ARTIFICIAL INTELLIGENCE AND THE CIRCULAR ECONOMY

AI AS A TOOL TO ACCELERATE THE TRANSITION

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Google

This paper provides an initial exploration of the intersection of two emerging megatrends: artificial intelligence and circular economy. Built on insights from over 40 interviews with experts, the work is a collaboration between the Ellen MacArthur Foundation and Google, with research and analytical support provided by McKinsey & Company. As well as identifying cross-sector circular economy applications for artificial intelligence, the paper also takes a closer look at the food and consumer electronics industries and how artificial intelligence is being used, or could be used in future, to enable and accelerate the transition in these sectors. It presents the first steps towards a deeper understanding of the subject, and presents a baseline on which to build more comprehensive analysis.

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EXECUTIVE SUMMARY

Over the past 200 years, humans have developed an impressive industrial economy that has provided unprecedented prosperity. The result of our collective intelligence, this economy has been built by years of gradual improvement and is powered by new technologies. However, this system is in need of change to sustain rapid growth in the global middle class without being overwhelmed by negative environmental and social impacts.

A circular economy, in which growth is gradually decoupled from the consumption of finite resources, offers a response. Its principles are to design out waste and pollution, keep products and materials in use, and regenerate natural systems. The advantages of such an approach are substantial. For example, research has shown that a circular economy in Europe can create a net benefit of EUR 1.8 trillion by 2030, while addressing mounting resource-related challenges, creating jobs, spurring innovation, and generating substantial environmental benefits.[1]

The challenges and negative impacts of the current economic model are massive, cumulative, and set to grow in line with the global economy, which could almost double over the next 20 years.[i] It is clear that we need new approaches and solutions to put us on an accelerated transition to a better model. New technologies, including faster and more agile learning processes with iterative cycles of designing, prototyping, and gathering feedback, are needed for the complex task of redesigning key aspects of our economy.

Artificial intelligence (AI) can play an important role in enabling this systemic shift. AI is a subset of the technologies enabling the emergent ‘Fourth Industrial Revolution’ era,[ii] and deals with models and systems which perform functions generally associated with human intelligence, such as reasoning and learning. AI can complement people’s skills and expand their capabilities. It allows humans to learn faster from feedback, deal more effectively with complexity, and make better sense of abundant data. A growing number of initiatives are exploring how AI can create new opportunities to address some of the world’s most important challenges.[iii]

This paper offers a first look into the cross-section of two emerging megatrends: how AI can accelerate the transition to a circular economy. It finds that AI can enhance and enable circular economy innovation across industries in three main ways:

1. **Design circular products, components, and materials.** AI can enhance and accelerate the development of new products, components, and materials fit for a circular economy through iterative machine-learning-assisted design processes that allow for rapid prototyping and testing.
2. **Operate circular business models.** AI can magnify the competitive strength of circular economy business models, such as product-as-a-service and leasing. By combining real-time and historical data from products and users, AI can help increase product circulation and asset utilisation through pricing and demand prediction, predictive maintenance, and smart inventory management.

i OECD real GDP long-term forecasts.

ii The Fourth Industrial Revolution is the fourth major industrial era since the Industrial Revolution in the 1800s, characterised by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres, marked by emerging technology breakthroughs in a number of fields, including robotics, artificial intelligence, nanotechnology, quantum computing, biotechnology, The Internet of Things (IoT), 3D printing and autonomous vehicles. - Professor Klaus Schwab, WEF, The Fourth Industrial Revolution (2017).

iii An exploration into how AI can be used for social good has been carried out in the report by McKinsey Global Institute: Notes from the AI frontier: AI for social good (2018).

3. **Optimise circular infrastructure.** AI can help build and improve the reverse logistics infrastructure required to 'close the loop' on products and materials by improving the processes to sort and disassemble products, remanufacture components, and recycle materials.

To illustrate the range of applications across sectors, this paper looks at two value chains: food and agriculture; and consumer electronics. These examples, one centred on biological materials and the other on technical materials,[iv] highlight the potential of AI to increase the circularity of a broad range of economic activity.

The potential value unlocked by AI in helping design out waste in a circular economy for food is up to USD 127 billion a year in 2030. This is realised through opportunities at the farming, processing, logistics, and consumption stages. Specific applications include: using image recognition to determine when fruit is ready to pick; matching food supply and demand more effectively; and enhancing the valorisation of food by-products.

The equivalent AI opportunity in accelerating the transition towards a circular economy for consumer electronics is up to USD 90 billion a year in 2030. Applications here include: selecting and designing specialist materials; extending the lifetime of electronics through predictive maintenance; and automating and improving e-waste recycling infrastructure through the combination of image recognition and robotics.

The essential similarities between the opportunities in these two industries suggest that the opportunities for AI to unlock value in a circular economy are not industry specific. Combining the power of AI with a vision for a circular economy represents a significant, and as yet largely untapped, opportunity to harness one of the great technological developments of our time to support efforts to fundamentally reshape the economy into one that is regenerative, resilient, and fit for the long term.

Creating a broader awareness and understanding of how AI can be used to support a circular economy will be essential to encourage applications which span, and go beyond, the areas of circular design, operating circular business models, and optimising circular infrastructure. Ultimately, AI could be applied to the complex task of redesigning whole networks and systems, such as rewiring supply chains and optimising global reverse logistics infrastructure, in any sector.

Both collaboration between relevant stakeholders and a degree of oversight will be needed to support these systemic applications of AI, ensuring that data can be shared in an open and secure manner, and that AI is developed and deployed in ways that are inclusive and fair to all.

iv For more information on biological and technical materials, refer to Box 1 • Circular economy concept and principles on page 7.

1 • A CIRCULAR ECONOMY WORKS IN THE LONG TERM

The Industrial Revolution of the 1800s resulted in huge levels of growth. With economic and technological development we became better at extracting resources and creating value from them. We gradually designed a complex economy and built institutions such as universities, governments, and corporations that create jobs, make products, and deliver services that make our lives better. But at the heart of our economy lies a linear 'take, make, dispose' model, which relies on consuming large quantities of finite materials and fossil fuels.

Any system based on continual extraction and consumption will eventually experience limits to growth. Today's economy is hugely wasteful, which results in large losses of value. For example, in 2016 the world produced 45 million tonnes of electronic waste (e-waste), with an estimated value of EUR 55 billion in raw materials.[2] A hefty portion of this value is never recovered, as only 20% of this waste is collected and recycled appropriately.[3] Similarly, the global food system currently grows more than enough food to feed the world's population, but roughly a third is lost or wasted throughout the supply chain and during consumption.[4]

In some instances, the linear system is leading to a decline in overall quality of life. Health outcomes are increasingly affected by poor air quality in cities, and livelihoods threatened by climate change caused largely by the greenhouse gases emitted by burning non-renewable fossil fuels. Several global systems are under severe pressure. For example, to feed the global population, approximately 60-70% more food is needed by 2050,[5] but the vast majority of industrial scale, extractive agriculture practices degrade soil quality, which (along with generating greenhouse gas emissions) results in serious concerns about how many harvests are left.[6]

Consequently, there is an urgent need for innovation to meet these challenges, by redesigning our economy to be one that creates rather than extracts value, keeping finite technical resources in flow within the economy and protecting and regenerating biological systems.

The circular economy vision: a regenerative system fit for the future

The concept of a circular economy has gained significant momentum in recent years, with increasing interest from businesses, governments, and academics. It rests on three principles: design out waste and pollution; keep products and materials at their highest value; and regenerate natural systems. The economic, environmental, and societal benefits of a circular economy are becoming increasingly evident.[v] They include addressing mounting resource-related challenges, generating growth and jobs, and reducing negative environmental impacts such as carbon emissions. In a circular economy, creating value is increasingly decoupled from consuming finite resources. It presents organisations small and large, local and global, private and public, with the potential to create an economy that is distributed, diverse, and inclusive.

v See the Ellen MacArthur Foundation website for reports and publications on the benefits of a circular economy.

Box 1 • Circular economy concept and principles

The circular economy is based on three principles:

First, waste and pollution are designed out. This means that the products of today can become the resources of tomorrow and the negative impacts of economic activity that cause damage to human health and natural systems are eliminated. This includes factors such as the release of greenhouse gases, the use of toxic and hazardous substances, the pollution of air, land, and water, and the landfilling and incineration of waste.

Second, products and materials are kept in use. This includes favouring activities that increase product utilisation, and reuse to preserve the embedded energy, labour, and materials. Examples include designing for durability, repair, reuse, remanufacturing, and ultimately recycling.[vi] For biological materials, this could mean cascaded use of by-products, before nutrients are returned to the biosphere.

Third, natural systems are regenerated. This entails, for instance, deploying agricultural practices that not only avoid degrading soil, but actually rebuild soil health over time.

The circular economy model distinguishes between technical and biological cycles. In biological cycles food and biological materials (e.g. cotton or wood) feed back into the system through processes such as composting and anaerobic digestion. These cycles regenerate living systems such as soil, which provide renewable resources for the economy. Technical cycles recover and restore products, components, and materials through strategies including reuse, repair, remanufacturing, or recycling.

vi A circular economy approach encourages designers and manufacturers to extend the use period of products, through activities such as design for durability, repair or refurbishment. When this is no longer feasible, efforts to recover the value of materials come into play.

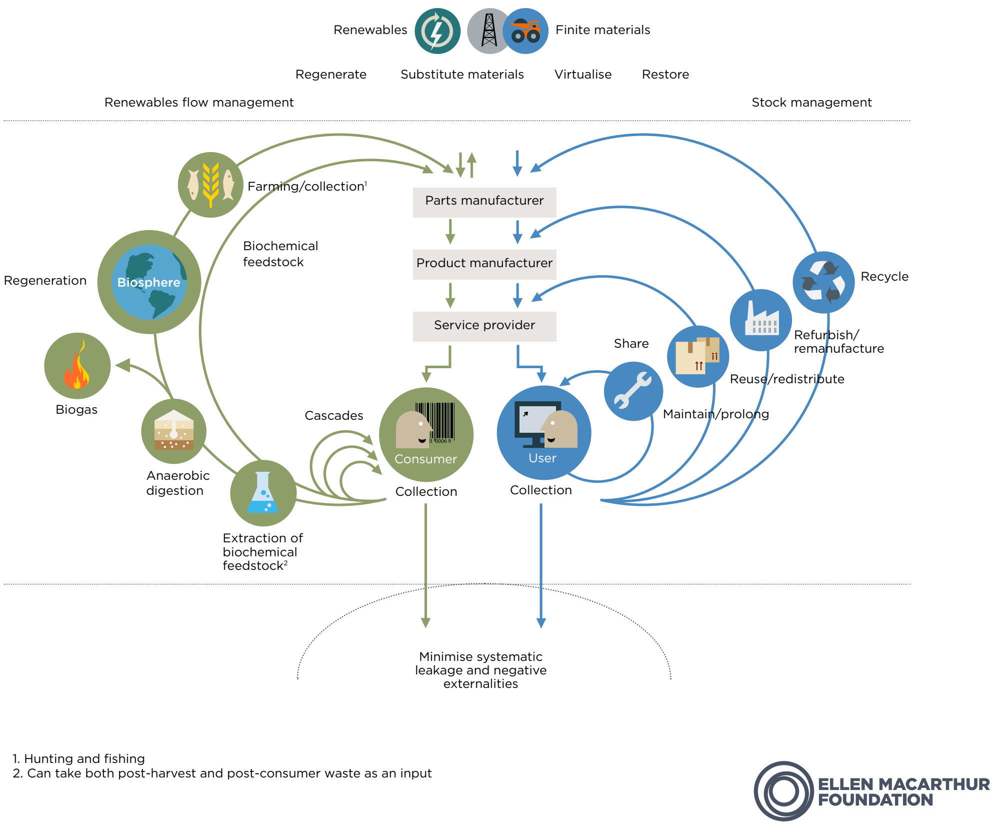


Figure 1: The circular economy system diagram[vii]

Importantly, the transition to a circular economy does not only amount to adjustments aimed at reducing the negative impacts of the linear economy. Rather, it reflects a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits.

Technology is crucial to realising this vision at scale

Technological innovation plays a major role in bringing the circular economy vision to life. For instance, intelligent and connected assets can enable predictive maintenance to prolong the asset life; blockchain can create traceability and transparency in supply chains to reduce waste; and repair is made easier by 3D printing of spare parts.

AI, as an emergent 'Fourth Industrial Revolution' technology,[viii] can support and accelerate the pace of human innovation to design products, bring together aspects of successful circular business models, and optimise the infrastructure needed to loop products and materials back into the economy. Utilising AI capabilities could create a step change which goes beyond realising incremental efficiency gains to help design an effective economic system that is regenerative by design.

vii Ellen MacArthur Foundation; Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

viii For further discussion on how the digital technologies grouped under 'Fourth Industrial Revolution' can support the transition to a circular economy, see the World Economic Forum and Accenture report, *Harnessing the Fourth Industrial Revolution for the Circular Economy: Consumer electronics & plastics packaging* (2019).

2 • ARTIFICIAL INTELLIGENCE CAN ACCELERATE THE TRANSITION TO A CIRCULAR ECONOMY

Since the 1950s, the ability of artificial intelligence to help solve problems has grown tremendously, in part due to significant increases in processing power and availability of data. Its applications and capabilities have evolved and are now seen as a promising technology for many sectors and businesses. It is estimated that in 2016, AI attracted between USD 26 billion and USD 39 billion in global corporate investments,[7] fuelling the advancement and dissemination of this technology; and artificial intelligence is predicted to add an extra USD 13 trillion to global economic activity by 2030.[8]

To explore what role AI can play in the transition to a circular economy, the current capabilities and future potential of AI need to be understood, and how these can be used to help design, operate and optimise a circular society.

AI can help solve complex problems faster

Artificial intelligence is an overarching term for a collection of technologies, dealing with models and systems that perform human-like cognitive functions such as reasoning and learning. AI helps to solve problems through pattern recognition, prediction, optimisation, and recommendation generation, based on data from videos, images, audio, numerics, text and more.

The development of an AI algorithm typically follows a process of data collection, data engineering, algorithm development, and algorithm refinement, to produce an output which can solve a particular problem. First, the required data is collected, through capturing images and other metadata. The data is then consistently labelled and engineered into a format which is machine-readable and an algorithm is developed. Different types of algorithms can be employed depending on the use case. Figure 2 on page 10 illustrates the algorithm development for a deep learning application. The algorithm is then refined in an iterative process, during which it gets trained on training data sets until it can infer its learning to new and unknown data, so it can be used in real-life applications such as visual identification of a particular object.

Creating and implementing AI is not easy and requires a set of basic elements to be in place. Experts are needed for algorithm development, the preparation of training data and the translation of the algorithm output into results that make sense for humans. Another requirement is the availability of sufficient high-quality data to train the algorithm. Rubbish in, rubbish out, means that badly engineered data leads to poor quality outputs.[ix] Despite creating 2.5 quintillion bytes of data daily[9] (as a comparison, this number is equivalent to a quarter of all living insects at any moment),[10] most of this data is not usable for AI due to insufficient data labelling. Also, data privacy and security can limit usage and access. This points to another basic element: AI infrastructure. For example, to capture value from AI, organisations need to establish digital processes, an open culture around AI, and on a technical level, appropriate processing power to handle all data inputs.

ix A widely held discussion about unbiased data for algorithm training is currently happening. The concept of bias in, bias out is also true and has led to widely supported effort and focus to create an inclusive approach to algorithm training and AI in general.

In a world that is increasingly digital and connected, that produces more and more data, AI can complement and expand human skills and capabilities. It holds significant potential to make sense of large quantities of diverse and complex data. Through capabilities such as inductive reasoning and pattern recognition, AI can draw connections between different parts of a network or dataset and generate solutions that go beyond human capacity and speed.

AI applications have arisen across many different industries, from number plate recognition used by the police, to face recognition to unlock smartphones, and from voice-controlled virtual assistants, to algorithms which help retailers to gain better customer insights and personalise marketing efforts. The number and diversity of AI applications being developed is set to grow considerably over time. Initiatives such as TensorFlow, an open source software platform that makes machine learning and deep learning tools available to everyone, are also making the use of AI more accessible to a broader audience. If businesses and other market players with circular strategies harness the capabilities of AI, it could lead to the design and quick and successful implementation of a variety of circular economy solutions.

Similar to the human brain AI processes data and learns from it to make better decisions over time.

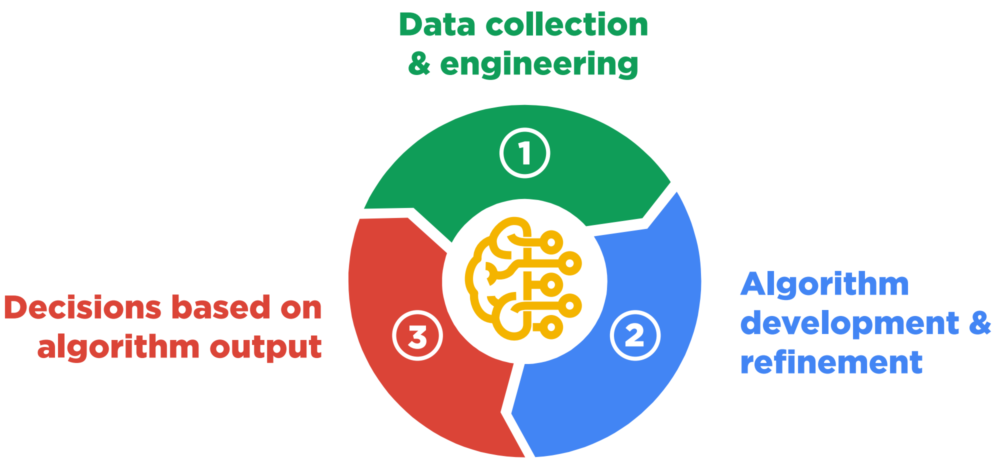
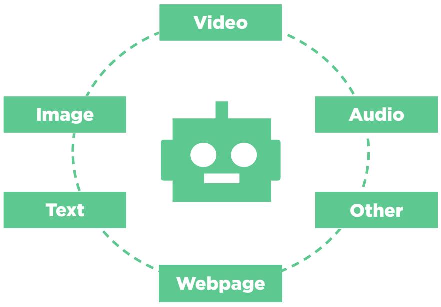


Figure 2: The AI algorithm development process for a specific use case

Data collection & engineering

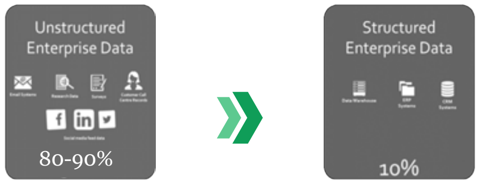
AI algorithms perceive the world through data...



...but need the data to be in the right format to process it

Unstructured, unlabelled data

Structured, labelled data



Information that is difficult to organise or search

High degree of organisation, easy to search

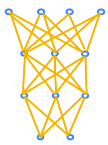
Algorithm development & refinement

First, an untrained algorithm is developed...

...which is trained on existing data sets...

...to then make interferences on new data using the trained model

DEEP LEARNING EXAMPLE



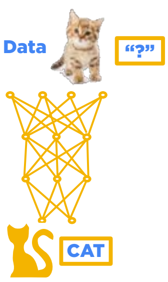
Neural Network Model

Training Data

Learn from existing data

Trained Model

New Data



Decisions based on algorithm output

The algorithm can be used for different functionalities, such as:

Pattern recognition	Prediction	Optimisation & planning	Integrated solutions with robots
Financial risk classification Data model building Music and voice recognition	Medical diagnosis Targeted advertising Recommendation engines	Route planning Spend optimisation Dynamic pricing	Autonomous driving Robotic surgery Household robots

AI can help unlock circular economy opportunities by improving design, operating business models, and optimising infrastructure

AI capabilities can help build a circular economy, at a faster rate than would be possible without AI. AI can boost development and design of completely new circular products and businesses. Equally, it can help traditional players in their transition to become more circular.

Across industries, AI technologies can unlock three high potential circular economy opportunities: (1) Design circular products, components, and materials; (2) Operate circular business models; and (3) Optimise infrastructure to ensure circular product and material flows.

Design circular products, components, and materials

Circular economy calls for design innovation to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. Design can empower cycles of reuse, repair, refurbishment, and recycling of technical materials and the cascading and looping of biological nutrients.

Circularity requires more features to be taken into consideration for the design of products, components, and materials, such as disassembly, upgradability, or recycled content. Add to this list of features the wide choice of materials and the possibilities of manipulation of structures with 3D printing and other manufacturing techniques, and the design options become countless. AI technology can be a helpful tool to enable designers to manage this complexity when making decisions. A continuous feedback process where designers test and refine AI generated design suggestions could lead to a better design outcome in a shorter time period.

Design of new materials can help to substitute harmful chemicals and materials. It can enable distributed manufacturing with technologies such as 3D printing, using locally available materials and by-products, and it ensures materials retain more value as they are cycled. To design a new material, material scientists need to evaluate a significant amount of data about the structure and properties of materials, which AI could analyse quickly to suggest new materials.

In addition, by training an algorithm to analyse known chemical data, AI could potentially be used to predict the toxicity of chemicals or materials where it is not known in a more economic and efficient way. However, while large quantities of data exist around the properties of different materials, much of the data is propriety and inaccessible which currently limits the possibilities for AI applications in material design.

An example where AI has been used to assist and accelerate material design is the Accelerated Metallurgy project, run by the European Space Agency together with a group of leading manufacturers, universities, and designers. AI technology was used to create a rapid and systematic way to produce and test new metal alloys. Not only did it produce completely new materials, it also discovered them faster than ever before.

Case Study • Using AI to design new materials for a circular economy

About the project

Funded by the European Space Agency, the project 'Accelerated Metallurgy' conducted research on the rapid and systematic development, production, and testing of novel alloy combinations.

Contributing to a circular economy...

The project aimed to develop new metals with the same performance in a more efficient way. Alloys designed with circular economy principles in mind: are non-toxic; are designed to be used and reused; have longer use periods; and could be made using additive manufacturing and processing methods that minimise waste. Additionally, improved material properties can implicitly reduce resource use through enhanced product performance.

...by using AI

Accelerated Metallurgy uses AI algorithms to systematically analyse huge amounts of data on existing materials and their properties to design and test new alloy formulations. By capturing details of the chemical, physical, and mechanical properties of these unexplored alloys, the algorithms can map key trends in structure, process, and properties to improve alloy design using rapid feedback loops.

Solving real business problems

Using AI to improve and accelerate the material design process can lead to the development of alloys that can circulate at high value in the economy and that support product and technology innovation (e.g. alloys that can convert waste heat to electricity), as well as other potential benefits such as increased performance and extended product life.

With potential for system level impact

"Accelerated Metallurgy has achieved for the metallurgy industry a drastically reduced time to market. Moreover, emphasis on environmentally friendly alloys at an early design phase, in combination with life-cycle analysis, will contribute to conserving natural resources and the move to low-carbon technologies."

EUROPEAN COMMISSION

Another company using AI for materials development to accelerate the material design process is Citrine Platform. Working with materials data, Citrine Platform uses algorithms and AI technology to develop new chemicals and materials for high performance applications. For example, using the platform to find a 3D printable, aerospace-grade aluminium alloy enabled the possible candidates for the alloy to be narrowed from 10 million to only 100. Using AI technology that is adaptive and sequentially learns as experiments progress can enable companies to augment the traditional 'trial and error' process, and improve and optimise their design and innovation process for materials.

Applying similar AI techniques more broadly could lead to the rapid prototyping and design of materials, components and products which can be used and reused and safely circulated in the economy.

Operate circular business models

Developing successful and profitable circular business models requires the organisation of business functions such as marketing, pricing, and sales, after sales services, customer support, logistics, and reverse logistics, underpinned by circular economy principles. It involves introducing new business propositions such as asset sharing and product-as-a-service, but also making existing circular products compete successfully with linear ones. Dynamic pricing and matching algorithms have unlocked the potential for sharing and access models for things like cars and bicycles – other industries are ripe for innovative circular business models, too.

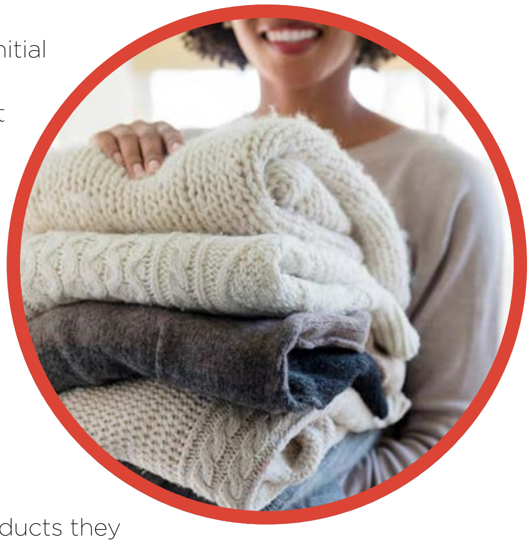
Making reverse logistics and remanufacturing work requires solving several problems, including the fluctuating demand and supply of used products and components, and the widely varying condition of the returned components.[11] For a company to choose the next use cycle for each returned product – such as reuse, recovering components through parts harvesting for remanufacture, or recycling – it would have to take into consideration a combination of factors regarding the product's condition, as well as the current market situation. Only with the ability to collect large quantities of product and customer data, and a powerful AI-based analytical model to make sense of it, does such a decision-making model become feasible.

A compelling use case in which AI is used to support price setting, forecast demand, and to create trading platforms for secondary resources, components and products, is Stuffstr. Stuffstr buys and collects used products from consumers and sells them in second hand markets. An AI algorithm helps Stuffstr to set competitive prices for the seller, while offering Stuffstr a good margin on the second hand market.

Case Study • Using AI in dynamic price setting for circular business models

About the company

Founded in Seattle in 2014, Stuffstr offers consumers the opportunity to buy back used household items, with an initial focus on clothing and apparel, in exchange for vouchers, which can be spent at the original apparel retailer. As part of this process, Stuffstr collects the products and re-sells them through existing secondary markets.



Contributing to a circular economy...

Stuffstr boosts re-use of apparel by giving it a second life. The service offers consumers a low hassle solution for getting rid of unused stuff, with a financial incentive. The concept increases awareness for the value of unused clothing and also encourages consumers to sell back items they no longer need or want so they can be circulated.

... by using AI

Stuffstr uses AI algorithms for the pricing of both the products they buy from consumers and the products they sell in secondary markets. The backend of their service uses machine learning to ensure a consistent classification of all re-sale items. Finally, AI helps refine Stuffstr's sales strategy through constant experimentation and rapid feedback loops.

Solving real business problems

For retailers, Stuffstr provides an additional revenue stream as well as an improvement in consumer loyalty. Stuffstr itself generates revenue by reselling used apparel and servicing fashion brands by ensuring that their products are only sold in certain secondary markets. For consumers, the company pays for used and/or unwanted apparel in a transparent and convenient manner.

With potential for system level impact

"The CO_2 embedded in the household items we buy each year exceeds the emissions of the entire US. auto fleet. And almost 85% of US. textiles end up in landfill — about 70 pounds per person every year — yet most are eligible for recycling. Current circulation rates are incredibly low, for instance only 2% of apparel products enter a secondary market."

JOHN ATCHESON, CEO STUFFSTR

AI technology has huge potential to create circular value within current business models. AI technology creates the potential to cut inventory levels, without compromising the ability to meet customer demand. This could lead to a big reduction in waste from unsold products, as well as a reduction in cost.

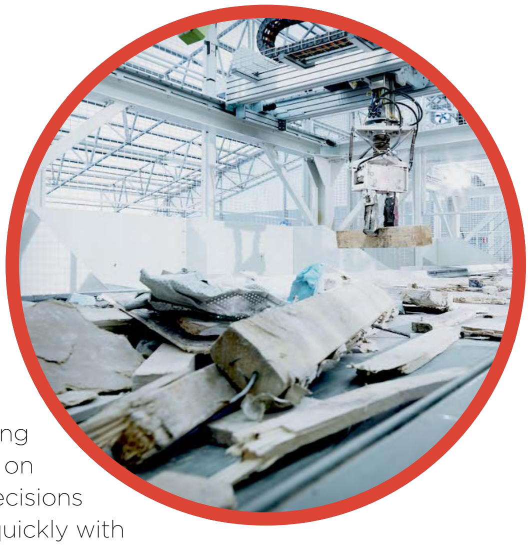
Optimise infrastructure to ensure circular product and material flows

A key feature of a circular economy is that materials and products are not consumed and disposed of, but used over and over again. This requires reusing, repairing, remanufacturing, and recycling of technical products and winning back nutrients from biological waste streams for which an efficient and extensive infrastructure for collecting, sorting, separating, treatment, and redistribution is needed.

A common challenge to generate value from used material streams, from kitchen waste to used computers, is that these streams are mixed and heterogenous in materials, products and by-products, both biological and technical. Effective recovery of valuable materials requires homogeneous, pure flows of material and products. In general, the better material streams are pre-sorted and separated, the higher the recovery level, the more components can be identified for reuse and remanufacture, and the higher the quality of materials extracted during recycling.

AI is already showing how it can create value in realising circular material flows and in enabling enhanced valorisation of materials and products, by sorting post-consumer mixed material streams through visual recognition techniques. ZenRobotics, for example, works with cameras and sensors, whose imagery input allows AI to control intelligent waste sorting robots. These robots can reach an accuracy level of 98% in sorting myriad material streams, from plastic packaging to construction waste.

Case Study • Using AI to improve and optimise infrastructure for a circular economy



About the company

Founded in 2007, ZenRobotics was the first company to apply AI and robotics in a demanding waste processing environment. The company combines AI and robotics to recover recyclables from waste.

Contributing to a circular economy...

ZenRobotics's technology allows greater flexibility in waste sorting, enabling operators to react quickly to changes in a waste stream and increasing the rate of recovery and purity of secondary materials.

... by using AI

Waste is monitored by cameras and sensors. The AI software, called ZenBrain, analyses the sensor data, creating an accurate real-time analysis of the waste stream. Based on this analysis, the heavy-duty robots make autonomous decisions on which objects to pick, separating the waste fractions quickly with high precision.

Solving real business problems

ZenRobotics waste sorting solutions offer opportunities to improve performance and efficiency of waste sorting. This increases the value that can be generated from material streams through improved recovery rates and overall quality of outputs.

With potential for system level impact

"Intelligent robotic systems can process almost any given waste stream, and sorting capabilities can be redefined for every new market situation—even on a daily basis. Furthermore, increased flexibility in recognition gives plant operators the possibility to explore new use cases."

WASTE MANAGEMENT WORLD

Development of AI towards circular economy solutions

The opportunities in design, business models and infrastructure extend across all industries. All relevant stakeholders should explore where the highest potential lies in their individual organisations and industries to harness the capabilities of AI to realise circular economy ambitions.

Taking design as an example, AI could be used to improve and speed up the design and material selection process to improve the circularity of nearly all materials and products. As well as the specific use cases for AI in the food and consumer electronics industries explored in this paper, AI could, for example, help material scientists and designers develop solutions for the 30% of plastic packaging that requires fundamental redesign and innovation,[12] or engineers and architects to optimise building design features based on circular design principles, such as the type of connections or architectural finishes.[13]

Realising the potential of AI-enabled circular economy solutions requires awareness of both the maturity and the limitations of AI. For AI to prove solutions, such as the examples mentioned above, it not only requires the four steps of data collection, data engineering, algorithm development, and algorithm refinement, it also requires a clear understanding of the actual problem and what we specifically need AI to solve. Put simply, if humans cannot establish the relevant inputs and outputs clearly, a machine cannot solve a problem.

Although not unique to the application of AI for circular economy, there are challenges which will need to be addressed in order to scale up and capture the full potential of AI. These include: ensuring the development of AI algorithms is value-driven, so the technology is safe and beneficial to society; ensuring that the technology is held to account by humans; avoiding creating or reinforcing unfair bias; and incorporating privacy design principles for use of data.

The transition to a circular economy can not be done by one company alone; it requires value chains and an entire network and ecosystem of partners to build trust and to work together. Transparency, with open or easy access to data, is required but rarely found. The Global Fishing Watch, is an inspiring example of how transparency and data sharing can lead to more insights and value (in this case, for monitoring fishing fleets and building a sustainable fishing industry) for all parties, allowing its AI technology to support the development of a fishing sector that works for governments, fishermen, consumers, fish and the oceans alike.

The Global Fishing Watch is an example of AI in action at a system level. Ultimately, AI could be used to help redesign whole systems, and optimise networks and national and global infrastructure towards a circular economy. AI's capabilities to deal successfully with multiple complex parameters, perform rapid testing, feedback learnings, adjust assumptions and understand connections between multiple parts of a system make it well suited to design the best solution for a system as a whole.

Other examples of using AI to optimise a system for a beneficial outcome include: using real time traffic camera data to reduce traffic congestion in cities;[x] optimising energy usage for cooling the thousands of servers housed in data centres;[xi] and an electric car sharing collaboration between car-sharing firms, automotive companies, and infrastructure operators in China, integrating AI and autonomous network solutions to ensure that charge points and refuelling stations can match electric vehicle demand.[xii]

x For more information, visit http://www.bbc.com/future/story/20181212-can-artificial-intelligence-end-traffic-jams

xi A well known example is Google applying Deepmind's AI technology to optimise the energy efficiency of the cooling system in their data centres, resulting in a reduction in energy usage up of to 40%. More information can be found on the DeepMind website.

xii For more information, visit http://www.bbc.com/future/story/20181212-can-artificial-intelligence-end-traffic-jams

3 • IN FOCUS: AI CAN HELP PUT THE FOOD SYSTEM ON A PATH TO A REGENERATIVE FUTURE

Over the past two centuries, the industrial food system has worked wonders to rapidly increase global food production, in conjunction with vast growth of the world's population. While the industrial food system has made large productivity gains, it is in essence extractive, wasteful, and unfit to meet the world's long-term food needs. In the current food system, for every USD 1 spent on food, society pays USD 2 of economic, social, and environmental costs.[14]

Vision of a circular economy for food

In a vision for a circular food system, food production improves rather than degrades the environment and people have access to healthy and nutritious food. Agriculture is regenerative, improving the overall health of local ecosystems and people. Food is produced on a global, regional and local scale, according to where food types grow best. Food is designed and marketed to make healthier food part of people's daily diet, both from a nutritional standpoint and how it is produced. Food by-products are seen as value streams rather than waste streams, and food waste is designed out.

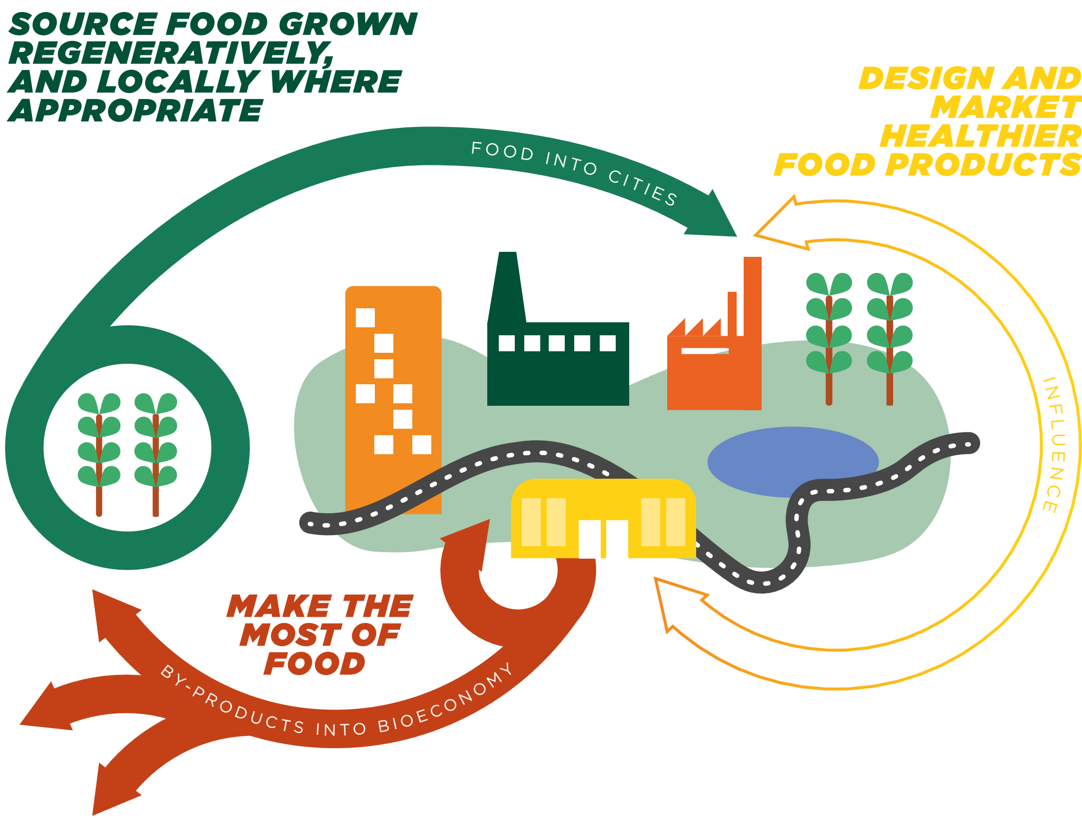


Figure 3: Three ambitions for cities to build a circular economy for food[15]

Technological innovation, including artificial intelligence, plays a major role in bringing this circular vision to life. Digital capabilities support distributed food production and by-product treatment. Drones make it easier for farmers to accurately determine soil health; blockchain helps create traceability and transparency so people know where their food is coming from; 'smart' bins in cities allow more effective separation and sorting of food and non-food waste; and food labs and start-ups are using algorithms to rapidly prototype plant-based proteins and lab-grown meat, as alternatives to conventional animal protein sources.

AI can help grow food regeneratively and make better use of its by-products

To set the transition to a circular food system on the right path, the three main ambitions are to **source food grown regeneratively and locally where appropriate**, **make the most of food**, and **design and market healthier food products**.[16] AI can play an important role in achieving these three ambitions and revolutionising the way food is grown, designed, purchased, and enjoyed.

By helping design out food waste, AI can generate an estimated **economic opportunity of up to USD 127 billion a year in 2030**, calculated as growth in top-line revenue.[xiii] This is realised through opportunities at every step of the value chain, from farming, processing, logistics, and consumption. Specific applications include: using image recognition to determine when fruit is ready to pick; matching food supply and demand more effectively; and enhancing the valorisation of food by-products.

Source food grown regeneratively and locally where appropriate

Currently, most food is grown in a way that withdraws more from natural systems than it returns, leaving waterways polluted, and soils and agrobiodiversity depleted. In order to safeguard and protect future soil health, the agricultural sector needs to switch from practices of conventional agriculture, such as mono-cropping, blanket application of synthetic chemical fertilisers and pesticides, and intensive land use, to more regenerative agriculture practices.[xiv] In addition, the supply chains that deliver food to consumers need to be rewired to mix food from local, regional, and global sources, according to where it grows best.

There are many reasons why transitioning to more local and regenerative production will be challenging. Many farmers are already operating on low margins and the investment in time, equipment, and operational changes required to adopt regenerative practices may be difficult to finance. Finally, the 'rewiring' of food supply chains to favour local sourcing will be a hugely complex exercise.

Technologies and innovation hold some of the answers to these challenges. With the rise of food-tech and ag-tech, a new set of food and agricultural solutions are emerging. Farmers can now use data driven, sophisticated software and AI solutions to help them manage their farming practices more effectively, and to get an idea of what the outcomes could be for regenerative agriculture practices, without expensive and time consuming field trials. For example, CiBO Technologies uses data analytics, statistical modelling and artificial intelligence to simulate field trials and agricultural ecosystems under different conditions.

xiii McKinsey & Company modelling and analysis based on expert interviews and additional research.

xiv The focus of regenerative farming practices, described in its broadest sense, is to build healthy, biologically active ecosystems. The regenerative mindset focuses on desired outcomes, including healthy soils indicated by improved soil organic material, water-holding capacity and microbial population.

Using data collected from fields by drones, remote sensors, satellite imagery, and smart farm equipment, AI can also provide farmers with real-time information about what is actually going on in their fields. Having access to real-time information about variables like localised quality of soil, health of crop and livestock, market conditions for inputs and outputs, and weather conditions can help farmers make better decisions about, among other things, which crop to grow where, how to optimise crop rotation patterns, and predict the right time to sow, apply compost and harvest crops.

> ***"The food and agricultural system is too complex to fully understand with traditional analytical methods. Building a circular food system adds additional complexity, this is where AI is needed."***
>
> MERIJN DOLS, SR. DIRECTOR, RESEARCH & INNOVATION AT DANONE

PlantVillage, a research and development unit of Penn State University, offers an example of AI being used to obtain a better understanding of crop health for smallholder farmers. Their mobile app assistant 'Nuru' uses machine learning to train algorithms to recognise plant disease symptoms from pictures taken using a smartphone camera. Other companies like FARMWAVE, Taranis and Aerobotics are using AI to interpret smartphone, satellite and drone imagery of crops to detect signs of pests and diseases as early as possible, so farmers can target their interventions and reduce crop loss. Companies such as Farmers Edge use satellite imagery and precision technology to help growers identify, map and manage farmland variability, from soil moisture content to overall crop health.

Additionally, AI algorithms carrying out visual identification and precision farming can be combined with robotic technologies to further automate and increase control in the farming process. Companies such as FarmBot and EcoRobotix have done this for conventional outdoor farming, with the potential to also use the technology for indoor urban farming applications such as multi-storey soilless hydroponic or aeroponic farms. Harvest CROO Robotics employs AI to interpret images of strawberries and determine when they should be harvested using autonomous robots. This reduces the likelihood of food wastage in the field and allows for more accurate yield forecasting, improving information along the supply chain and allowing for better utilisation of storage and cooling facilities.

Regenerative agriculture promotes the use of organic compost, which often contains beneficial microbes. Indigo Agriculture, Concentric, and Pivot Bio have used algorithms and machine learning to identify beneficial microbes which farmers can use to promote crop growth and resilience without synthetic fertilisers.

Demand signals from retailers and consumers inform the types and amounts of crops that farmers and producers have to grow. AI can play a role in forecasting demand using historical and real time data, potentially improving efficiency of supply chains leading to less overproduction and less overstocking, caused by distortion of demand information moving upstream in the supply chain.[xv]

Furthermore, AI could be used to map the current landscape of global food supply chains and determine the optimal way to 'rewire' supply chains to source and consume ingredients locally where appropriate, and to process food as close as possible to where it is grown and consumed, enabling better matching of supply and demand for food.

xv This is known as the 'bullwhip effect', where distorted information from one end of a supply chain to the other can lead to tremendous inefficiencies such as excessive inventory investment, MIT Sloan Management Review (1997).

Artificial intelligence and a circular economy for food

Design out avoidable food waste during storage and distribution by using AI for automated and objective inspection, sorting, and processing of fresh food. Use AI to map and optimise global food supply chains that source, process, and use ingredients locally where appropriate

Better match demand and supply by increasing local production and processing, minimising waste in retail channels through AI-enabled dynamic pricing and demand prediction, and valorising food by-products at the point of consumption using AI tools and smart hardware in kitchens

Create digital platforms and marketplaces which connect food by-product producers to users, creating opportunities to turn waste streams into new revenue streams

Enable valorisation of food by-products by using AI to analyse the nutrient content and micropollutant contamination of organic materials, and sort them according to potential use

Enable regenerative farming using AI solutions to help implement more effectively regenerative farming practices such as using organic compost, crop rotation, and diverse crops

Optimise recipes and food production processes by using AI to help source regeneratively grown ingredients which are safe to cycle

Make the most of food

Making the most of food involves designing out avoidable food waste, preventing edible food from being thrown away, and valorising unavoidable food waste and by-products. Globally we grow more food than we need to feed the world, but up to one third of all food is spoiled or squandered before it is consumed by people. In 2011, food losses and waste amounted to roughly USD 680 billion in industrialised countries and USD 310 billion in emerging economies.[17]

Designing out avoidable food waste

Food waste occurs at three stages: during production and processing; during distribution and storage; and during preparation and consumption. Preventing food waste at each level relies not only on technology solutions and better alignment in the supply chain, but also changes in human behaviour and purchasing patterns.

It is worth noting that in emerging economies, 40% of loss occurs at post-harvest and processing levels while in industrialised economies more than 40% of loss occurs at retail and consumer levels.[18] Therefore, the use of AI solutions to reduce production and processing waste depends to a large extent on access to relevant technology and infrastructure in emerging economies.

Production and processing

While AI-enabled precision farming techniques can help reduce waste in agriculture and food production, there is potential for AI to be used in reducing food waste during processing. An example is TOMRA's food sorting solutions which use AI algorithms to analyse images and data from cameras, near infrared spectroscopy, x-rays and lasers, to identify non-uniform produce such as carrots and potatoes, and sort each one according to its optimal use.

Case Study • Using AI to improve sorting, separation, and valorisation of food

About the company

Founded in Norway in 1972, TOMRA provides a wide range of ways to increase resource productivity in sorting and collecting processes. In the food industry, they provide advanced sorting, steaming, and peeling equipment and can provide insights into the ripening processes of food.

Contributing to a circular economy...

With its range of technical solutions, TOMRA optimises the resource use needed to produce food while attaining the required product quality and ensuring food safety. TOMRA technologies detect and measure food, helping redirect good quality produce not considered suitable for direct sale to consumers for use in other food products, preventing them from becoming waste.

... by using AI

TOMRA's sensor based solutions autonomously evaluate food products based on different criteria, such as stage in the ripening process. AI algorithms help detect, analyse, and sort products based on potential uses. Other AI algorithms ensure that processing machines cut products into consistent pieces, regardless of original shape and size, thereby reducing overall waste.

Solving real business problems

TOMRA's solutions reduce food waste in food processing stages and help valorise produce which may not be suitable for direct sale to consumers.

With potential for system level impact

"Halving food loss and waste is needed for keeping the food system within environmental limits. Halving food loss and waste could, if globally achieved, reduce environmental impacts by up to a sixth (16%)."

DR MARCO SPRINGMANN ET AL.,
OPTIONS FOR KEEPING THE FOOD SYSTEM WITHIN ENVIRONMENTAL LIMITS, NATURE (2018)

Distribution and storage

Once packed and shipped, fresh food is evaluated multiple times for regulatory and company specific requirements including quality, safety, size and appearance before reaching the retail and food service operations. Quality managers inspect batches of products according to guidelines and processes documented in lengthy manuals. This manual process is time consuming, expensive and inaccurate. The decision to accept or reject a batch is based on a small sample size and often subjective. When trailers of produce are rejected, the seller must scramble to find a buyer in a secondary or terminal market. If no buyer is found, food is sent to landfill.

Technology which enables automated, objective inspection, potentially implemented upstream from distribution hubs, can have a dramatic impact on reducing the amount of food which is discarded, by providing data to drive appropriate decision making. For example, the Food Team at Google, in collaboration with X (formerly Google X), the moonshot lab within Alphabet, is exploring how visual imagery techniques could help accelerate the food inspection process to improve food supply chain efficiency, minimise waste and enable more accurate retailer planning.

Preparation and consumption

Once on the supermarket shelves, companies like Wasteless help retailers to sell food before it goes bad, using AI-enabled tracking and dynamic pricing based on expiration dates. Tackling the issue of food waste in institutional and restaurant settings, kitchen technologies, such as Leanpath and Winnow, offer tools to capture, track and categorise data on food waste. These current solutions can be fully automated by machine learning algorithms which will further accelerate widespread adoption by kitchen staff. Furthermore, companies like Tenzo use artificial intelligence algorithms to forecast and predict sales enabling restaurants, retailers, and other hospitality institutions to more effectively connect supply to demand when ordering food, and reducing avoidable food waste.

"Food deals with high volume, diversity and variability. There is a huge data gap of what is thrown away, for which we can use AI and computers that basically have eyes and ears as interfaces, to analyse and present measures for waste reduction."

MARC ZORNES, FOUNDER OF WINNOW

Valorisation of unavoidable food waste and by-products

Some amount of food waste is unavoidable, from trim waste such as carrot peels, to catered food that cannot be repurposed in ways that meet food safety regulations. While reducing overproduction is the first and foremost best way of reducing food waste, unavoidable by-products, along with peelings, clippings and sewage, could be turned into valuable products,[xvi] if effective infrastructure for collection, sorting and treatment of this waste were in place. Food design and upstream innovations are equally important for keeping organic material streams uncontaminated.

The Food Program at Google, in collaboration with X, is exploring food waste intelligence technologies to help turn leftover food into valuable products. Google produces 226,000 meals a day for its staff and has partnered with Leanpath to reduce millions of pounds of pre and post-consumer food waste in its cafes.[xvii] Smart hardware enables the automated and objective capture of data about pre-consumer food waste. AI tools can then provide suggestions for potential recipes to make use of leftovers. Take excess bread in a food service kitchen for example. Once it can no longer be served as bread, it might be turned into croutons for soup, and then into breadcrumbs. Any bread leftover may be used to feed animals or composted, obtaining additional value from excess food which may otherwise have been thrown away.

Even if all surplus edible food was redistributed, a large volume of inedible food by-products, human wastes, and green waste would continue to be generated. These organic materials contain valuable nutrients that can be used for a range of purposes. It is important to know the nutrient content of organic waste streams and the presence of any micropollutants, in order to valorise organic by-products in the right markets. The application of AI could help to improve the information about the makeup of these organic streams, as MIT's Senseable City Lab and the Alm Lab have done with their Underworlds prototype smart sewage platform. The platform combines physical infrastructure and biochemical measurement technologies with artificial intelligence computational tools and analytics to interpret and act on findings about the pathogens in human sewage, which could ultimately enable the use of sewage in a regenerative food system.

Design and market healthier food products

A significant volume of the world's food crops pass through some kind of intermediate 'food design' stage or processing to create the final 'product' we eat. In the US for example, processed food makes up to 70% of people's diet.[19] In the years to come, as populations continue to urbanise and become more affluent, the volume of processed food is likely to increase, driven for the most part by the convenience and time saving benefits offered to the lives of busy citizens and the extended shelf life of processed food.

As demand for convenient, easy to prepare food increases, so the opportunity grows to design and process food in a circular way. By using AI as a tool to help source regeneratively grown ingredients, replace animal protein ingredients with plant-based proteins, reduce processing waste, and avoid unsafe additives, food innovators and designers can make it easier for people to access healthy food products. Food design augmented by AI can design out potential contaminants from organic material streams, so by-products can more easily be valorised and safely returned to the soil. For instance, food brands and providers can

xvi What constitutes the 'most' valuable product is dependent on context and could be food for human consumption, animal feed, fertiliser, biomaterials or bioenergy.

xvii For further information about this initiative visit https://sustainability.google/projects/rews/.

use AI to create innovative new recipes that avoid the use of any additives and other non-nutritional ingredients that may be unsafe to return to soils as organic fertilisers.

To illustrate how AI can augment food design, consider the process of identifying and creating plant-based alternatives to animal proteins. Replicating animal products with plant-based ingredients requires the consideration of nutritional value, colour, texture and taste, as well as how different ingredients interact together and how they respond to different conditions like heat and moisture. Knowing which ingredients, combinations and recipes to test is a complex task requiring specialist knowledge.

Companies such as Impossible Foods, NotCo, Beyond Meat and JUST are speeding up this innovation process by using AI algorithms to originate plant-based foods that replace meat, fish, dairy and egg based products. A similar approach is being taken by New Age Meats, which uses AI to model and optimise the conditions for producing lab-grown meat.

Case Study • Using AI to design and market plant-based foods

About the company

Founded in Chile in 2015, NotCo creates plant-based substitutes for foods made from animal products. NotCo's first product is an egg-free alternative to mayonnaise, and the company aspires to launch five additional products over the next two years.

Contributing to a circular economy...

NotCo provides plant-based substitutes so people can rely less on animals for protein, which require a lot more natural resources such as soil and water to grow than their plant counterparts, without needing to change their dietary habits.

... by using AI

The machine learning algorithm used by NotCo identifies new plant-based foods and composes food formulas by detecting patterns at a molecular level and analysing flavour molecules. Food scientists then test and taste the formulas and provide feedback to the algorithm to ensure the final product tastes as good as the original one. The scientists also evaluate the feasibility of the algorithm's output with regards to economics and availability.

Solving real business problems

The solution improves the cost effectiveness of R&D by increasing the speed with which new food sources and ingredient combinations can be identified, tested and iterated. For customers it offers the opportunity to eat healthy and delicious plant-based foods, while satisfying dietary preferences and avoiding a significant price premium.

With potential for system level impact

"Without meat and dairy consumption, global farmland use could be reduced by more than 75%, an area equivalent to the US, China, the European Union and Australia combined, and still feed the world."

JOSEPH POORE, DOCTORAL RESEARCHER - OXFORD UNIVERSITY

4 • IN FOCUS: AI CAN BOOST CIRCULARITY IN THE CONSUMER ELECTRONICS SECTOR

Consumer electronic products[xviii] have become an essential part of our daily lives, affecting how we work, spend our free time and even how we communicate and relate to each other. Despite this, we dispose of these products after a short use period; every year 10.5 million tonnes of consumer electronic waste (e-waste) are produced.[xix] China is the biggest producer of e-waste in the world, with some 6 million tonnes of domestically consumed electronic products discarded every year.[20] Globally, only 20% of this waste is recycled through channels that allow for recovery of valuable materials while avoiding damage to the environment or to human health.[21] The majority of e-waste is discarded rather than recovered or recycled, which leads to the loss of embedded energy, resources and value, as well as severe negative environmental and social consequences, especially in the informal recycling sector.[xx]

Vision of a circular economy for consumer electronics

In a circular economic future, e-waste is a concept of the past. Electronic devices are used for longer, by one or by several users. Used devices are not disposed of; they are reused, repaired, refurbished, remanufactured and circulated between users with different and changing needs, for instance through redistribution into market segments with lower performance requirements. This use period extension is enabled through design, upgradability for software, and new, innovative business models. Devices are designed to be repaired by technicians or users who have appropriate knowledge and tools, or by a remanufacturer, and passed on to the next user. Other devices are provided through access models, rather than sold and owned, and used for as long as they serve the need of the user; after which they are returned to the producer or passed on to another user. Markets for used products facilitate the exchange and trade of devices between users. Finally, all post-use consumer electronics are collected and recycled into materials that find their way back into the production of new devices.[22]

AI can help circulate consumer electronics products, components, and materials

To realise this vision, the industry needs change and innovation. **Design of new products and materials** is needed to build devices that can be used and reused, or disassembled so that components can easily be replaced and materials recovered. **Innovation in circular business models** needs to provide a viable alternative to traditional linear systems, and **investments in infrastructure** will be necessary for collection and sorting to enable reuse, remanufacturing and recycling.

AI can play an important role in accelerating the transition towards a circular economy for consumer electronics, generating an estimated **economic opportunity of up to USD 90**

xviii Defined for the purposes of this paper as smartphones, computers, TVs, and smart personal and home devices.

xix This represents a portion of the total e-waste produced (44.7 million tonnes in 2016, The Global E-waste Monitor 2017), which includes white goods such as fridges and washing machines.

xx https://www.prb.org/e-waste/. For example, primary and secondary exposure to toxic metals, such as lead, results mainly from open-air burning used to retrieve valuable components such as gold. Combustion from burning e-waste creates fine particulate matter, which is linked to pulmonary and cardiovascular disease.

billion a year in 2030, calculated as growth in top-line revenue.[xxi] The opportunity has four aspects:

1. **Use period extension:** circular design and business models aim to increase the use period and usage of products and components, and can unlock a potential value of USD 50 billion through AI-enabled design, targeted marketing, dynamic pricing, 'predictive maintenance' and other measures.

2. **E-waste recovery:** circular infrastructure optimised using AI solutions could enable the recovery of USD 24 billion of additional value from reused, repaired, remanufactured or recycled devices, components and materials. AI can help capture a significant part of the total e-waste market, which is estimated to be USD 107 billion.

3. **Material efficiency:** AI can help generate material use efficiencies and reduce waste in production, which has a potential value of USD 8 billion.

4. **R&D optimisation:** AI has the ability to optimise and speed up innovation processes, leading to cost effective allocation of resources through rapid testing. This opportunity is estimated to be worth USD 8 billion.

Design consumer electronics for circularity

An important lever of change is the design of products and materials. Consumer electronics and their components need to be designed in a more uniform and modular way to allow for disassembly for refurbishment, remanufacturing and recovery of materials. At the same time, personal data needs to be easily transferable to promote device reuse and access models such as phone-as-a-service. Finally, manufacturers need to ensure that products maintain software compatibility to allow for upgradability and to avoid disposal of fully functioning devices.

AI technology could speed up and support the design and product development process for consumer electronics. Algorithms are capable of rapidly generating large quantities of design alternatives, optimising for multiple circular variables, as well as other design features. In addition, feedback from products currently in use can be analysed for best practices to be included in new designs.

An example of a company using AI in the design of electronics is Motivo, whose services provide insights about the optimisation of the design of integrated circuits, using big data from multiple sources and machine learning algorithms. With its technology, design processes that used to take up to a year were shortened to about four weeks, saving time and money on iterative testing.

AI can also be used to change how materials are designed for electronics. For example, many efforts are being made to identify safer alternatives to flammable liquid electrolytes used in lithium-ion rechargeable batteries found in most laptops, mobile phones and other rechargeable consumer electronics. Researchers at Stanford have used AI and machine learning to screen more than 12,000 lithium containing compounds using several criteria including stability, cost, and abundance, to identify 21 solid electrolytes that could potentially replace the volatile liquids in future.[xxii]

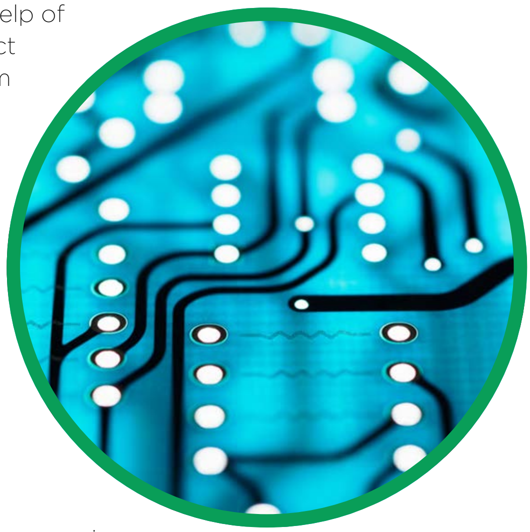
xxi McKinsey & Company modelling and analysis based on expert interviews and additional research.

xxii For more information visit https://news.stanford.edu/2016/12/15/no-burning-batteries-stanford-scientists-turn-ai-create-safer-lithium-ion-batteries.

Case Study • Using AI to accelerate the design of electronic components

About the company

Founded in 2010 in San Francisco, Motivo has developed a computational suite to optimise the design and manufacture of integrated circuits. With the help of machine learning, Motivo has shortened the time to detect complex chip failures by incorporating best practices from past designs.



Contributing to a circular economy...

Motivo's technology has the potential to reduce waste in the manufacturing process of integrated circuits for electronic products.

... by using AI

The computational suite uses non-iterative machine learning and advanced analytics on multiple data sources to calculate optimal designs for integrated circuits, taking into account throughput, cycle, and maintenance optimisation.

Solving real business problems

Based on the insights from Motivo's tool, semiconductor companies have been able to reduce the cost of design iterations and testing. In two pilots, it was shown that the tool can reduce semiconductor design processes from several years to a few weeks.

With potential for system level impact

"With advanced data analytics, we have the potential to alter the current paradigm dramatically. If companies look more broadly at chip design, they could reduce the lead time for yield ramps and the number of iterations required to eliminate problems with new products and processes tenfold. That would have a big impact on timelines and silicon costs."

BHARATH RANGARAJAN, CEO MOTIVO

Operate circular business models

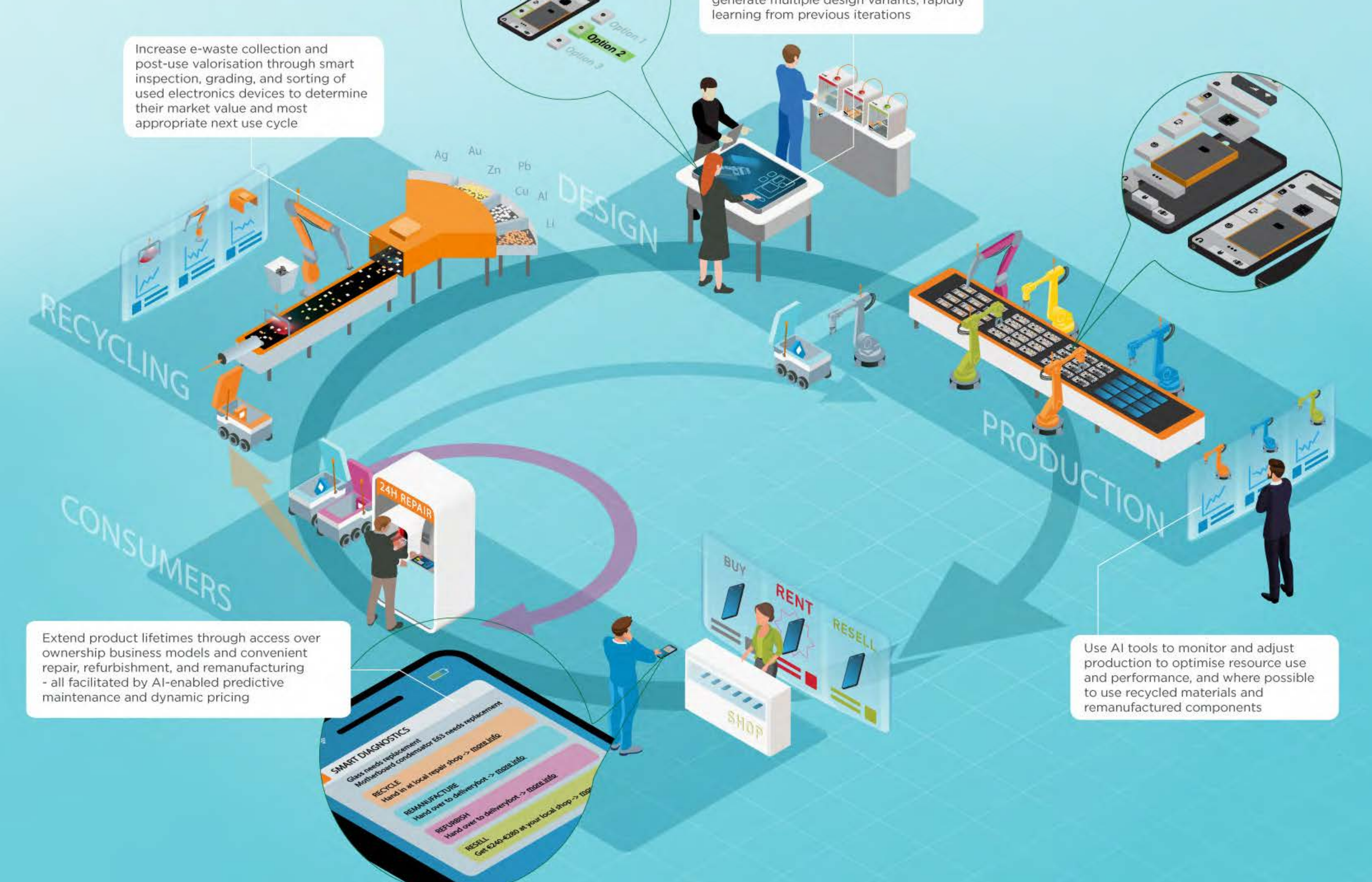
Products in a circular economy, such as consumer electronics, require specific business models, which include features such as incentives to ensure a reliable return flow of products and components and efficient reverse logistics processes for collecting and transportation.

These circular business models, such as product-as-a-service models, and enablers, such as effective secondary markets, need to overcome several challenges to be able to effectively compete with linear models. For example, the uptake of secondary markets for consumer electronics can be limited by concerns that personal information might be left on a device or uncertainty around the condition of a second hand device and whether it is fairly priced.

"Enabling pricing of used products is instrumental to boosting product circulation, because it both drives people to resell through secondary markets the items they're no longer using, and to shift their buying preferences to items that hold their value longer. AI can help price a complex variety of used products by taking into consideration market conditions and product-specific characteristics such as age and brand."

JOHN ATCHESON, CEO STUFFSTR

Artificial intelligence and a circular economy for consumer electronics



To increase the competitiveness of circular business models, AI-enabled tools can come into play. Dynamic pricing of used and rented products, determined by AI-driven insights into customer behaviour, can help create markets for these products and stimulate trade and reuse by capturing cost advantages over buying new linear products. Additionally, through AI technology and use of intelligent assets with diagnostic software and a network of sensors, AI algorithms may be able to radically improve the assessment of a product's condition, enabling predictive maintenance and the ability to determine the secondary value of a used device more accurately.

AI-enabled predictive maintenance, which is currently widely applied to industrial machinery and installations, could be adapted and applied to consumer electronics to help assess the device's condition and inform consumers and/or the manufacturer when a device is in need of an upgrade or replacement.

When more is known about the condition of used devices, AI can also help to create transparency on options for further use cycles. By combining data from sources such as product reuse marketplaces, spare part databanks and recycled material prices, algorithms can provide consumers or providers with an overview of reselling, repair, refurbishment, remanufacturing or recycling options. This facilitates demand for new components as replacement parts, as well as supply of used devices and components, which are both needed to help secondary markets become more effective. Adding information about prices for each option will further stimulate the development of these secondary markets and could lead to greater efficiencies, for instance decreasing the cost of electronics collection.

Lastly, targeted marketing based on AI-enabled consumer preference analysis could increase the awareness of access-over-ownership and other circular business models for consumers.

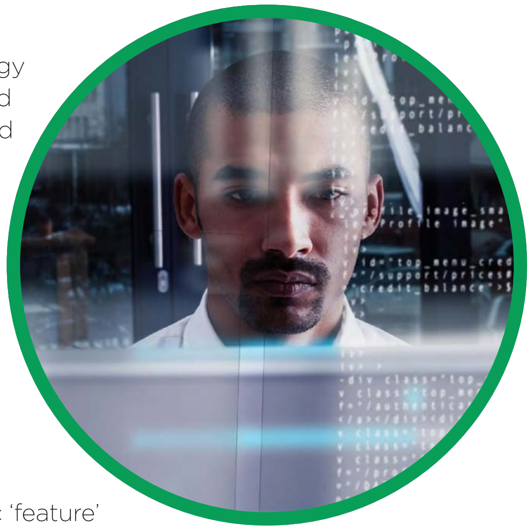
Innovate processes and infrastructure for reuse and recycling

If the current linear model is to be transformed into a circular one, feedback loops need to be established at several stages of product life. To maximise value preservation, electronics in usable condition should be reused, upgraded, refurbished, repaired or redistributed; products no longer in good condition should have their components harvested and remanufactured; and, finally, as a last resort, products and components at the end of their use should be recycled to recover their materials.

Companies such as Teleplan use AI to help provide after market and lifecycle care services to keep electronics products in use, such as managing reverse logistics, screening and testing, and repairing and refurbishing of used electronic devices. Teleplan uses AI to generate objective, consistent and cost effective grading of used devices, by assessing the external or cosmetic condition of the devices and determining if they can be reused or resold, whether they need to be repaired, refurbished or recycled, and their market value. Reliably knowing the condition of a device can be key for consumers to accept a used device.

At the moment, where infrastructure, systems and processes that support reverse cycles for consumer electronics, including collection, disassembly, sorting and recycling, are available, they are cumbersome, fragmented and labour intensive. This reduces the amount and quality of materials which are currently recovered from electronics recycling. Today, 80% of electronic waste is not treated appropriately[23] as a result of poor collection, technical complexity and the cost of recycling, remanufacturing and refurbishment; despite growing legislation and policy aiming to enforce increased waste treatment.

Case Study • Using AI to boost reuse of electronic devices



About the company

Teleplan is an industry leader in lifecycle care of technology products, focusing on screening and testing, repairing and refurbishing, and recovering value from large flows of used electronics.

Contributing to a circular economy...

After a first use cycle, many devices or their components can be cycled back into economic use, supported by the right repair or refurbishment solutions. Teleplan provides such solutions.

... by using AI

Teleplan can assess the cosmetic condition of electronic devices (often referred to as 'grading'), which is key for consumers to accept a used device. Machine learning is helping Teleplan differentiate between what is a cosmetic 'feature' of a phone (e.g. a logo or a speaker) and what might be an 'anomaly' (e.g. a scratch or dent), leading to more consistent, reliable and accurate classification of used devices.

Solving real business problems

Sorting and grading of used devices is essential for any reuse strategy. Machine learning increases the objectivity, consistency, reliability, speed, and accuracy of the grading process, and reduces the cost per unit. With better grading, wholesalers can have a higher degree of confidence in used devices and components, which supports reuse models and the ability to resell used devices.

With potential for system level impact

"In essence, we were tasked to create a technology that could not only ignore standard elements but also identify defects that have – by nature – no patterns, given no two defects are ever the same. This was a mathematical challenge that only machine learning could solve effectively. Any other more traditional methods would be more costly and require continuous adjustments to software algorithms."

AIVAR ELBRECHT, GLOBAL DIRECTOR, INNOVATION, TELEPLAN

AI can be employed to solve some of the technical challenges of recycling and to reduce costs in remanufacturing. A research group including Caterpillar, MG Motor and Meritor is developing an AI-driven robot system that autonomously or semi-autonomously inspects and disassembles returned equipment. With increasing technological maturity of AI and robotic systems, remanufacturing solutions could also become a positive business case in consumer electronics.

"Intelligent assets containing artificial intelligence technology are instrumental in making remanufacturing of high tech components competitive with other, more consumption focussed models. Intelligent assets make the assessment of their condition after a use phase much easier and more accurate, reducing the costs of remanufacturing up to 75%."

PROF. NABIL NASR, ASSOCIATE PROVOST FOR ACADEMIC AFFAIRS AND DIRECTOR, GOLISANO INSTITUTE FOR SUSTAINABILITY, ROCHESTER INSTITUTE OF TECHNOLOGY

Further applications for AI in remanufacturing and refurbishment are spare part matching and fault detection. For example, Humai has developed a tool called xRec; combining AI technology and computer vision to automatically identify components or parts for machine maintenance and simplifying time consuming processes such as reordering spare parts and accessing documentation.

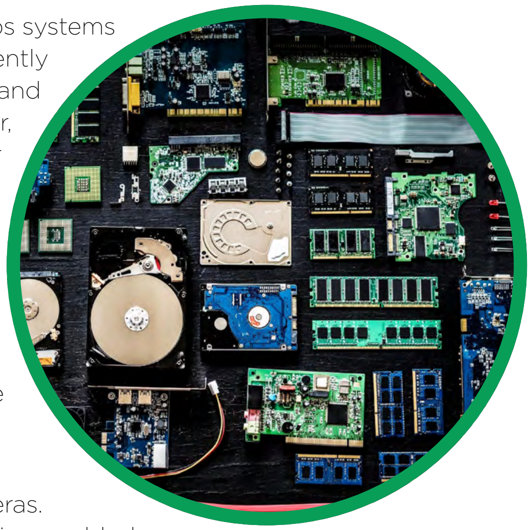
Moreover, AI can be trained to help tune and optimise existing recycling equipment and infrastructure to handle specific types of material flows. E-waste comes in many sizes, shapes and conditions. These different features can require tailored settings and processes, requiring manual adjustment of recycling equipment and causing machine downtime. AI could handle some of this work in existing recycling, refurbishing and remanufacturing facilities by identifying the condition of end of use consumer electronics and automating adjustments to the settings of processing equipment.

Refind Technologies has developed several proof-of-concept systems which are capable of automatically identifying and sorting batteries or classifying and sorting mobile phones. Companies such as ZenRobotics, AMP Robotics, Sadako Technologies and Bulk Handling Systems, are using AI to overcome the complexity of general waste sorting. Their systems use machine learning to recognise materials based on visual input. Combined with traditional sorting systems and robotics, e-waste can be separated more effectively.

Case Study • Using AI to improve e-waste recycling

About the company

Founded in Sweden in 2014, Refind Technologies develops systems for intelligent sorting and classification of e-waste. It currently operates with a focus on subsegments such as batteries and phones. The company has just launched the Refind Sorter, a fully automatic classification and sorting technology for used products.



Contributing to a circular economy...

Refind enables companies to extract the full value from (mixed) e-waste streams in two ways. First, it helps reduce e-waste by improving overall recycling and refurbishing rates. Secondly, it increases valorisation by identifying whether a product's condition is more suitable for refurbishment or recycling.

... by using AI

The sorting systems are equipped with sensors and cameras. Through visual recognition and supervised machine learning enabled technology, the sorting systems can classify the type, and if perceptible the condition, of e-waste at a granular level. Currently, the system requires manually labelled images to train the AI algorithms.

Solving real business problems

The sorting machine provides safer, faster and higher quality sorting of e-waste, replacing a mostly manual process. The increase in catch rate and quality of sorting provides extra revenues through the sale of parts and materials.

With potential for system level impact

"We believe our machines can enable a more cost-efficient and advanced sorting, more similar to human sorting, leading to more reuse being possible."

JOHANNA REIMERS, CEO REFIND TECHNOLOGIES

5 • REALISING THE POTENTIAL OF AI FOR A CIRCULAR ECONOMY

AI can be an enabler and accelerator of the transition to a circular economy. This paper suggests that AI technologies can be applied to three key aspects of a circular economy: design circular products, components and materials; operate circular business models; and optimise infrastructure to ensure circular flows of products and materials.

The global economic opportunity artificial intelligence can bring by 2030 has been estimated at USD 13 trillion.[24] However, the potential to pioneer its use in circular economy applications, which this paper suggests is substantial, is currently largely untapped. To capture a greater amount of this potential, we suggest some areas for consideration: in particular understanding where such opportunities lie for different stakeholders, and putting in place the conditions to realise them effectively.

Creating greater awareness and understanding of how AI can support a circular economy is essential to encourage applications in design, business models, and infrastructure

Using case studies and potential use cases in this paper as inspiration, stakeholders can explore relevant opportunities for circular economy applications of AI, based on a sound understanding of what AI can and cannot do, as well as an appreciation of how circular economy principles could apply to their area of interest or industry.

Circular economy experts, and businesses with circular economy strategies can explore how AI could be used to accelerate their circular economy ambitions. Equally, organisations and individuals with technical knowledge and expertise in AI can consider how their specific areas of work could be applied for a circular economy.

Additionally, the investment community can seek opportunities to direct the significant and increasing investment in AI towards initiatives which contribute towards the transition to a circular economy.

Exploring new ways to increase data accessibility and sharing will require new approaches and active collaboration between stakeholders

Access to relevant, high-quality data, both to train algorithms and to use as input data, will be instrumental to the development of AI applications for circular economy.

New mechanisms for sharing relevant datasets will need to be tested, and efforts made to ensure high-quality data labelling. Large scale, open source data resources, such as Image-Net and The Materials Project, are one option which could be explored further as a mechanism for providing the high quality data required to develop AI technologies.

The scaling up and successful application of AI for the complex task of redesigning many aspects of our economy will depend on the willingness of key actors to collaborate, facilitated by new, cross sector mechanisms and convening bodies. Such collaboration between stakeholders across the system, including companies, governments, and NGOs, will be especially important when it comes to the generation, collection and sharing of data. In some cases, such as where the relevant data is captured by different actors in the supply chain or across sectors, a central facilitation body may be needed to support this effort.

As with all AI development efforts, those that accelerate the transition to a circular economy should be fair and inclusive, and safeguard individuals' privacy and data security

The development of AI is creating new opportunities to improve the lives of people around the world, from business to healthcare to education. It is also raising new questions about the best way to build fairness, privacy, and security into these systems. This holds true when considering the application of AI to accelerate the transition to a circular economy, and organisations looking to seize opportunities in this area should engage with efforts to answer these questions.

While the use cases in this paper set out some compelling examples of the opportunities and benefits which arise at the cross section of two emerging megatrends - AI and circular economy - there is still much work to be done to move towards the ambition of using AI to help with the complex task of redesigning whole economic systems.

It seems clear though that new forms of cross value chain collaboration, underpinned by a shared vision and guiding principles, could harness the power of AI to help reshape the economy into one that is regenerative, resilient, and fit for the long term.

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The Ellen MacArthur Foundation was launched in 2010 with the aim of accelerating the transition to the circular economy. Since its creation, the charity has emerged as a global thought leader, putting the circular economy on the agenda of decision-makers around the world. The charity's work focuses on seven interlinking areas: insight and analysis; business; institutions, governments and cities; systemic initiatives; learning; circular design; and communications.

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