and storage) can also facilitate information sharing, reduce information asymmetries, and improve traceability in the supply chain. These should be complemented by certifications (i.e. to assess the quality of raw materials or products). Cooperation among different actors can also enable novel solutions such as a "digital product passport", or similar product initiatives that track information about the product as it moves along the supply chain. The adoption of common key performance indicators or metrics related to circularity, which are easily understood by all relevant supply chain actors, should also be encouraged.

Circular supply chains will be characterised by systems where it is easier to track the flow of materials or products in different stages of the value chain, allowing the producers to recover them with ease when needed. This is only possible if different actors in the value chain are coordinated and aligned with shared objectives. When choosing to adopt and implement a technology to support circular manufacturing, it is important to ensure that relevant actors such as suppliers are informed and that the implications for them are fully understood. This ensures the engagement and participation of all stakeholders. Competence centres can play a key role in promoting dialogue and facilitating shared learning among these stakeholders. The goals towards circularity are in many cases challenging and ambitious and can only be achieved by enabling the cooperation of different actors in the value chain.

4. PROMOTE BUSINESS MODELS AND VALUE PROPOSITIONS THAT EMBRACE CIRCULARITY

- **Encourage product-as-a-service models**
- **Design products to facilitate eventual recovery, remanufacturing, and reuse**
- **Exploit industrial symbiosis platforms to trade waste and surplus assets**

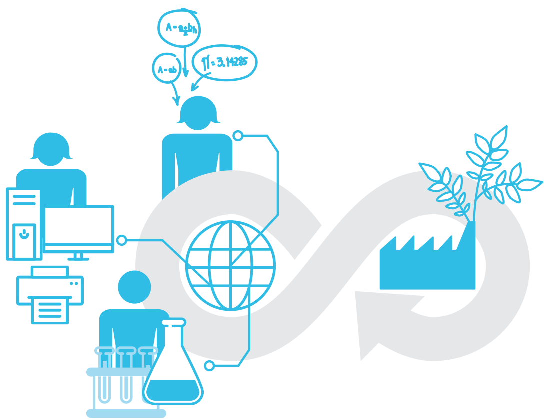
The circular economy provides many opportunities for manufacturers to earn economic benefits, but not at the expense of the environment. Companies must understand that it is not business as usual and that the circular transition has important repercussions on their business models. Circular business models perpetuate the life cycle of materials through recycling and remanufacturing, reducing waste in the process and therefore the number of resources that are extracted from the environment. It is therefore an opportunity for manufacturers to look at their existing business models and assess how they can be transformed with circularity in mind.

Many circular business models leverage the sharing economy, which increases the utilisation rate and life cycle of products, including assets. The promotion of product-as-a-service (PaaS) models allows manufacturers to retain ownership of a product and generate revenue streams from customer use. These models also allow manufacturers to obtain information on consumer usage patterns, enabling them to improve product performance and service levels over time as well as to innovate in the service provisioning arena. As emphasised in previous recommendations, the producer should take responsibility for a product beyond the delivery to customers. This changes their mindset from being a product manufacturer into being a service provider and this can only accelerate the adoption of product-as-a-service models.
Circular business models also allow the creation of new products from "waste". With open-loop recycling, materials are recovered and regenerated for use in different products. Closed-loop recycling, on the other hand, uses the material to create the same product. To enable this, it is important to build into the manufacturers' capabilities the ability to track the flow of resources across the entire value chain. Manufacturers can leverage technologies such as the Internet of Things (IoT) to track product degradation and other relevant information that facilitates the recovery and remanufacturing of products.

The design of products is important for enabling circular business models, as it facilitates the recovery of materials and eventual disassembly and remanufacturing. The use of modular designs which allow product parts to be easily disassembled for recycling or refurbishment should be promoted. In the same way, vendors can support products for longer through software updates as well as providing reliable maintenance services to incentivise customers to use products for a longer time. For example, more and more mobile phone manufacturers are pledging to support their products for longer periods through over the air (OTA) updates, reducing the urgency to upgrade and therefore lessening the impact on the environment. To compensate, companies provide services such as cloud storage and content to their customers. Similar schemes can also be implemented for other products.

Manufacturers can also develop schemes allowing them to buy back used products directly from consumers for eventual resale such as in the garment industry. In this way, consumers are also engaged and contribute to the pursuit of circular economy goals. In the same way, governments can provide economic incentives for digital platforms that buy used goods, refurbish them and eventually resell them to consumers. Manufacturers can also take advantage of industrial symbiosis platforms to trade surplus assets with other organisations for use in production. Creating this market for waste provides advantages for both producers and consumers who are bound by shared goals in the transition to the circular economy.

5. IMPLEMENT POLICIES GLOBALLY THAT RECOGNISE DIGITAL TECHNOLOGIES AS THE MAIN ENABLER FOR CIRCULAR MANUFACTURING



- **Increase commitment to global initiatives for the circular economy**
- **Address the digital divide globally, especially in least developed countries**
- **Set up sandboxes and testbeds to promote learning, experimentation, and innovation**

Integrated global policy frameworks are indispensable in the transition to the circular economy. Currently, different approaches are observed in different countries. For example, there is still no common understanding globally of what circular economy means and how digital technologies can enable this transition. It is therefore important to set up coordination mechanisms to drive coherent policy-making worldwide. Such mechanisms must outline overarching principles and, at the same time, consider the individual characteristics of countries and their role in global value chains. These policies should not be short-sighted but designed with the goal of achieving long-term sustainability in mind.

As outlined in Chapter 3 of this Report, global initiatives such as the United Nations Sustainable Goals and the Paris Climate Accords, or regional ones such as the European Green Deal, outline shared objectives related to circularity and bring nations together to undertake actions to reach those goals. It is important to increase the commitment of societies and nations to such agreements. Furthermore, there must be alignment among global, regional, and national policies, finding synergies among the three levels.

In addition, it is important to promote policies that acknowledge the role of technology in the transition to circular manufacturing. As stressed in the Report, there cannot be a full ecological transformation without digital transformation. Therefore, policies should broadly address the barriers related to digitalisation in companies and create other pre-conditions that allow companies to exploit technologies in the transition to circular manufacturing. Policies should address the digital divide globally with particular emphasis on least developed countries. In the last decade, many countries have developed national strategies to support the digitalisation of industry. Different policy measures include creating sufficient technological infrastructure and providing economic incentives for companies to enable digitalisation (i.e. digital capabilities). These digitalisation strategies should be aligned with the circular economy objectives of that particular country as they are complementary. This can only be made possible if different government agencies, that in many cases work in silos, cooperate more closely (i.e. the Department of Industry with the Department of Environment).

With regard to the role of technologies in enabling circular manufacturing, while there is a lot of research about the potential of digital technologies, there is a lack of guidance in their practical implementation, limiting the uptake in industry. In this area, governments and industrial associations have an important role to play in speeding up the uptake by providing information and training and other incentives to support digital transformation. Concrete measures are needed to support the transition to circular manufacturing such as the promotion of digital innovation hubs. The development of sandboxes and testbeds will allow companies to learn from and experiment with new technologies in controlled environments and innovate as a result of such learning and experimentation.

6. PROMOTE ECONOMIC MEASURES THAT DRIVE THE TRANSITION TO THE CIRCULAR ECONOMY AND ADOPTION OF ENABLING TECHNOLOGIES

- **Devise taxation schemes to drive resource efficiency and the use of secondary materials**
- **Incentivise companies and investors that invest in circular projects**
- **Provide incentives to consumers to drive circular behaviour**

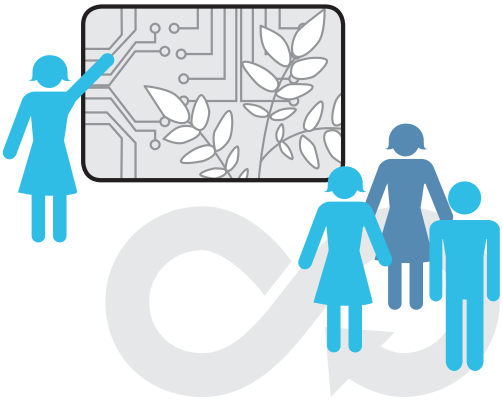
Economic measures or market-based instruments can support the transition to the circular economy. One important measure for policy makers is the development of tax schemes that incentivise companies to achieve circular economy goals. For example, resource use can be taxed instead of labour in such a way that companies are more motivated to avoid waste and use resources in the most efficient way possible. Another method is to encourage the use of secondary resources, which can be put into place by providing incentives to companies or requiring a minimum percentage of recycled content in products.

Policy makers can also provide incentives to companies and investors that invest in circular projects involving digital technologies. It is important to mobilise financing, such as by providing direct subsidies or loans with favourable payment terms to support the upgrading of companies' technological capabilities to support their circular transition, or venture capital to support projects that involve the development or use of technologies to achieve circularity. When evaluating projects to finance, policy makers should evaluate the potential impact on the environment and their scalability or the possibility of their being used on a wider scale in other settings. Furthermore, it is important to link incentives to clear targets, developing a framework to measure the impact of projects on the environment. As discussed in Recommendation 4, the circular economy will be characterised by new (circular) business models built on services. Policy makers should therefore provide incentives to support companies in developing capabilities that enable them to develop product-as-a-service (PaaS) business models. This is particularly true for Small and Medium-sized Enterprises which may not have the same resources to transform their business models as larger organisations.

In funding projects, different schemes can be explored such as public-private partnerships which pool resources from different companies, government institutions, and other organisations. These partnerships promote cooperation among various actors who have a stake in the circular economy. Policy makers can also support the creation of locally sustainable ecosystems that are interconnected to a wider value chain network.

While supporting companies has an immense impact on promoting circular manufacturing, it is equally important to support consumers to shape their behaviour so that it is supportive of this circular transition. For example, credits can be given to incentivise consumers to buy environmentally sustainable products. For instance, in the emerging area of electromobility, many governments already provide credits to consumers who would like to buy electric cars, effectively reducing their out-of-pocket costs. Policy makers can also work with companies to develop the necessary system(s) to facilitate the recovery from consumers of products that can be remanufactured for reuse. In return, customers can receive credits to finance their next purchase.

7. TRAIN THE WORKFORCE FOR DIGITALLY ENABLED CIRCULAR MANUFACTURING



- **Update skills and competencies to work with enabling digital technologies**
- **Prepare the workforce for emerging green occupations**
- **Reinforce the sustainability component in school curricula**

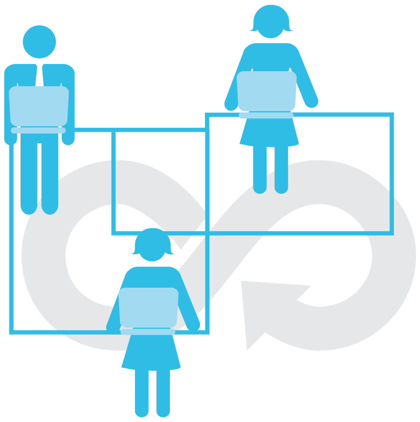
Workers have a key role in the transition to circular manufacturing. As companies adopt digital technologies to support circular economy objectives, workers must be equipped with the right competencies and skillsets to work with those technologies. It is important to address the general skills gaps phenomenon in manufacturing, which is driven by the rapid evolution of technology and the added complexity brought by the circular economy. Therefore, companies must keep pace by providing frequent upskilling and reskilling to their workers. Workers need to adopt a culture of lifelong learning, given the significant pace of technological innovation in the manufacturing sector. Furthermore, the opportunity to improve skills should be made accessible for workers, and special attention should be given to certain categories such as older workers, who may not be aware of their skills gaps and required training.

Updating workers' skills and competencies is important, as they will have to deal with more complex circular value chains and business models that are service-driven. Technical skills will need to be reinforced, especially those that relate to the most promising technology enablers such as Big Data, Artificial Intelligence (AI), the Internet of Things (IoT), and Additive Manufacturing, among others. Soft skills will also become more important, such as the ability to deal with increased uncertainty and complexity as well as adaptability to new environments. Furthermore, communication and teamwork skills will increase in relevance as cooperation with various actors will be key to achieving ambitious circular economy objectives. Workers must also possess critical thinking, problem-solving and creative skills to identify the challenges and opportunities afforded by the circular economy to generate value for their organisations.

The transition to circular manufacturing will give more relevance to new (green) occupations such as environmental compliance auditors and environmental engineers, each with their required skillsets and competencies. In addition to these new (green) occupations, it is necessary to understand the implications of the circular economy for all existing occupations, as the circular economy will fundamentally transform manufacturing production and the broader value chain.

To ensure that the workforce is equipped with the right skills and competencies, educators and training providers must rethink educational content and training delivery, ensuring that they are still relevant in a sustainable world. It is important to include or reinforce the "sustainability" and "digital" components in curricula. As mentioned in previous recommendations, each individual should think in a "circular" way, and educators have an indispensable role in cultivating this "circular mindset" among students. New courses and educational programs are undeniably needed to prepare workers for emerging (green) occupations or to enable them to work with novel digital technologies.

8. LEVERAGE ON DATA TO SUPPORT THE CIRCULAR TRANSITION IN THE MANUFACTURING SECTOR



- **Promote a data-driven culture in organisations**
- **Exploit data from the value chain to drive product and production innovation**
- **Create shared data spaces that facilitate trustworthy data sharing**

Data has an immense value in the transition to circular manufacturing. In the circular economy, manufacturers rely on large amounts of data to obtain information on production processes, consumption, and value chains so that it can enable circular business models. However, many companies are not yet able to take advantage of this data-driven opportunity as there are many challenges to overcome. For example, many companies are not yet ready to use data as they lack the internal capabilities for obtaining, processing, and analysing large amounts of information to support their business decisions. Hence, building a data-driven culture in organisations is a prerequisite to exploit the opportunities of the data revolution in manufacturing. Manufacturers must carefully assess what kind of data is needed to support their objectives, how to collect them, and how they can be analysed to create value for the organisation and value chain. Key performance indicators to be tracked should be aligned with the strategy of that company and that value chain to achieve circular objectives such as resource efficiency. In this regard, it is required to build digital capabilities within organisations and value chains supported by a workforce with the technical skillsets to work with data.

To unlock its value, manufacturers must develop systems that allow the tracing of data at every stage of the product life cycle. Data about production processes are more easily accessible for manufacturers, while data on product usage is not straightforward. Leveraging on circular business models such as product-as-a-service models enabled by the Internet of Things, and collecting information on product usage can lead to product quality improvements, life extension, and innovation.

Success in the circular economy also relies on data sharing among different actors. Thanks to the massive surge in data generated from value chains, data is increasingly becoming an important source of competitive advantage for many companies. The emergence of data-driven marketplaces allows firms to monetise proprietary data by making them available for purchase. Potential buyers also benefit by acquiring data to which they normally would not have access. However, key issues need to be addressed when data are exchanged, such as security and compliance with regulations. The creation of shared data spaces provides the infrastructure and facilitates the sharing of data among different participants in a trustworthy way. Participants in data spaces are bound by frameworks on the storage and sharing of data while at the same time complying with existing regulations, creating a level playing field for data sharing.

9. EMPOWER SMES IN THEIR TRANSITION TO CIRCULAR MANUFACTURING

- **Address lack of information on the potential of technologies to achieve circularity**
- **Provide capital and assist in building a skilled workforce**
- **Increase access to data to support circular objectives and leverage on new sustainable business opportunities**

Small and Medium-sized Enterprises (SMEs) constitute a significant portion of manufacturing enterprises globally and are regarded as important drivers for innovation in the sector. However, SMEs have historically struggled with technological adoption as they face more barriers compared to large multinational companies. Furthermore, not only consumers but also companies (and in particular SMEs) need to be informed about the circular economy and its opportunities and implications for their activities.

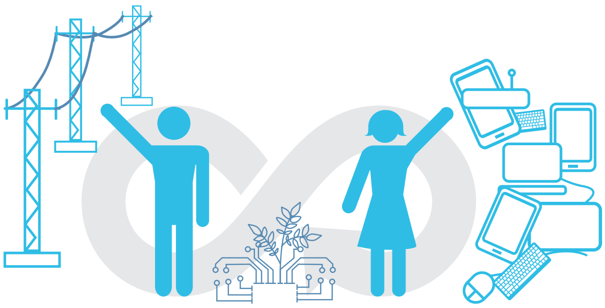
Throughout the report, digital transformation has been highlighted as an important driver for the circular transition. This makes it more difficult for SMEs to transition to circular manufacturing owing to their lower levels of digitalisation. It is therefore important to create the preconditions that allow SMEs to thrive and succeed in the era of circular manufacturing.

First, it is essential to assist SMEs in their digital transformation. Digital transformation is particularly difficult due to a lack of technological infrastructure, workforce competencies, and other resources. Often, SMEs also lack information on what kind of technologies are available and how those technologies can support their objectives, such as improving operational efficiencies and reducing waste in production. Knowledge sharing, therefore, is crucial to reduce the information gap and promote technology adoption among SMEs. To achieve these goals, industrial and trade associations and manufacturing clusters can share resources and best practices among themselves to speed up sustainable innovation. For instance, industry champions or innovative SMEs succeeding in digital transformation or using technologies to achieve circularity in production could be promoted to increase adoption among SMEs.

Specific barriers need to be overcome and need special attention from policy makers. One of the main issues to address is the lack of access to financing to support digital transformation. Hence, the provision of capital (i.e. access to loans with favourable terms or direct subsidies) to reduce the fixed investments for SMEs would be crucial for any digitalisation project. In addition, as mentioned in Recommendation 8, data is a key enabler for the circular economy. However, SMEs face many barriers in gathering and making sense of data to transform production and improve their business models. It is therefore important to build digital capabilities within SMEs to improve data gathering and processing, leveraging on smart solutions that take advantage of the Internet of Things (IoT) and Artificial Intelligence (AI), and to promote information sharing with other companies. This will allow SMEs to better track information in their value chains to assess their environmental impact and take steps to improve it. Moreover, governments and industry associations can support the creation of competence centres that provide training and support in the implementation of Industry 4.0 projects. It is important to note that no one solution fits every organisation and initiatives should take into consideration the sector, size, and other characteristics of SMEs.

Supporting the digital transformation, building (digital) capabilities, and improving access to information can help drive innovation in SMEs and help them transform their business and operating models to take advantage of the opportunities afforded by the circular economy.

10. ADDRESS THE POSSIBLE NEGATIVE ENVIRONMENTAL IMPACT OF DIGITAL TECHNOLOGIES



- **Perform a holistic and realistic assessment of technology impact**
- **Leverage on circular business models to deal with electronic waste**
- **Promote policies to address the unintended negative impact of technologies on the environment**

Digital technology is an important catalyst in the widescale adoption of circular manufacturing. However, it is counterproductive when the use of technology to drive circularity in manufacturing also harms the environment. It is, therefore, necessary to assess the ecological footprint of using digital technologies and the negative externalities of using such technologies.

One important issue is dealing with "e-waste", such as that from electrical and electronic products and components. As previously mentioned, IoT sensors obtain different kinds of data in the entire product life cycle and their adoption is only expected to increase. Manufacturers must be mindful of how this electrical and electronic waste is recovered and eventually disposed of, and, consistently with the principles of circularity, how it can be made useful at its end of life. As discussed in a previous recommendation, circular business models can be leveraged to find creative ways to better manage waste from electrical and electronic equipment, such as recovering components and materials that could be recycled or reused. In addition, it is important to address related issues, such as unsustainable mining of rare earth metals used in the production of these electronic products and components.

Another issue to deal with is the energy requirements to support the use of digital technologies, which in most cases require significant amounts of energy. The source of energy must be considered and ideally, energy should also be sourced from sustainable (renewable) sources. This is not currently the case, as combustible fossil fuels remain the main source of electricity worldwide. As an example, the use of blockchain can potentially support circular manufacturing goals but at the same time, consumes massive amounts of electricity. If not addressed, this can only worsen the ongoing climate crisis. The promotion of sustainable energy sources is therefore essential to ensure that the increasing use of electricity to enable digital technologies does not lead to more greenhouse gas emissions.

Data is an important enabler for circular manufacturing, but data storage and processing also has its environmental cost. In particular, data centres use significant amounts of energy to function and energy consumption is only expected to increase as they grow in number.

As with every major company decision, before adopting digital technologies, companies must conduct a holistic assessment of the costs and benefits of implementing a specific technology. Costs should take into consideration any harmful effects to the environment which could be the opposite of what circular manufacturing aims to achieve. Policy makers should also introduce measures that assess and monitor the sustainability of the use of technology and ensure that companies are also responsible for any unintended consequences such use. For example, policies on better management of e-waste should be encouraged in more countries. Promoting information and encouraging dialogue among different actors with regard to the potential benefits and costs (including any unintended costs for the environment) of technology implementation will be increasingly important in the transition to circular manufacturing.

Conclusion

The circular economy is an opportunity to transform manufacturing. As highlighted throughout the Report, the possibilities for manufacturers to transform production and their business models are profound, leading to more innovation in the sector. At the same time, the circular economy is a chance to create a positive impact on the environment. For many years, the "linear" way of manufacturing, which produces plenty of waste, coupled with relentless societal consumption, have put a strain on the environment, depleting finite resources and worsening the climate crisis. These negative effects will have lasting consequences, not only for the current generation but also for those in the future. Embracing the circular economy, therefore, is a step in the right direction, enhancing manufacturing's role as an important driver for societal well-being.

However, circular transition in manufacturing is not an easy task. It is important to stress that there can be no full circular transition in manufacturing without digital transformation. As evidenced in the Report, digital technologies will be the key enabler for circular manufacturing. Addressing the digital divide in manufacturing is a pre-requisite to exploit the opportunities in the circular economy and achieve lasting environmental sustainability.

Furthermore, everyone has a stake in the circular economy. Circular manufacturing is only possible if companies, consumers, governments, and society at large work together and change their mindset towards circularity. It is important to have circularity in mind in every business activity. Responsible consumption and a culture of recycling and reuse must be promoted. Educators and workers alike must ensure that the right skills are present to enable the transition to circular manufacturing. Policies should address the digital divide and create the pre-conditions for circular manufacturing. Each of us must do our part. The transition to digitally enabled circular manufacturing is a must, and there is no other time to do it but now!

YML

Young Manufacturing Leaders

Winning Case Studies on Digitally Enabled Circular Manufacturing

YML Contest for the 2021 World Manufacturing Report

Young Manufacturing Leaders is a global initiative for students, young workers and professionals interested in a career in the manufacturing sector.

The YML network is strongly committed to raising awareness of the opportunities in manufacturing, and to spreading knowledge of the skills needed in this sector. It supports members with different activities such as peer-to-peer seminars, mentorships with professionals and entrepreneurs, and participation in the activities of the World Manufacturing Foundation.

From March to July 2021, the YML Contest for the 2021 World Manufacturing Report was held, inviting young leaders from all over the world to submit a case study relevant to the topic of Digitally Enabled Circular Manufacturing. The submissions were evaluated by the World Manufacturing Foundation and the winning case studies are included in this section.

The Young Manufacturing Leaders network initiative, launched in 2020, now has nine partners: Politecnico di Milano, Chalmers University of Technology, Czech Technical University in Prague, IMH, Tecnalia, Technische Universität Braunschweig, University College Dublin, University of Porto, and the World Manufacturing Foundation. The initiative is co-funded by the European Union, within the framework of the EIT Manufacturing programme.

For more information visit youngmanufacturingleaders.org

Co-funded by the European Union

AI for iRecovery® System: Leveraging Digital Technologies to Improve Sustainable Steelmaking

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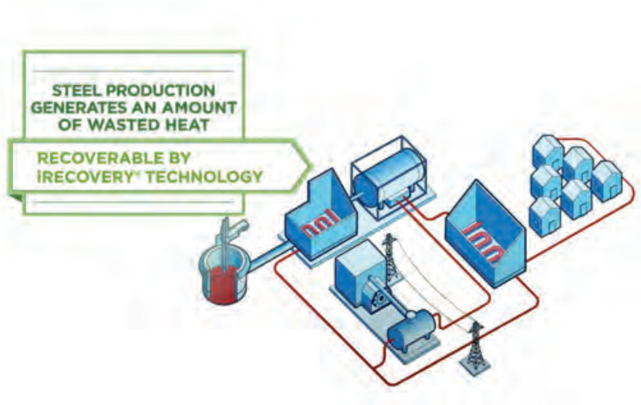
Tenova is a worldwide partner for the development of sustainable, innovative and reliable solutions in the metallurgical and mining industries. As such, we provide our customers with a fully integrated range of products, innovative technologies and high-quality services in the field of metalworking, hot stamping, heat treatment and cold rolling. We are active at the forefront of the ecological transition and digitalisation process; the strategic importance of these two processes has led us to coin a neologism, “Sustenovability”, to denote our resolution to provide tech solutions enabling the green transition of the metals industry.

Closely coupled to sustainability is the concept of the circular economy, a disruptive change of paradigm from the linear economy, where the “take, make, dispose” model is replaced by a “reuse, remanufacture, recycle” pattern. An important role in the circular economy is played by the valorisation of waste materials, along with the reduction of the resources needed to manufacture products and the related environmental impact of those processes.

In the steel industry these concepts are not new: steel can be recycled, without loss of quality, over and over, an infinite number of times. Indeed, steel is the most recycled material in the world, with 650 million tonnes of steel recycled every year.[1] This is exactly what happens when steel is produced by an electric arc furnace (EAF), since its main input is recycled scrap metal coming from very different sources. The EAF uses electricity as its primary energy source, drastically reducing emissions of greenhouse gases and pollutants in the environment. Proceeding towards a zero-waste approach, Tenova has developed a technology, named the iRecovery® System, which has the ambitious goal of recovering the thermal energy contained in the fumes generated during the scrap melting and superheating process in the electrical furnace. The energy extracted from the fumes by the iRecovery® System is used to produce steam, which is made available to transfer the recovered heat to any thermal users.
In the Italian city of Brescia, the thermal energy recovered by fumes and converted into steam is firstly stored and then transformed, during summertime, into electrical energy through an ORC (Organic Rankine Cycle) turbine, or, during wintertime, into thermal energy, feeding a local district heating network. This is a closed-cycle system that does not waste water and can recover up to 75% of the energy that would normally be lost. The energy recovered in this way is able to provide around 2,000 households with thermal heat during winter, while during summer, 700 families can rely on clean electricity. Overall, the community benefits from a reduction of 10,000 tons of CO2 per year.



Leveraging the digital transformation taking place within the Industry 4.0 revolution, we are striving to further enhance the performance of the iRecovery® system. Our goal is to predict the mean thermal energy provided by the electric arc furnace over time, as a function of how the melting process is operated, using machine-learning techniques to develop a predictive model. This model will address the high discontinuity of the melting process, helping to provide a steadier energy flow to the ORC turbine and district heating unit. By forecasting the value of the available thermal energy, we can optimally set up the controller by regulating the amount of power delivered. This will result in an increase of the overall efficiency of the system, which will be able to recover, transform and deliver more energy.

This project will make use of Artificial Intelligence models, learning the correlations between the input features, characterising the melting process, and the target, the steam production, from plant data. Just like any other data science project, the modelling phase is not the most complicated part. A machine-learning model is of no use if it is not properly surrounded by an architecture that is able to respond to different needs, such as supplying data to the model in order to produce the desired predictions, feeding them into the automation control system that regulates the operation of the industrial process, while monitoring the model continuously and retraining it periodically, so as to maintain a high and consistent performance over time. Consistency of performance is, in fact, one of our main concerns when designing a new machine-learning project, especially in a sector such as manufacturing: a model should always perform well, in spite of changing operating conditions, modifications to the equipment, or other variable exogenous factors.

The only way to address this variability is through accurate model monitoring and retraining. Underestimating the importance of having such an architecture when building machine-learning products is, in my opinion, one of the causes of the extremely high rate of AI projects in industry that have failed to meet company expectations, hovering around the 90% mark.[2] On the other hand, developing the architecture surrounding an ML model is complex and expensive; doing this for every different project is simply neither advantageous nor scalable. For this reason, it is advisable to create a machine-learning life cycle management system, referred to as "MLOps", that automatically manages these aspects for every data science service deployed to a customer, similar to the way in which "DevOps" has become a common practice for traditional software management.

In order to foster the development of digital and data science projects we developed the Tenova IIoT (Industrial Internet of Things) Platform, which addresses all the requirements stated above. This is done with the help of the TenovaEdge, an edge computer installed at our customer's plant that gathers real-time data from our machines and transmits it to the Tenova cloud platform with the highest security standards, where the data is stored. On our platform, data is transformed in such a way as to be used to train and improve our machine-learning models; when their performance meets our requirements, the model can be deployed to the customer. The model is fed with real-time data and the resulting predictions are exploited to fulfil the model's scope, such as monitoring an industrial process, performing anomaly detection and predictive maintenance tasks, or tuning the set-points of our automation systems.

In a company like Tenova, where the focus has always been on providing technologies able to take the metals industry in the direction of sustainable manufacturing and carbon neutrality, digitalisation and Industry 4.0 can represent the right set of tools to accelerate this transition and meet governments' goals, like the European Commission objectives fixed with the Green Deal for 2030 and 2050.[3]

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Additive Manufacturing in a Circular Economy Framework: f3nice Case Study

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Additive Manufacturing (AM) is "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing"[1] (ASTM F2792). In recent years, the wide availability of CAD software, the increased automation in 3D printing machines thanks to Industry 4.0 digital disruption and major industry and government investment have pushed AM technological development.
Additive Manufacturing is cited as one of the key enablers in the transition towards a circular economy (CE) framework[2], fulfilling the need for a long-term sustainable perspective.[3] CE is a system "restorative and regenerative by design, and aims to keep products, components and materials at their highest utility and value".

As in nature, in a CE framework resources are preserved and balanced, and waste is considered as an added value.[4]
Opportunities offered by AM are leveraged throughout the value chain. Digital design enables extensive customisation capabilities, shifting production from economy-of-scale to economy-of-one, ending unnecessary stocks3 and possibly extending product lifespan, for instance, by enabling the repair and upgrading of parts.[5]

AM is paving the way to a "design-based economy", lowering the barrier between knowledge of the product and the product manufacturing process.[3]
The design of parts may be augmented by topological optimisation, resulting in a significant weight decrease of the component and in a reduction of physical assembly by merging multiple parts into one. Additionally, significant material savings due to precise material addition and to the absence of tools3 can be obtained, reducing raw material waste.

Lower energy consumption during processing[6] and the use of a decentralised economic system by localising the production closer to the end user result in a reduction in the environmental impact of the production process.[3]
In this context, in May 2020, f3nice, an innovative Italian start-up, was founded with the aim of creating a circular ecosystem for additive manufacturing feedstock production from 100% recycled scrap metal. In January 2021, the start-up raised $120,000 pre-seed funding from TechStars and TechStars Energy Accelerator in Partnership with Equinor. F3nice believes in securing a more sustainable world, by rethinking the traditional industrial production cycles and proposing smart ways to confer additional value to waste. The standard production method for additive manufacturing powder consists in three main phases: raw metal mining, pre-treatment, and atomisation. F3nice, on the other hand, offers an innovative patent-pending solution to produce high-quality powder from scrap metal (e.g. decommissioned valves and obsolete spare parts). Highly valuable metals such as high-alloyed steels, Ni- and Ti-based alloys are recycled to produce green powder in different size ranges, either for Additive Manufacturing or conventional powder-based processes.
The expected impact of the project in terms of sustainability can be explained by the words of Matteo Vanazzi (co-founder and CTO of f3nice): "The major sustainability impact derives from the patent-pending powder production process employed, that uses 100% recycled material.

Metal recycling is a generally diffused practice; in any case, it is not usually employed in a 1:1 ratio, rather, a refinement of the composition of the alloy is made by adding pure raw material from mining extraction. Therefore, in standard alloys it is difficult for the percentage of recycled materials to exceed 60%-80%. Through the accurate selection of scrap material and the patent-pending process, on the contrary, f3nice can produce metal powder with the finest quality with 100% recycled material. This will impact significantly on the energy savings of the process. Compared to a traditional production process, estimated savings range from 40% to 70%, depending on the specific alloys.

An evaluation of CO2 emissions reduction strongly depends on the energy mix considered. Localising the innovative powder production process in zones characterised by a favourable energy mix (100% renewable energy), it is possible to obtain savings of up to

90% compared to a standard European energy mix (e.g. in Italy, the UK or Germany), where most powder production takes place today." It is important to emphasise that a study is under way at the Politecnico di Milano Department of Energy Engineering to validate all these estimations.
The challenge f3nice has taken on is remarkable, since the goal is to establish a business that is innovative, sustainable, and, at the same time, economically successful.

In an interview, Luisa Mondora, CEO of f3nice, shared the major issues that the company has faced during the start-up period: "Primarily, it was very difficult to dispel the doubts of potential clients with regard to the quality of a product coming from recycled materials". In terms of performance and part quality, the multiphysics nature of the AM process results in high sensitivity to the powder-related parameters: particle shape, size and distribution. "Before connecting with main investors", affirms Luisa Mondora, "we self-funded two proofs of concept, one at laboratory scale and another at industrial scale, to demonstrate that powder produced with our process has comparable or even better quality than powders obtained from raw material mining currently available on the market". F3nice is able to count on the great support of AIDRO Hydraulics and 3D printing, one of the company leaders in the AM European landscape led by the CEO, Valeria Tirelli, for the production and qualification of parts realised with 100% recycled green powder.

In conclusion, Additive Manufacturing technology fits perfectly into the circular economy framework. Digital design and part optimisation enables unmatched production flexibility with reduced energy and material consumption. Great environmental benefits are made possible by the strategic decentralisation of economic systems and the more customer-oriented demand manufacturing.[3]

In this dynamic landscape, f3nice is paving the way to a more sustainable production of feedstock powder for additive manufacturing, providing cross-cutting competences in terms of material science and process engineering. The circular flow is finally closed, giving new value to scrap metal, to create high-quality powder for high-performance parts.

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Circularity Enabled by Additive Manufacturing: a General Electric Case Study

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As one of the world leaders in the industrial sector, General Electric (GE) has shown an increased interest in the use of additive technology in the aerospace sector for more than a decade. GE Aviation, as a part of a multinational conglomerate, plays a crucial role in producing lightweight and durable components with complex geometry. Additive Manufacturing (AM), with the main focus on 3D Printing (3DP), is a manufacturing method which allows the creation of parts with specified parameters but also effectively reduces production time and fuel consumption in comparison to traditional components.[1]

Digital solutions like AM with 3DP will allow the local market to be supported and the country or continent will become less dependent on imports of scarce raw materials. 3DP is essential for a circular economy (CE) as it is resilient to supply chain disruptions and as it uses less material than traditional production. CE promotes a smaller environmental footprint, enhances the development of a sustainable business model, and represents systems that reuse, recycle, and recover materials, and seeks a more efficient use of resources. These objectives are supported by AM and 3DP since they aim to accomplish environmental quality and prosperity for future generations.[2, 3]

GE seeks to examine the nature of AM and raise awareness for its use in aviation. To do this, GE needed to investigate a comparison of traditional manufacturing techniques and AM processes. Since the 1990s, 3DP has attracted a lot of interest, while GE Aviation has been working closely with Morris Technologies to print prototypes of newly designed engine parts. They set out to investigate the usefulness of lasers for welding thin layers of a metal powder to print nozzle tips from a nickel alloy. The parts were combined into a single unit which weighed less, and the final product was more durable than a conventionally manufactured nozzle tip. This has led to the establishment of a solution that would avoid the use of bolts, welds, or nuts, but also provides a path to cost reduction and enables fuel burn to be improved by 20%. GE has also reduced development time by a third while using rapid prototyping that systematically reviews product data at the start of the design process, thus allowing improvements at an early stage of the process.[1,4] The additional objective of the project focused on AM intended to determine the extent to which GE can replace parts that may no longer be produced by supply chains in the future. Only a few suppliers invest in the aerospace sector. GE needed to examine options that could help avoid being affected by the cost models of other businesses and which would not reduce the speed of production.[5]

To take metal additives into full-scale production, GE delivers innovation by utilising Direct Metal Laser Melting (DMLM) machines. The Concept Laser M2 Series 5 printer is intended for serial production and allows us to create thinner walled structures using materials such as stainless steel, aluminium, nickel, titanium, and cobalt.[6, 7] Another advanced solution is offered by the M Line Factory machine, with a separated process and handling unit. It suppresses the secondary times in the AM process, such as removing parts and setting up a machine for another process, and it prevents delays in production.[8]

In 2014, GE announced plans to invest $50 million in GE Aviation in Auburn to prepare the facility for AM. They began producing fuel nozzle tips and reached production of 30,000 additive nozzles for CFM International's LEAP engine. The original nozzle tip had about 20 pieces and the number of parts was reduced to one whole piece, reducing the weight by about 25%. It also led to the production of five times more durable parts with a 30% cost efficiency improvement. This example leads to the use of AM in mass production in aviation.[9]

Previous research and attempts have helped establish the development of the GE Catalyst turboprop engine that consisted of more than 800 conventionally produced parts, recreating it using only 12 components. A similar strategy was utilised for the GE9X engine, which combines more than 300 conventional parts; this was reconceived so that it needed only 7 printed parts. By 2020, the company had identified more than 80 additional components that could be reworked with 3DP. In 2019, GE Aviation and GE

Additive began working with the U.S. Air Force (USAF) to find faster production of spare parts to replace damaged parts. The first project investigated the utilisation of AM for a F110 engine sump cover, which is used in F-15 and F-16 aircraft. The sump cover can be considered less functional in a complex engine, but it is a very important part that must meet several conditions, such as durability and rigidity. The main reason for starting to think about the use of AM in the USAF were difficulties with suppliers and the long delivery times, which are approximately 2-3 years. The implementation of the plan has begun with searching for simple parts and then transitioning to complex systems. The M2 machine was used for the first production of the F110 sump cover, after which the engineering team's focus shifted to the recreation of the 40-year-old TF34 engine sump.[10, 11]

AM brings great value to the market and indicates the need to understand and overcome various challenges, e.g., the temperature inside the jet engine exceeds 1300 degrees Celsius, and we must learn how the AM can cut costs and support repairs in such conditions. GE has made investments in technology and development and has begun to take AM to the next level by sharing the know-how with its units.1 M.Eng. Vít Havránek, Product Definition Lead Engineer and Designer of Additive Components at GE Aviation Czech, states, "The last two years of the additive design sector have been focused mainly on cooperation with the European Space Agency (ESA) and Brno University of Technology (VUT). We are trying to convert conventional components from the engine of the GE H-Series into additively manufactured parts. To make sure that we achieved the expected goals, parts manufactured by conventional production methods and AM production parts were compared in order to determine the influence of additive methods on assembly, compare strength analysis and evaluate the achieved accuracy of newly designed components."

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Digital Technology for the Recycling of Waste in the Steel Sector

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Nowadays, companies are increasingly introducing digital technologies in order to solve different problems in their production and also, to be more environmentally sustainable. This project will be focused on the steel industry, specifically in a factory that produces cut taps. The problems that the company have are the difficulties in recycling the emulsion waste and also the steel chip waste. Once the emulsion is used, it is adulterated by steel chip from the taps, dust from the cutting wheels and different oils and lubricants. With these problems, the project will consist in proposing a solution for the reuse of waste for the purposes of being more sustainable and also to obtain benefits.

There are different types of waste but in general, those which may cause more problems within the steel industry are emulsion and steel chip waste. Government policy requires companies to have strict control of the waste that they produce in order to reduce world pollution levels. This means that there is an urgent need for manufacturers to be more eco-friendly so that it is possible to meet the standards that climate change laws demand of industries with a view to decreasing their impact on Earth's global warming.

In the first place, one of the problems is emulsion waste. Emulsion is used in the machines to aid their processes, which makes it a very important component of factory production. The composition of emulsion is oil (approximately 5%) and water (around 95%), depending on its uses. Besides, the initial properties start disappearing when it is used and instead of oil and water, the emulsion starts to assimilate other oils, steel waste and dust wheel. This combination between different outside factors and the emulsion becomes a highly polluting waste product, so factories need to find a solution to recycle or reuse it.
For the time being, there is no perfect solution for emulsion waste but by using digital technologies, factories can start controlling the amount of different waste in the initial emulsion and they can also reuse it. Taking advantage of digital technologies, factories can be furnished with digitalised emulsion filters. These filters have sensors that send various data to a computer. They send data relating to the amount of non-liquid particles so that the oil and water can be separated from the dust and steel chip, and also, once separated, the sensors send the information about the percentages of oil and water. If the levels of oil and water are acceptable (these values are established by the supplier and the factory), the emulsion can be filtered by adding a barrier through which only the emulsion that is going to be reused can pass. The oil that can no longer be used can be converted into fuel.

On the other hand, the factory has two types of steel chip waste, that which the machines generate while they are grinding the taps and that which is obtained when they filter the emulsion. One of the problems in both situations is that the steel chip is in continuous contact with the emulsion, in particular that which is accumulated in the filter. This means that before the company can recycle or reuse it, the chip has to go through a cleaning and drying process. Once the chip is free of emulsion, there are different options regarding its use. The most environmentally sustainable may be reusing the oil obtained from the emulsion as fuel for heat, or melting the steel in furnaces at different temperatures. The problem with the steel waste in this factory is that they work with M2 and ASP23 steel and both of these have a high melting point. For this reason, melting the steel requires a specific furnace.

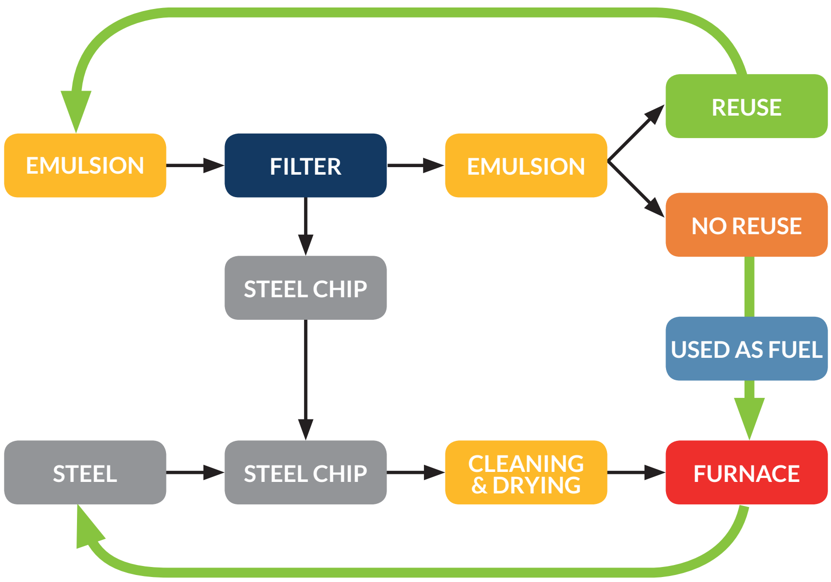
Currently, the factory sells the steel waste instead of recycling or reusing it. In order to have a circular economy and also to be more eco-friendly, the proposal in this case is to install a specific furnace in the heat treatments area which has the capability of raising the melting point of each material. As is known, it is not an easy job to obtain a furnace with these characteristics, so the process can be split into two phases. The first heats the steel to a defined temperature; for this process, the company can reuse the current furnaces and recondition them by adding sensors that will send different types of data (temperature, durability, errors, etc.) to a computer. In this phase, the fuel that it is needed will be obtained from the emulsion. Once the steel reaches the desired temperature it will be moved to the other furnace. This other furnace will also have different sensors to store all the data in a computer and will be able to analyse it. In this second phase, the steel will be completely melted so that it can be reused for different applications by giving it the desired shape.

Figure 1. Illustration of Processes

The main advantage of using this technology is that by reusing the emulsion and the steel chip there will be less pollution, which means that the environment will be more sustainable and so global warming will be decreased. A further advantage is that despite the expense that can be generated by the digitalised emulsion filters and the digitalised furnace, the factory will increase earnings in the long term by reusing the waste because they will have a closed circuit that distributes, filters and reuses the emulsion and also harnesses the steel.

To conclude with the advantages, there is that of having all the information about the emulsion and the steel chip process digitalised, which allows the company to store all the data in a computer. They can use this data to decide how long the reuse of the emulsion is viable and when more will need to be ordered, to monitor the levels of pollution in the emulsion, and so on. In addition to these advantages, there are some disadvantages. In economic terms, one of the main disadvantages is that to install the digitalised filters and the digitalised furnace in the factory, they will have to make an initial outlay that not all the companies are willing to do. Another point is that the design of the sensors has to be precise and that is arduous work because they will have to be exposed to high temperatures, so the material of which they are made must be high-temperature resistant.

To conclude, factories need to reconvert their processes into a sustainable, non-contaminated production system as soon as they can, in order to decrease global warming. By reusing the waste that this type of factory generates, it will become more eco-friendly and will also make money in the long term. Manifestly, to get to this point, companies will need to make a high initial outlay and most of them are unwilling to do so. If governments finance a part of these projects, therefore, in the coming years factories will become more sustainable because they will reuse their own waste as illustrated in this case.



Digital Twins: a Catalyst for Developing Environmentally Sustainable Manufacturing

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A Digital Twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process. It not only showcases form and materials, but also analyses the function of the object and the way it works in a real-life context.[1] This is achieved by combining experimental data and mathematical models, in particular finite element analysis (FEA).

Finite Element Analysis (FEA)[2] is the simulation of a physical phenomenon using a numerical mathematic technique referred to as the Finite Element Method (FEM). This process is at the core of mechanical engineering, as well as a variety of other disciplines. Its current applications are fundamental for the understanding of the mechanical behaviour of materials as well as more complex structures. In the same way as this can help researchers to understand the nature of a component or a material, it can teach the software how to run the simulation of the digital twin.

Products, as well as whole machines and factories, can be represented with a digital twin, which is able to simulate the structure and the activity of the real-world counterpart, also acquiring real-time data from it so than it can be compared to the digital simulation of the twin, in order to eliminate inefficiencies and correcting faulty processes. For this reason, they are the backbone of Industry 4.0, and their application can contribute enormously to the sustainability of the manufacturing processes. The continuous comparison between real-time data and data obtained from the simulation can be used by the software to improve the digital twin's understanding of the real-world issue, hence resulting in more accurate simulations.

This case study highlights two ways through which digital twins can help to improve the sustainability of production processes. The first is by comparing real-world data to the digital simulation of manufacturing systems in order to find flaws and inefficiencies. By comparing the simulation with data from sensors, it is possible to isolate the location and even the cause of flaws in the system with absolute precision. This very process can be replicated using a digital twin of the supply chain that runs behind every industrial activity and can help to point out inefficiencies and bottlenecks throughout the chain. The improvements in efficiency achievable by optimising the manufacturing system can greatly reduce the environmental impact, also leading to a smarter use of resources.

On the other hand, a digital twin can also be used to implement new secondary functions, such as finding new ways to recycle and reuse waste products resulting from manufacturing processes by running data regarding the nature of the waste products through Artificial Intelligence (AI) generative algorithms. This would enable the simulation of possible applications of waste products so that they can be cleverly recycled or reused. This is a crucial point when it comes to designing out waste from the manufacturing processes, a further step forward in the transition to a circular economy.

A clever application of digital twins coupled with generative algorithms was made by Siemens in 2019 while designing a gas mixing system: using simulations of Forman flow behaviour, AI was able to design a unique channel shape and configuration, which was not only significantly more efficient than previous designs, but was also designed in a relatively short period of time. Its related digital twin was also able to run tests and reliably simulate the behaviour of the product before it was even manufactured.

This process can be scaled to the size of factories and, coupled with technologies like gas atomisation and 3D printing using additive manufacturing, it can create production systems with a degree of flexibility never seen before, which can potentially lead to having fewer production lines which can produce a wider variety of products, enormously reducing the carbon footprint of factories. Furthermore, as observed in the case of Siemens' gas mixing system, digital twins would significantly speed up the experimental applications of new materials, processes and structures also with the help of FEA. Such applications have the potential to reduce the timespan from design to mass production by several orders of magnitude.
A digital twin could, for example, run series of algorithms

that cross reference composition and mechanical proprieties of existing alloys with FEA to simulate the proprieties of possible alloys that can be created with the waste metals of a manufacturing system, then using gas atomisation to create the actual alloy. The development of the new alloy would not only be quicker, but also simpler because the digital twin can take on time-consuming tasks such as running simulations.

In order to support such implementations, it is crucial that manufacturing systems become leaner, more resilient and have a high degree of reconfigurability; without a substantial improvement in these characteristics, none of the abovementioned benefits will be achieved. The reasoning is simple: having more resilient manufacturing systems allows the production of a wider variety of products using the same infrastructure, hence fewer manufacturing plants, hence fewer power plants to keep the factories going while maintaining the same production output. Digital twins can also help in this field by running simulations of new concepts of manufacturing systems to determine the degree of reconfigurability and the other abovementioned parameters, before the actual site is even built. Reconfigurable Manufacturing Systems (RMS) are designed in such a way as to sustain rapid cost-effective change in structure, as outlined by Dolgui and Proth[3], "RMSs are designed to permit quick changes in the system configurations, their machines and controls in order to adjust to market changes". This is so important because running an RMS in a factory would bring down the fixed costs for applying changes to the manufacturing system, thus making it easier to implement more sustainable solutions while also allowing the enactment of changes in a shorter timespan, forcing the system to remain idle for less time during upgrades.

These are just a few examples of what digital twins are capable of; their applications in the world of manufacturing are very diversified and still under development. As explored in the previous cases, this technology is bound to play a key role in the sustainability of manufacturing processes. It would improve resource efficiency by optimising existing processes and producing components that can retain their mechanical proprieties, while also using less material.

Given all the information above, digital twins have the characteristics to act as catalysers for a new, more sustainable industry, making innovation cheaper and easier to implement in every field of engineering.

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The World Manufacturing Foundation

Vision

"We strive to enhance manufacturing's role as a dynamic and positive driver for economic, social, and environmental growth and sustainability".

Mission

The World Manufacturing Foundation is an open platform spreading industrial culture worldwide. We promote innovation and development in the manufacturing sector, with the fundamental goal of improving societal well-being and inclusive growth in all nations through dialogue and cooperation among the manufacturing sector's key players.

We will pursue our goals by:

- Supporting and shaping local and international industrial agendas
- Providing a framework through which companies, governments, academic institutions and social organisations can interact or collaborate, acting as a catalyst for finding innovative solutions to major global challenges
- Creating and disseminating knowledge in both policy and technology through local and international meetings and publications.

WORLD MANUFACTURING FOUNDATION

Spreading Industrial Culture Worldwide

The World Manufacturing Foundation was formally established in May 2018 in Milan, Italy, as a platform to promote industrial culture and sustainable manufacturing practices worldwide. This undertaking was spearheaded by three founding partners: Confindustria Lombardia, IMS International, and Politecnico di Milano. The Foundation aims to spread industrial culture by expanding knowledge, promoting innovation, and fostering cooperation in the manufacturing sector.

The Foundation capitalises on its strong experience in hosting annual manufacturing events to discuss the most pressing challenges confronting the sector. In fact, long before the Foundation was formally established, the annual World Manufacturing Forum has been staged since 2011. The very first edition was held in Cernobbio in Lombardy and started as an important platform for global industry leaders and other stakeholders to exchange opinions on different issues related to manufacturing. The Forum started as a project funded by the European Commission, which has also supported its succeeding editions.

The World Manufacturing Foundation also has the support of important organisations. The Foundation was kick-started with the support of Regione Lombardia, which has also provided financial support in the last few years. In 2018, the World Manufacturing Foundation also signed a joint declaration with the United Nations Industrial Development Organisation (UNIDO) to promote a common global agenda on technological innovation and inclusive and sustainable industrialisation, and to advance the 2030 Agenda for Sustainable Development.

The business model which defines the Foundation is that of the Triple Helix. Its competitiveness is empowered through an intersectoral collaboration engaging industry, academia, and government. This is evident in the nature of its founding and key partners and a large community of institutional partners from all over the world, which support the Foundation's initiatives.

Founding Partners

CONFINDUSTRIA Lombardia

IMS

POLITECNICO MILANO 1863

Thanks to

European Commission

UNIDO
UNITED NATIONS
INDUSTRIAL DEVELOPMENT ORGANIZATION

Regione Lombardia

2021 KEY RECOMMENDATIONS BY THE WORLD MANUFACTURING FOUNDATION

1 PROMOTE A CIRCULAR COMPANY MINDSET THAT EMBRACES THE OPPORTUNITIES OF THE CIRCULAR ECONOMY AND THE ENABLING ROLE OF DIGITAL TECHNOLOGIES

2 DRIVE CIRCULARITY THROUGH CONSUMER RESPONSIBILITY, PROACTIVITY, AND CONSCIOUS DECISION-MAKING

3 ENABLE COOPERATION AMONG RELEVANT STAKEHOLDERS IN BUILDING CIRCULAR VALUE CHAINS

4 PROMOTE BUSINESS MODELS AND VALUE PROPOSITIONS THAT EMBRACE CIRCULARITY

5 IMPLEMENT POLICIES GLOBALLY THAT RECOGNISE DIGITAL TECHNOLOGIES AS THE MAIN ENABLER FOR CIRCULAR MANUFACTURING

6 PROMOTE ECONOMIC MEASURES THAT DRIVE THE TRANSITION TO THE CIRCULAR ECONOMY AND ADOPTION OF ENABLING TECHNOLOGIES

7 TRAIN THE WORKFORCE FOR DIGITALLY ENABLED CIRCULAR MANUFACTURING

8 LEVERAGE ON DATA TO SUPPORT THE CIRCULAR TRANSITION IN THE MANUFACTURING SECTOR

9 EMPOWER SMES IN THEIR TRANSITION TO CIRCULAR MANUFACTURING

10 ADDRESS THE POSSIBLE NEGATIVE ENVIRONMENTAL IMPACT OF DIGITAL TECHNOLOGIES

WORLD MANUFACTURING FOUNDATION

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