PACE

PLATFORM FOR ACCELERATING THE CIRCULAR ECONOMY

White Paper

WORLD ECONOMIC FORUM

COMMITTED TO IMPROVING THE STATE OF THE WORLD

Harnessing the Fourth Industrial Revolution for the Circular Economy

Consumer Electronics and Plastics Packaging

In collaboration with Accenture Strategy

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The Platform for Accelerating the Circular Economy (PACE) This report is published as part of the Platform for Accelerating the Circular Economy (PACE). PACE is a public-private collaboration mechanism and project accelerator dedicated to bringing about the circular economy at speed and scale. It brings together a coalition of more than 50 leaders and is co-chaired by the heads of Royal Philips, the Global Environment Facility and UN Environment. It is hosted by the World Economic Forum.

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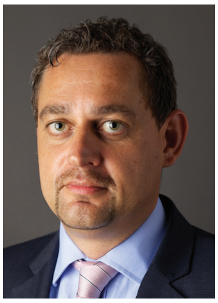

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Characterized by a fusion of technologies that is blurring the lines between physical, digital and biological spheres, the Fourth Industrial Revolution is fundamentally reshaping the way we live and work. We are approaching the realm of what used to be science fiction: both "quantum teleportation"[1] and a Star Trek-style medical "tricorder"[2] appear within our grasp. The art of the possible has never looked so promising.

As quickly increasing technological performance redefines what is possible, exponentially decreasing costs define what is feasible. The size of artificial intelligence experiments is growing exponentially – at more than four times the speed of Moore's law[3] – and by 2020, an internet of things sensor will cost less than 30% of what it did in 2004.[4]

Already reshaping areas like healthcare, mobility and finance, the Fourth Industrial Revolution presents an exciting opportunity to change the way we source, manage and value our resources. Its combinatorial technologies can help us transition to more circular systems – in which materials flow "within" rather than "through" our economy. In doing so, it can help unlock a global growth potential of $4.5 trillion,[5] and address the environmental challenges inherited from previous industrial revolutions: resource over-use, climate change, monocultures, water scarcity and massive waste.

In 2017, the World Economic Forum and its partners established the Platform for Accelerating the Circular Economy (PACE), a project accelerator and collaboration mechanism to drive action towards a circular economy at speed and scale. Under PACE, over 50 business and government leaders are united in collaboration to create the favourable conditions required for widespread adoption of circular economy models across regions. Building on the work of PACE and insights from contributing experts, this paper focuses on technology-enabled solutions for circular value chains in consumer electronics and plastic packaging. These two industries bring tremendous growth and societal benefits, but are also highly wasteful. Only 14% of plastic packaging is collected for recycling – and just 2% is recycled to similar quality level[6]; only 20% of electronics disposed each year is documented as collected for recycling.[7]

Five shared challenges need to be overcome to make these two sectors more circular:

1. *Opaque value chains* – Lack of transparency on material origin, content, condition and destination
2. *Linear product design* – Circular design alternatives are often not understood, considered or contextualized
3. *Linear lock-in* – Difficulties developing viable circular business models in yet linear systems
4. *Inefficient collection and reverse logistics* – Material leakage and fragmentation impeding economies of scale
5. *Insufficient sorting and pre-processing infrastructure* – Lack of efficient facilities delivering the mono-streams needed for high quality recycling

To address these challenges, we look at how Fourth Industrial Revolution technologies are used today, and what could be possible in the near future to envision a new way of managing our resources. The report illustrates 19 solutions across five solution areas that can be applied to accelerate the circular transition. These range from digital datasets linked to physical products using a product passport and Internet of Materials; artificial intelligence-based design tools; and blockchain-based reward schemes to hyper-intelligent sorting and disassembly supported by machine vision and robotics.

To unleash these innovations to their fullest potential five enabling conditions are required:

1. **Standards and regulations** in materials and processes are required to allow for solutions to scale – across products, industries and country borders.
2. **Change drivers**, such as policies, taxations, rewards and societal engagement, should be deployed to trigger all actors of the economic system to contribute to the transformation.

3. **Data-enabled infrastructure** is required that is interoperable, but tailored to local context.

4. **Investments** are needed from for-profit investors, public investors as well as societal stakeholders to build infrastructure and further develop technologies.

5. **Innovation and entrepreneurship** is essential, where multistakeholder collaboration and co-creation is nurtured, disruption is the ambition and the right skills and capabilities are built.

As these enabling conditions are put in place, it is imperative that public and private actors work together to digitize material flows, join up solutions in an interoperable and distributed architecture and develop the new norms for cross-border collaboration and governance.

We encourage leaders to set the context, explore the technologies and scale the solutions that will overcome the challenges of the two material streams. We must rise to the occasion and design an industrial revolution in which the benefits are more equitably distributed and the externalities better managed.

We are immensely excited by the ideas that have surfaced in this research, but realize we have only scratched the surface. It is our hope that leaders will be inspired to build on these beginnings and collaborate through PACE to take bold steps to design and scale an economic system that is fit for purpose and fit for the planet.

Introduction

The burning platform for a circular economy

The technological advancements of the last 100 years have helped society thrive – life expectancy at birth has risen globally from 48 in 1955 to 72 years[8] and GDP per capita grew on average about 1.9% per year since the 1960s.[9] Around the world, a rapidly expanding middle class is fueling consumption. As more consumers gain more to spend, demand for goods is growing. Under pressure to innovate and produce goods quickly – and at low prices – suppliers have relied on linear "take-make-waste" models.

The current production and consumption system has led to an overshoot in planetary boundaries: it now requires the equivalent of 1.7 Earths to replenish the resources consumed and absorb the pollution generated.[10] At this rate, by 2050 three planet Earths will be needed. The linear models that have brought so much are no longer sustainable.

Two sectors in particular – **consumer electronics and plastics packaging** – are attracting public attention as providing benefits to society, but at major social and environmental costs.

Consumer electronics

Electronic devices deliver huge convenience and efficiency gains. By enhancing connectivity and digitalization,[11] they are helping to achieve 11 of the 17 UN Sustainable Development Goals (SDGs).[12] Electronic waste is also the world's fastest-growing waste stream.[13] In 2016, 44.7 million tonnes of e-waste were generated, with an uncaptured raw material value of $55 billion.[14] Many of those built-in materials cannot economically be recovered due to design choices and infrastructure deficiencies. This adds pressure on the supply of metals such as lithium and cobalt that are critical for electronic devices, but also for the growing number of electric vehicles.[15] Cobalt prices have almost doubled in the past three years due to supply fluctuations and high demand.[16] Meanwhile, the benefits and burdens of electronic devices are unequally distributed. Africa produces less electronic waste per head than any other continent (1.9kg annually),[17] but it has become an illegal dumping ground for e-waste from around the world. Informal processing poses serious threats to human and environmental health.

Plastics packaging

The burden of single-use plastic packaging is dominating newspaper headlines. Accounting for 26% of the total plastics market, plastic packaging offers benefits in terms of convenience and performance. However, as most plastic packaging is designed for single use, 95% of its value is lost after its initial use – an annual loss of value estimated at $80-120 billion. Owing to product design and inefficient waste management systems, only 14% of the world's plastic packaging is collected for recycling and just 2% is recycled at similar quality levels.[18] Plastics leakage into the environment, where it takes up to 500 years to degrade,[19] has become an urgent issue: 8 million tonnes end up in the oceans every year. Micro-plastics have been found in the most remote parts of Antarctica.[20] Eaten by fish, there is evidence that suggests that micro-plastics now get into our food and into our bodies.[21]

To counter the challenges in both industries, the public and private sector are taking action. China, a former importer of two-thirds of global plastic waste,[22] recently banned imports,[23] forcing many developed countries to find alternative ways to process their waste. India introduced more stringent e-waste regulations in 2016,[24] but governance and enforcement of these policies remain a challenge. Towards the end of 2018, the Ellen MacArthur Foundation announced that over 250 businesses and governments had signed the New Plastic Economy Global Commitment to eliminate plastic waste and pollution at the source.[25] Around that same time, the Global Plastics Action Partnership was catalysed through PACE as a public-private delivery mechanism to help such businesses and governments reach their targets.[26]

These examples show that first steps are being taken towards circular models of production and consumption, yet ground-breaking technological innovations have the potential to significantly accelerate progress.

The Fourth Industrial Revolution opportunity

As their performance skyrockets and cost plummets, technologies are disrupting society at unprecedented speed and scale. The cost of robotic arms has dropped more than 25% since 2014[27] and about 300,000 industrial robots were sold in 2017.[28] By 2025, that cost is predicted to drop another 22%. Today, a combination of artificial intelligence (AI), tissue engineering and 3D printing is being used to design and print an implantable human organ. These combinatorial effects of digital, physical and biological technologies are the heart of the Fourth Industrial Revolution (4IR).

The power of the 4IR can be harnessed to improve the way materials are managed and steer society away from antiquated take-make-waste models towards sustainable, circular solutions. 4IR solutions will not solve all challenges and requirements to move to a circular economy, but they offer a tool to make it easier and more cost effective.

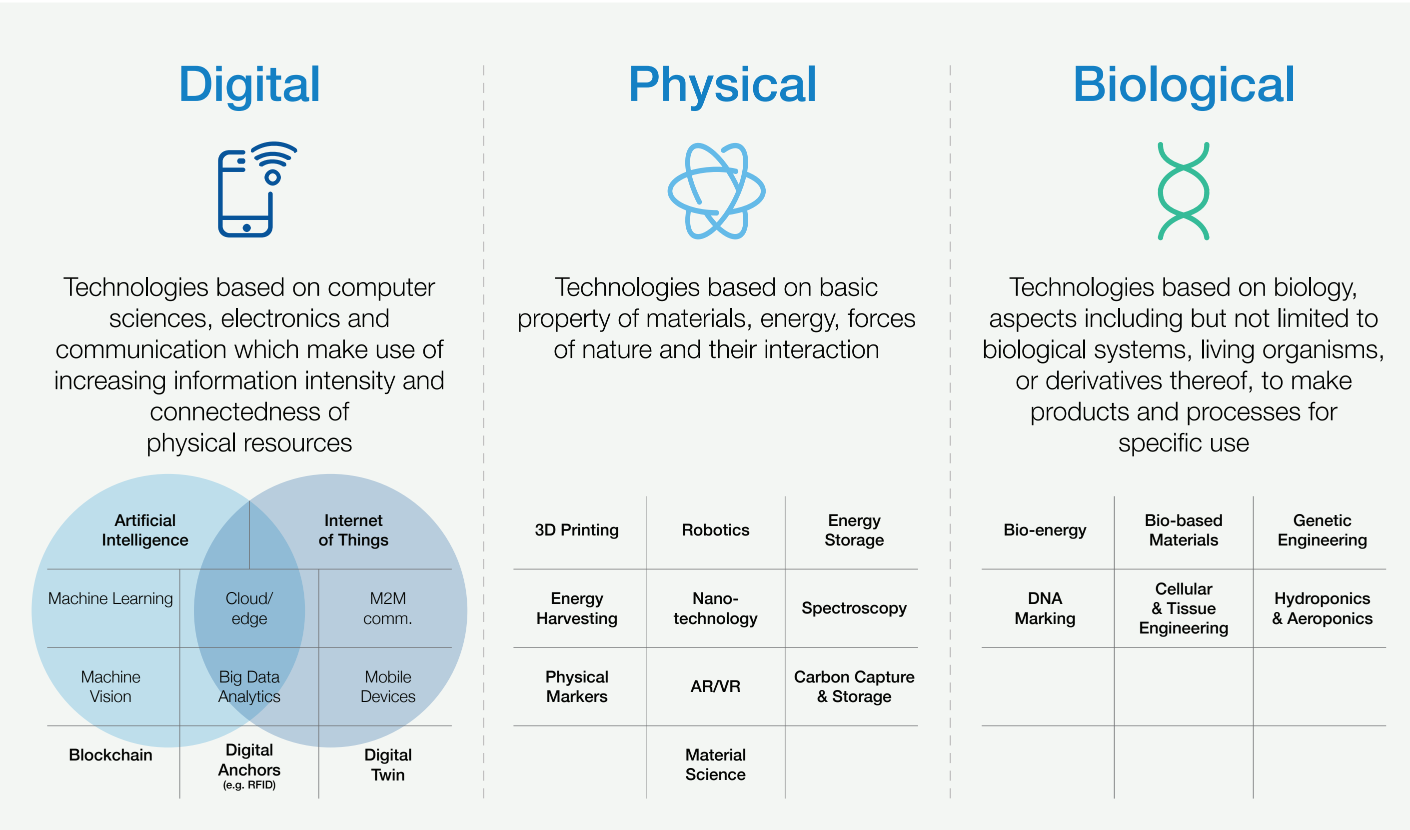
Identifying these solutions is an important first step, but unleashing their full potential requires an understanding of their applications and possible combinatorial effects. Most of all, it requires public and private leadership to create a vision on how to scale them up across markets, ensuring room for local adaptation and an equitable distribution of burdens and benefits. Previous industrial revolutions were largely inequitable: 13% of the world's population still have no access to electricity[29] and 55% have no internet access.[30] This revolution needs to be designed to be much more inclusive and to help reduce the disparities within socioeconomic systems.

Our approach

To build the insights of this report, a group of 37 contributing experts was convened to go through a design thinking process to discover, describe and co-create ideas. This methodology is designed to be iterative, continuously adapting to new thinking and insights, and co-creating with partners and experts to proactively drive innovative thinking. Stakeholder workshops were held during the World Economic Forum's Sustainable Development Impact Summit in September in New York in 2018 and the World Circular Economy Forum in October 2018 in Japan.

The research focuses on identifying system acupuncture points: areas where action can trigger a cascaded effect up and down the value chain. The next section will dive into five of these acupuncture points, highlighting the areas where system solutions are needed.

Figure 1. Fourth Industrial Revolution technologies (World Economic Forum and Accenture, 2018)



Shared Circular Challenges

In complex global value chains, businesses and governments struggle to scale circular business models such as product life extension or product as a service.[31] Although consumer electronics and plastics packaging are very different industries, they share five circular challenges (which are presented below) highlighting specific issues for each industry. The first challenge, "opaque value chains", impacts every stage of a product or material's lifecycle. The remaining four are connected to individual value chain steps and include: linear product design, linear lock-in, inefficient collection and reverse logistics, and insufficient sorting and pre-processing infrastructure.

Opaque value chains

Material transparency is essential in three areas: provenance of materials to ensure ethical sourcing; material composition and product condition to capture value from multiple lifecycles and embedded resources; and material flows through markets to improve waste management on a system level. In consumer electronics, only 21% of countries collect statistics on e-waste, often reporting metrics that are incompatible.[32] In a consumer survey on plastic packaging, 34% respondents named lack of information as the most common barrier to plastic recycling.[33]

Linear product design

Over 80% of a product's environmental impact is influenced during the design process.[34] Today's product designs are increasingly complex and integrated for the purpose of low-cost and high performance.[35] Designers often lack visibility on circular design alternatives and end-of-life impact of different design choices in specific market contexts. In consumer electronics, design can enable a positive business case for circular business models; for example, a study of rented ICT routers suggests that slight design changes (e.g. using scratch-resistant materials) can reduce refurbishment costs by about 50%.[36] Single-use plastic packaging often cannot be recycled due to design choices; for example, 13% of global plastic packaging by weight is mechanically unrecyclable multilayer packaging.[37]

Linear lock-in

Designing viable circular models within existing linear systems is challenging due to linear product design and a lack of asset management infrastructure required to ascertain the condition and value of used products. In consumer electronics, a reused iPhone retains 48% of its original value whereas its recycled components only retain 0.24%.[38] In plastics packaging, switching to multi-use would be feasible for at least 20% of packaging today, if companies changed their products and delivery models.[39]

Inefficient collection and reverse logistics

In lower-income countries where waste management infrastructure is often unavailable, over 90% of waste is dumped or openly burned.[40] The business case for collection infrastructure and viable and scalable reverse logistics and return systems is challenging and the lack of reliable data on available waste streams hinders investments in these areas. In consumer electronics, 80% of global e-waste is not documented for recycling, and is most likely landfilled, traded or processed informally.[41] Plastic packaging recovery rates in high-income countries are relatively high, but recycling rates are much lower. In 2016, the EU's recovery rate was 74.2%; its recycling rate was 42.4%.[42] Many countries ship plastic waste to other countries, often with lower infrastructural and environmental control standards.

Insufficient sorting and pre-processing infrastructure

Separation of waste streams into homogeneous material streams is a prerequisite for high-quality material recovery. Today, those streams are often cross-contaminated due to a lack of material standardization and issues in identifying and separating different materials.[43,44] Without economies of scale, the process is expensive and investments in high-quality infrastructure are lagging. In many electronics product groups, manual dismantling can help recycle 90% of materials; mechanical processing (e.g. crushing, shredding) delivers recycling rates below 60%. The system thus faces a trade-off between economic viability and recycling rates.[45] In plastics packaging, the recyclate of high-value, food-grade applications such as PET, PP and HDPE milk bottles, must have at least 95% purity to be resold at virgin resin prices.[46]

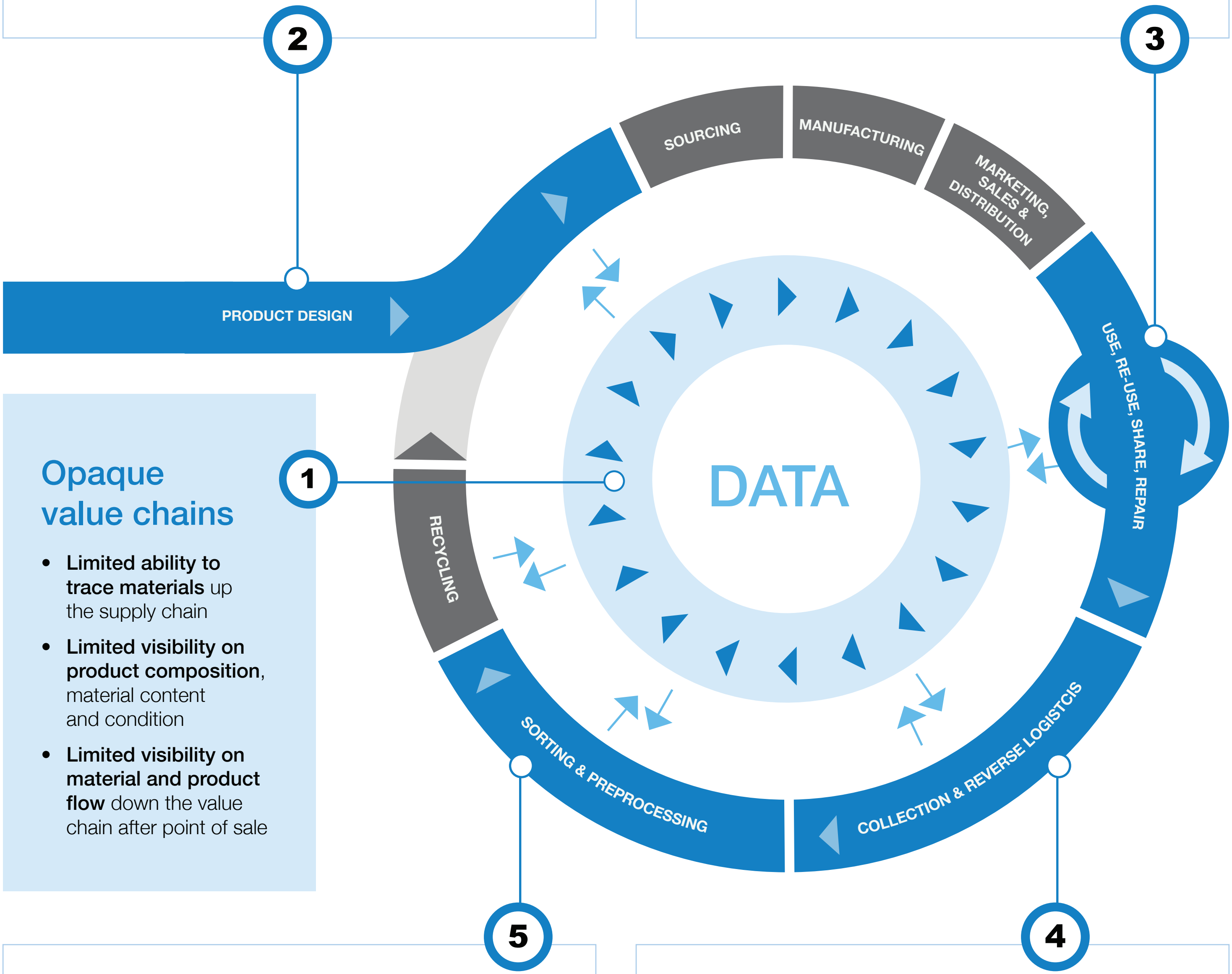
Shared challenges

Linear product design

- **Linear product design choices** with a focus on cost and performance that inhibit high value after-use
- **Limited understanding** of available alternatives and connected benefits
- **Limited visibility** of impact of design choices on after-use considering given local market infrastructure

Linear lock-in

- **Difficulties identifying** viable business models in yet linear systems
- **Lack of infrastructure** and capabilities for product lifetime extension (e.g. IoT for remote diagnostics)
- Lack of data to **assess conditions** and value of used products



Opaque value chains

- **Limited ability to trace materials** up the supply chain
- **Limited visibility on product composition**, material content and condition
- **Limited visibility on material and product flow** down the value chain after point of sale

Insufficient sorting and pre-processing infrastructure

- **Material fragmentation** due to a lack of standardization in materials and collection infrastructure
- Difficulty of **identifying and separating** different materials streams
- **High costs, lack of economies of scale and low sorting yields limiting** investments in high quality infrastructure

Inefficient collection and reverse logistics

- Lack of **consumer awareness and incentives** to properly dispose or return products
- **Leakage** of (especially high value) **material from formal collection systems**
- Missing business case **for investment in collection infrastructure** in densely populated and remote areas
- **Difficulties to establish economically viable** reverse logistics systems and return models

Figure 2. Overview of shared challenges along the value chain (Accenture, 2018)

Solutions: Now and Next

The next section showcases existing tech-enabled solutions (the "Now") that, if scaled further (the "Next"), will support the transition to a circular economy.

Solutions were prioritized that showed potential for systems improvement and a need for public-private collaboration to deliver successful scaling. Given the urgent challenges and PACE's ongoing project work in plastics and electronics, solutions were selected that can be implemented within the next 3-5 years and fully scaled within 10 years.[47]

To support a systemic transformation that is greater than the sum of its parts, our chosen solutions need to be connected, so that they mutually reinforce each other. What follows are two holistic descriptions of the solutions and their interactions along the consumer electronics and plastics packaging value chains. For standalone descriptions of each solution, please refer to Figures 3 and 5.

Electronics

How can we ensure material flows are more transparent?
Transparency requires linking a digital data flow to the physical material flow. The important data pieces to generate and make accessible are: provenance of materials and components; how these were assembled into a product; product condition and ownership during use; and product lifecycle journey. A blockchain-based **provenance tool** can generate data on the origin of a material. Everledger and Provenance already work in this area, focusing on improving transparency in diamond and food supply chains. Information on product origin, contents and condition can be communicated to selected value chain players via a digital **product passport** that travels with the product throughout the chain.

Shipping giant Maersk established a Cradle-to-Cradle Passport for its newly built vessels. With input from suppliers, the database documents around 95% of a ship's components. To support end-of-life recycling, it contains details of the different types of steel used in the main parts.

The passport can be stored on a device itself, in the cloud or on a blockchain solution. It is accessed by scanning a unique "cryptographic anchor"[48] attached to or embedded in the product to authenticate it and establish a link between the product and its accompanying data stream. Anchors can be physical (e.g. fluorescent markers, watermarks), digital (e.g. RFID tags, micro-computers) or biological (e.g. DNA markers). Although advanced anchor technology is in its infancy, the combination of crypto-anchors and blockchain technology has the potential to enable scalable and secure authentication, condition monitoring and traceability of material flows across the value chain.

A product passport for electronics can also include repair and disassembly instructions to facilitate reuse and recovery. The information can be publicly available or available on a permission basis to ensure data privacy (e.g. for use-phase data) and protect sensitive business data (e.g. on specific components or designs).

The passport provides transparency on an individual product level. For visibility on all electronic materials that are put on the market, collected and treated, product passport data should feed into the **internet of materials (IoM)**, a decentralized data system connecting data on different products and materials through standardized communication protocols. Data should be supplied by producers as products are sold, tying in data on material provenance and product design. Ensuring data confidentiality and anonymity are key here to avoid competitive and anti-trust challenges.

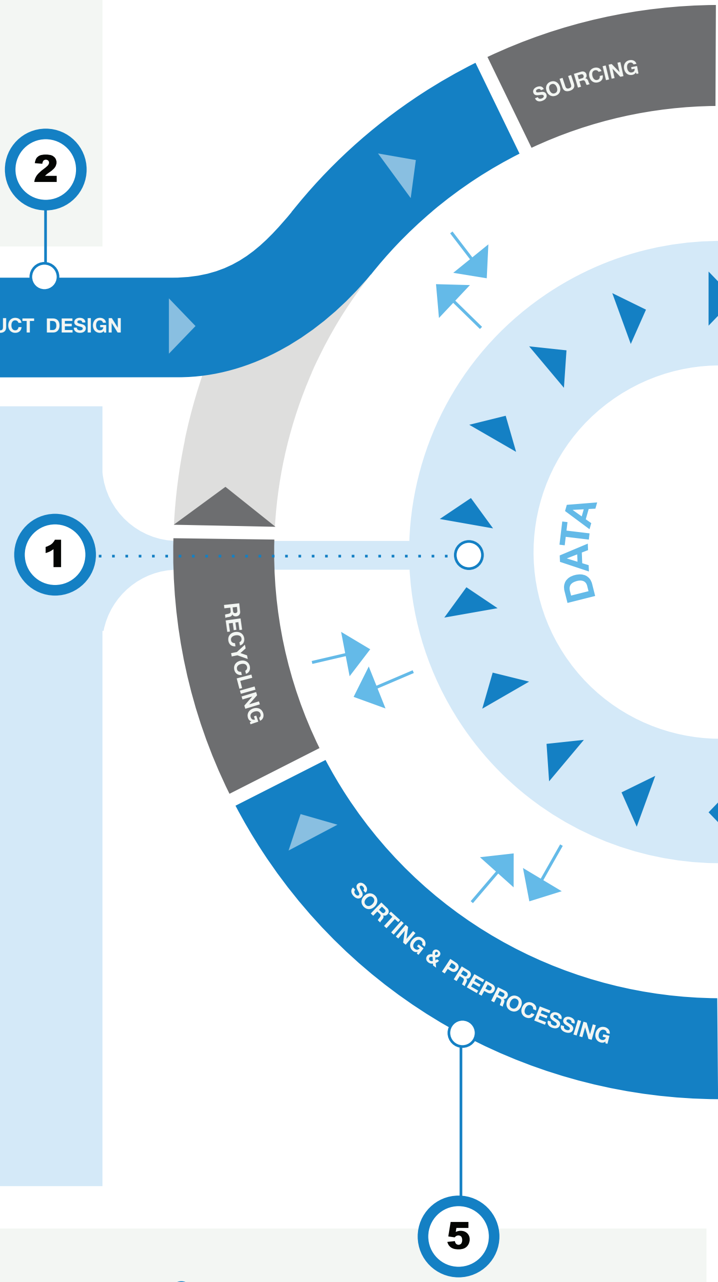
Dutch start-up Circularise is developing a blockchain-based communication protocol called "smart questioning" to promote value chain transparency without public disclosure of datasets or supply chain partners. Questions on a product (e.g. does it contain mercury?) are directed upstream and a yes/no answer is returned. A question is posed by scanning a product's anchor and an answer is communicated automatically, based on a hashed Bill of Materials (BOM) verified in advance by a third party. This pre-validation guarantees data accuracy without the need to disclose sensitive company or product information.

How can we...

...Design for best possible after-use in a given market?

Durable design tool
AI-based application supporting design choices by connecting data on alternatives to hazardous or hard-to-recycle material given the product's target market recycling infrastructure. Product modularity and overall durability is evaluated and results are communicated though an overall circularity index for the designed product.

Big Data | Artificial Intelligence | Digital Twin



...Enable transparency on material flows?

Provenance tool
Blockchain enabled tracing of material to origin.

Cryptographic Anchors | Blockchain

Product passport
Standardized dataset including product specifications and real-time condition.

Cryptographic Anchors | Blockchain

Internet of materials
A decentralized data system building on a standardized digital dataset registering material types and volumes sold, collected, and treated across markets.

Cloud Computing

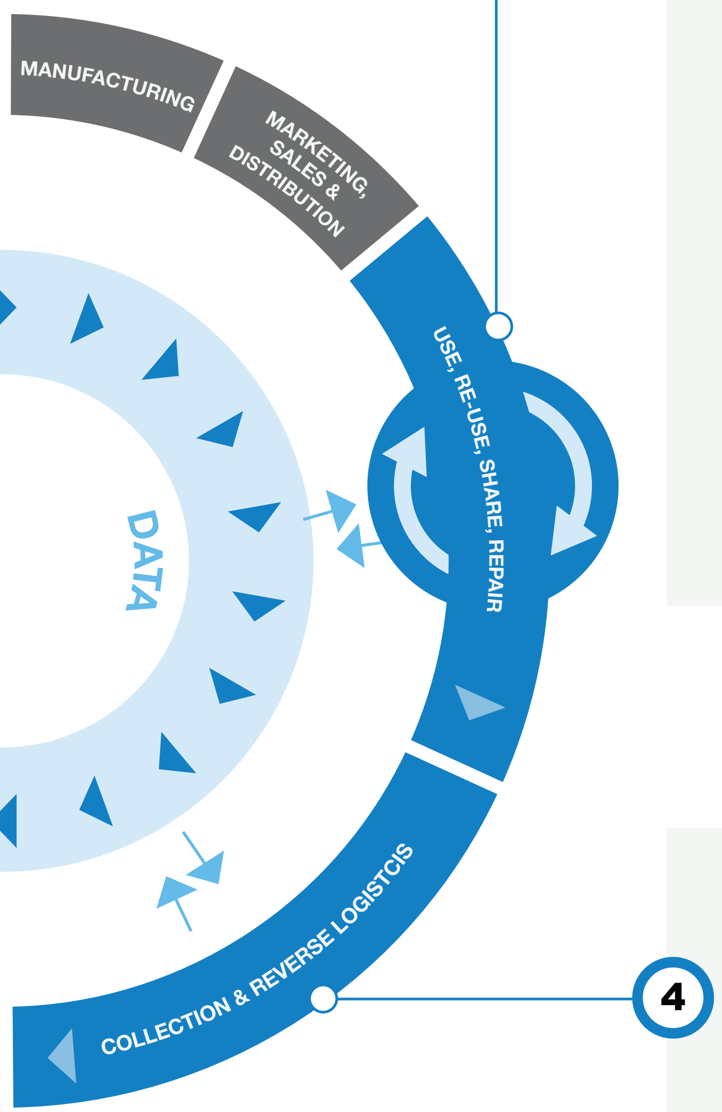
...Optimize sorting and pre-processing processes?

Hyper-intelligent sorting systems
Machine vision and robotic-based sorting enabling cost-efficient and accurate sorting across products, components and brand owners, allowing for closed loop material recycling models

Machine Vision | Robotics | Cryptographic Anchors

Learning disassembly robots
Disassembly processes with robots using dismantling commands stored in product passport, or in the case of open loop systems robots that can adapt their dismantling routines by learning from human colleagues working hand in hand

Robotics | Machine Learning | Cryptographic Anchors



...Enable efficient reuse of products?

Service-based models

Sensor-based tracking of product condition throughout the use phase by device manufacturer to offer customers targeted repair and upgrade services/solutions.

Internet of Things

Blockchain

Value assessment tool for used products

Tool allowing consumers/resellers to read a product's condition, certify its value and assess most appropriate after-use pathway to increase trust and efficiency in second hand markets.

Internet of Things

Big Data

Blockchain

Cryptographic Anchors

...Optimize collection & reverse logistics?

Value-based return incentives

Collection stations equipped with product identification and value assessment capability offering incentives (e.g. tokens, discounts, donation) through a blockchain-based remuneration scheme.

Machine Vision

Blockchain

Mobile

Waste taxi

Reversed logistics for high-value products leveraging existing infrastructure of customer-facing delivery services (e.g. taxis, parcel delivery).

Big Data

Artificial Intelligence

Internet of Things

Figure 3. Solutions along the consumer electronics value chain (Accenture, 2018)

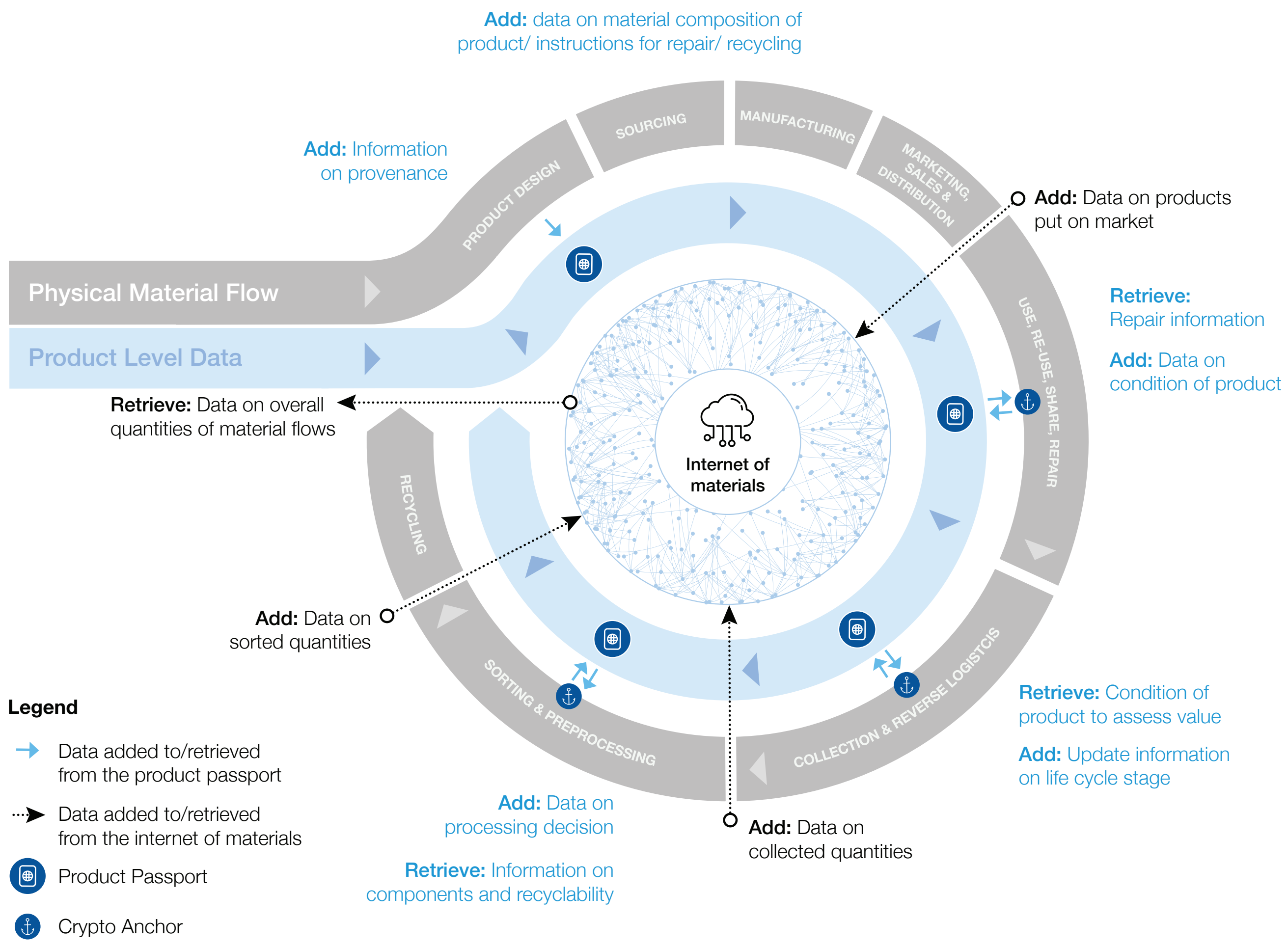


Figure 4. The internet of materials (Accenture, 2018)

IoM can serve several purposes. For example, it could provide Extended Producer Responsibility (EPR) schemes with detailed company-level data about materials put onto the market. It could also help governments and waste management players plan infrastructure investments by forecasting recyclate availability, or enable producers to get market level transparency on their product flows as input to designing closed loop business models.

Like the regular internet, the IoM requires parties to agree on standardized datasets and communication protocols. It could be managed by a neutral governing body working with industry players to define data standards, privacy requirements and related access authorizations. Anonymized aggregated data can be provided open source to visualize material flows across markets.

European statistics institution Eurostat already maintains a central database collected under the WEEE directive.[49] However, it is limited by the quality of data from different EPR schemes across Europe and by the time lag (2-3 years) between product sales and data being put online.

How can we design for best possible after-use in a given market?
Product designers require information to understand the effect of their design choices on a product's after-use potential. A digital **durable design tool** can be introduced that builds on existing integrated design tools, but is open source and applied at wider scope and scale. Such a tool provides a virtual representation of a product (a "digital twin") to model and predict product performance and after-use impact. Big data analytics allows the tool to identify the most suitable material and assembly choices, not just generally, but based on the available reuse or recycling systems in the selected market, and suggests alternatives to hazardous or hard-to-recycle substances.

The tool should be set up as an interactive platform available across the industry, allowing re-users and recyclers to provide feedback on the circularity of designs (subject to data protection requirements). Using artificial intelligence, the tool can learn from every design choice and subsequent feedback to continuously improve its recommendations. Integrated in the tool is a market-specific circularity index KPI that quantifies the circularity of a product design in a given market. This index can be built on existing circularity indicators, such as Thinkstep's GaBi lifecycle assessment tool and be expanded to incorporate information on repairability (e.g. based on iFixit's repairability index), modularity and market infrastructure. The index definitions and scoring system can also support a certification scheme for component reuse or recycling consortia: when a certified device is returned, regardless of its producer, its component quality is assured, allowing components to be safely incorporated into the new products. In the future, the circularity index could be stored as part of the product passport, accessed through the IoM, and validated by repair shops and recyclers along a product's life.

How can we encourage efficient reuse?
Once a product moves out of the design phase and begins its useful life, sensors and the internet of things (IoT) can help brand owners monitor and extend that life through remote maintenance, device upgrades and other targeted

service-based solutions. As sensors and other IoT technologies improve and costs decline, these solutions will become widely available for electronic devices. By 2020, the cost of IoT sensors is set to have fallen 70% from its 2004 level.[50] Product condition and use can be tracked in real time by sensors communicating directly back to the manufacturer and/or by storing product repair and maintenance transactions in the product passport. For example, if the hard drive of a computer is replaced, the device's crypto-anchor can be scanned by a repair shop and proof of the transaction is stored in the computer's product passport.

HP's Instant Ink uses sensors to detect when a printer's cartridge needs replacing, then automatically ships a replacement and facilitates cartridge return for refill or recycling. This way, customers do not deal with disposal or new orders. The solution cuts the carbon footprint of the ink's purchase and return process by 84% and reduces material consumption by 57%.[51]

Drawing on the passport's use-phase data about the device's condition, information on its remaining life expectancy and real-time value can be accessed by consumers or third-party resellers and shared with interested buyers. Introducing a "condition read-out" and **value assessment tool** will increase trust and promote second-hand markets. If a blockchain-based product passport is available, users could download certificates validating the condition of their used device and receive an indication of its real-time market value. Similar technology is already used in the car industry where a computer is connected to a vehicle to detect faults, validate its condition and facilitate second-hand sales.

US-based start-up Stuffstr developed an app for consumers that links their account to their favourite online shops. With every purchase, an automated inventory of bought items is built. For each item in one's inventory, the app shows an estimated second-hand price and possible second-use options (e.g. resale, sharing, donation, recycling).

How can we optimize collection and reverse logistics?
Collection systems should incentivize returns, minimize leakage and optimize convenience. Complementary to existing channels (e.g. municipal or in-store) can be return stations with the capability to automatically identify a product, assess its value and provide **value-based return incentives** in the form of discounts, tokens, cash or donation options. In the US, EcoATM operates more than 2,000 kiosks in places like shopping malls, providing gift cards in return for used devices.

On the B2B side, Optoro offers a platform for automatic assessments of the highest value pathways for returned and excess goods. In the near future, product identification through machine vision or crypto-anchors will use product passport data to make value assessments of returned devices much more accurate.

For more convenience, brand owners or collaborative collection schemes could use existing customer-facing infrastructure and services (e.g. last-mile delivery services) as **waste taxis**. For World Environment Day 2018, Uber piloted UberRECYCLE, offering e-waste collection on demand by its partner-drivers from participating business parks in Dubai.[52] Combining such services with incentive schemes in which rewards are automatically transferred (potentially using blockchain) to the consumer and the logistics provider upon pick-up will significantly drive up collection rates.

How can we optimize sorting and pre-processing?
By radically improving sorting yields, streamlining processes and generating data on collected materials, machine vision and robotics enable **hyper-intelligent sorting**. Combining a camera capturing images, an AI algorithm identifying the captured items and a robot arm sorting them accordingly, machine-vision solutions sort between different electronic devices, models or components with increasing speed and accuracy rates. Where digital crypto-anchors and product passports are available, those anchors can also be used for identification purposes.

Machine-vision sorting offers significant potential for scale because its performance improves exponentially as more data is fed into its image-recognition database stored in a cloud network and shared across installations.

Disassembly of devices will soon also harness the rapid improvements in robotics. In closed-loop systems, robots can be fed with model-specific disassembly information stored in its product passport. In open-loop recycling systems, machine learning robots could learn how to dismantle new products from human colleagues.

Apple's disassembly robot Daisy can disassemble nine different iPhone models at a rate of up to 200 iPhones an hour, simultaneously segregating and removing components.[53]

Rethink Robotics develops smart, collaborative robots that learn new routines by following human movements as a person disassembles a product.

Product assembly and component information stored in product passports will make disassembly much easier in the future, as will the adoption of more circular design principles and communication standards for disassembly information.

At the final stage of the value chain, recyclers can report recycling information back into the IoM and feed back into the durable design tool on the circularity of product designs on a voluntary basis. The WEEE Forum, an association of European e-waste take-back systems, has a tool that allows downstream treatment facilities to report back on the treatment results of different products.[54] The circularity index could build on the methods and standards applied in such existing efforts. Data standardization and harmonization across markets and schemes will help to improve the data fed into the IoM. In addition to recyclers, other players along the value chain, like collection sites and sorting facilities, can input data into the IoM to increase transparency on materials flows.

How can we…

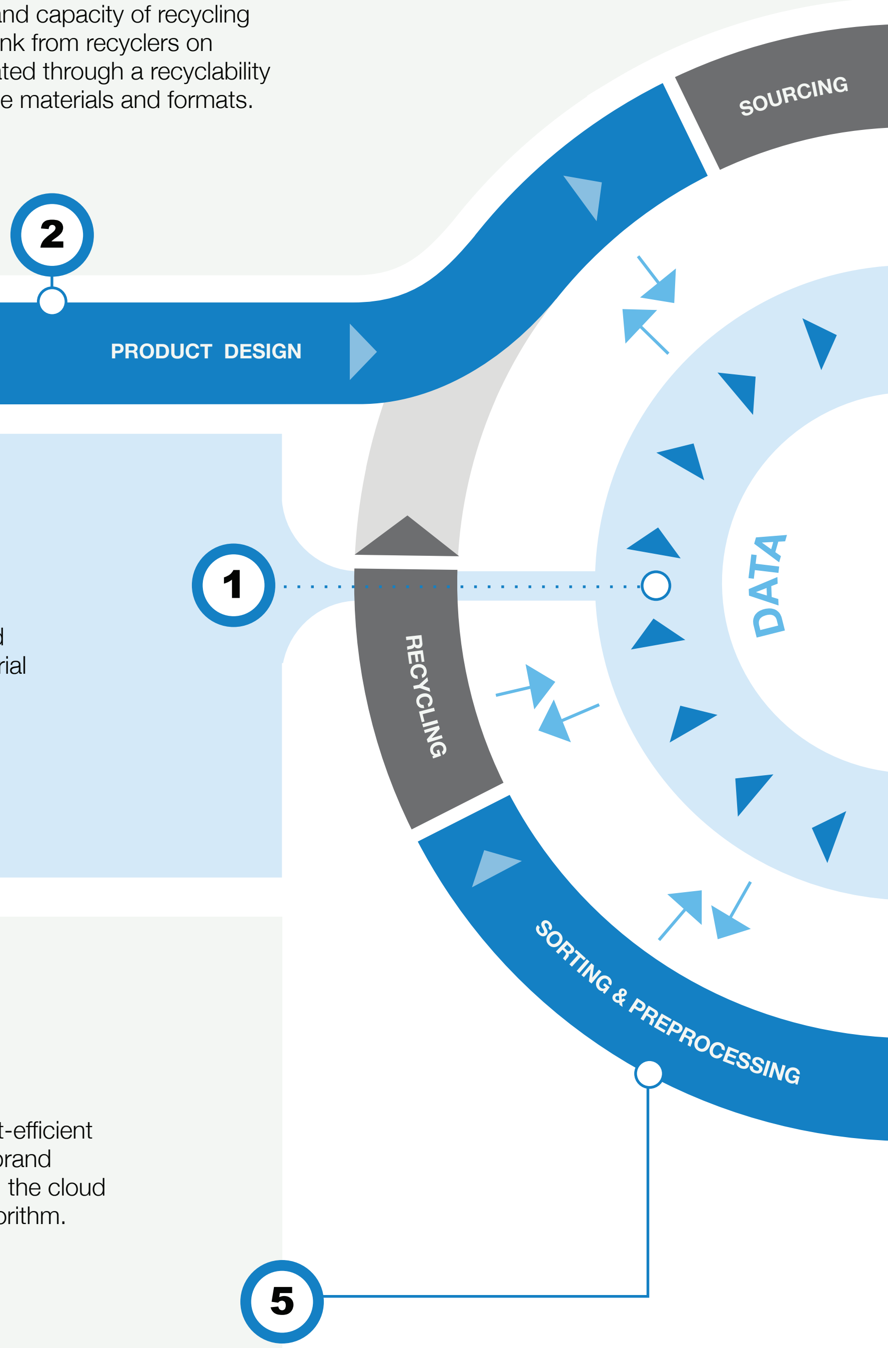
…Design for best possible after-use in a given market?

Durable design tool

Application for designers providing them access to data on recyclability of plastic types in target markets (based on availability, maturity and capacity of recycling infrastructure). The tool includes a voluntary feedback link from recyclers on design decisions. Insights from the tool are communicated through a recyclability index and support industry collaborations to standardize materials and formats.

Artificial Intelligence

Big Data



…Enable transparency on material flows?

Internet of materials

A decentralized data system building on a standardized dataset and communication protocols registering material flows across markets.

Cryptographic Anchors

Blockchain

…Optimize sorting and pre-processing processes?

Hyper-intelligent sorting systems

Machine vision and robotic-based sorting enabling cost-efficient and highly accurate sorting across material types and brand owners. Collected data across installations is stored on the cloud and used to continuously improve the identification algorithm.

Machine Vision

Robotics

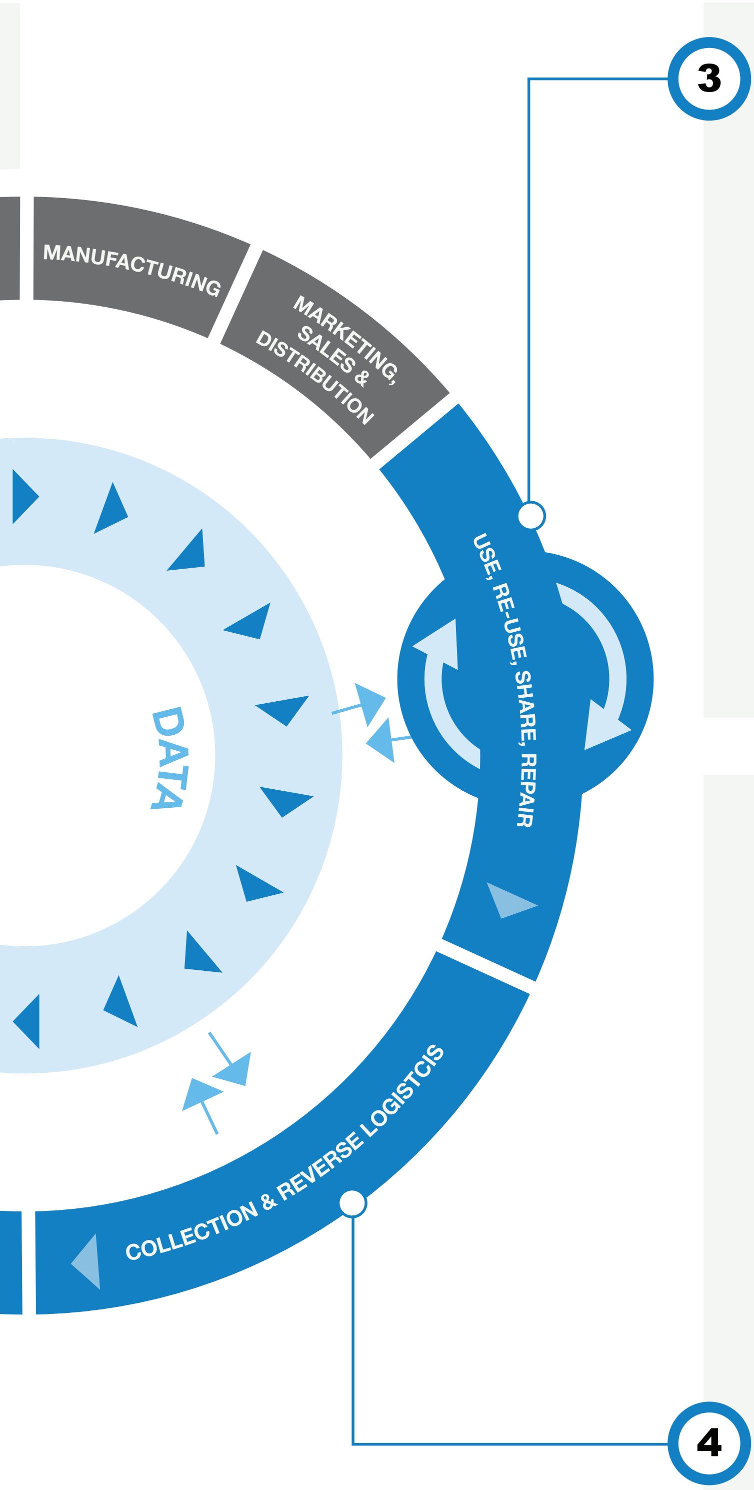
Visual signature sorting

Sorting of packaging by scanning visual signatures such as fluorescent markers using spectroscopy.

Cryptographic Anchors

Spectroscopy

Figure 5. Solutions along the plastics packaging value chain (Accenture, 2018)



...Enable efficient reuse of products?

Connected reusable packaging

Refillable premium packaging connected with IoT and offered through existing retail e-commerce and delivery services. The packaging signals to the supplier when content is running low and triggers the exchange of an empty package for a refilled one with the next delivery.

Big Data
Internet of Things

Smart in-shop dispensers

Refillable product dispenser systems to replace small format packaging in low-income countries. Dispenser systems are equipped with IoT and crypto anchors and connected to a block-chain based tracking system to mitigate risks of counterfeits and ensure timely refills.

Cryptographic Anchors
Blockchain
Internet of Things

...Optimize collection & reverse logistics?

Tokenized rewards system

Blockchain based rewards system using tokens to incentive local waste collection. Through immutable data entries, the system also provides reliable information on the sources of these recycled plastics.

Blockchain
Mobile

Connected bin system

IoT-equipped collection bins enabling smart logistics systems with optimized collection routing and frequency. Solar-powered compression functionality in bins can additionally reduce required collection frequency.

Artificial Intelligence
Internet of Things

Virtual waste management platform

Platform connecting individual waste collectors and transportation vehicle owners to make logistics more efficient, transparent and compliant. The solution enables tracking of waste management players and material flows.

Big Data
Artificial Intelligence
Internet of Things
Blockchain
Mobile

Plastics

How can we make material flows transparent?
To provide transparency on packaging contents (e.g. food or non-food), material composition and optimal recycling methods, a common dataset at a stock-keeping-unit (SKU) or batch level can be introduced for plastic packaging.

Downstream players can identify packaging materials at the SKU level through image recognition or by scanning a cryptographic anchor attached to or embedded into the packaging. IN-Code has developed advanced forensic markers in the form of programmable, tamper-proof, inert and edible chemical codes that can be embedded in materials, components, products or packaging to mitigate product counterfeits and enable traceability from source to end-of-life.

In the near future, such packaging data can be stored on an IoM, a decentralized data system using standardized communication protocols to allow a large number of parties to safely and efficiently exchange information. The information should include SKU-level information on the quantities, types and composition of plastics across markets and should be provided by producers as products are sold. Data access is managed on permission basis to allow downstream players to optimize sorting and treatment processes.

Global steel company SSAB offers a traceability tool called SmartSteel 1.0 that gives steel a digital identity. Customers can identify steel products by scanning its identifier, examine material properties, download certificates and give feedback. Subsequent producers can utilize and add to the data. The system is to be developed into a platform where actors across business boundaries can share data (e.g. with information to enable reuse and recycling).

The **Internet of Materials** can serve as a data input to EPR schemes while also making material streams transparent to allow for better forecasting and infrastructure planning. It should be governed by a neutral party responsible for setting data and protocol standards, permission-based access and quality assurance. In Germany, a Central Packaging Registry was introduced, that collects and manages material registration data of manufacturers, including data on quantities and types of packaging as part of the new German Packaging Ordinance and the new German Packaging Act in force since early 2019.

How can we design for best possible after-use in a given market?
To increase packaging recyclability, designers can use an AI-enabled application that supports **durable product design** and deploys a recyclability index to assess designs. The tool should build on existing design tools, metrics and guides, such as Nike's Making app using the Nike Materials Sustainability Index[55] or the APR Design Guide for Plastics Recyclability, and be expanded to include market specific design recommendations. Connected to the IoM, the tool assesses the contextual recyclability of a design using market-specific recycling infrastructure and capacity information. Business engagement in this area is increasing as consumer goods companies such as the Coca-Cola Company are mapping recycling potential across their markets with the ambition to match packaging design with market-level recycling capacity.[56]

In addition to contextuality, the tool also differs from existing applications in that it should be set up as an interactive platform where recyclers can feed back on packaging design choices. An upgrade to this solution would be a standard feedback loop in which recyclers (or an independent institution) test and confirm the recyclability of newly developed packaging before it enters the market.

South American waste management company TriCiclos has tracked the recyclability of packaging items flowing through its operations for over 10 years. It uses these insights to advise manufacturers on how to make designs more recyclable. This process is currently not yet automated but has led to the development of the company's own recyclability scoring system.

Key to success for the design tool is widespread industry adoption and agreement on the scope and methodology behind the index. If that is achieved, such an index can be used not just to optimize design, but also to incentive circular design choices through differentiated fees in EPR schemes rewarding more circular design practices.

Late 2018, the Dutch plastic packaging EPR scheme, Afvalfonds Verpakkingen, introduced a differentiated EPR fee for plastic packaging. The scheme works with the manufacturer's design administrators to audit packaging designs, and rewards manufacturers with more recyclable packaging with a 40% reduction in fees.

As material science advances, return to nature, rather than recycling, could also become a viable after-use pathway in certain contexts. Next-generation materials such as fully biodegradable and home-compostable plastics could soon be considered as material alternatives – if they are developed based on sustainable feed stock and processes, are fully bio-benign, safely degrade in natural environments and only if applied in contexts where strict separation from other streams is ensured. Bio-innovation in this domain is in its infancy, but with growing market demand, innovators like Polymateria and others are likely to be able to scale.

How can we encourage efficient reuse?
Reducing packaging is an essential step in achieving a circular economy for plastics. Some producers are already working towards more lightweight packaging.[57] Getting rid of packaging completely or introducing reusable packaging often requires new delivery models, which technology can make more efficient and cost-effective. For refillable consumer goods, such as detergent or shampoo, **sensor-equipped, reusable packaging** is a solution that can use existing e-commerce channels to deliver and return packaging. To work at scale, a combination of IoT sensors and big data analytics should be used to maintain the optimal number of packaging items in the system to best serve customers while controlling costs.

TerraCycle's Loop initiative launched early 2019 is an alliance of some of the world's largest consumer goods and retail players. Its reusable, premium packaging makes products such as shampoo refillable while providing extra features to the consumer. Home deliveries are made through existing e-commerce retail channels (e.g. local grocery deliveries). In the future, if these products are connected via IoT, the packaging signals when content is running low and triggers the exchange of a new package for the empty one upon the next delivery. Loop is being piloted in New York and Paris in 2019, with plans to scale rapidly across products and markets.

In low-income countries, small format packaging (e.g. sachets) is in common use to provide affordable access to daily items like shampoo or coffee, but due to their small size and low-value this packaging is often unrecovered. **Smart in-shop dispensers** can provide an alternative to reduce waste while still providing affordable products to local populations. Crypto-anchors, such as optic sensors that recognize materials by physical patterns, can be placed inside the dispenser. Furthermore, chemical or DNA markers can be embedded into the product to prevent substitution of the product with counterfeits. The IoT can trigger timely refills of the dispensers and optimize logistics across the installed base.

How can we optimize collection and reverse logistics?
In some countries official waste collection infrastructure and return schemes already exist, albeit with varying collection rates. In countries with existing centralized infrastructure, combining **sensor-equipped smart bins**, solar-powered compression and smart logistics systems is the next step to optimizing collection routing and frequency.

Ecube Labs has developed a smart compression bin that holds up to eight times more waste than traditional bins, reducing collection frequency by 80%. Companies like Enevo offer connected bins with sensors that communicate fill levels in real time. Data from the sensors can optimize collection frequency and routing, prevent overflows and save municipalities both time and money.

Where no municipal collection infrastructure exists, decentralized private collection, transportation and storage capacity can be deployed. Collection in such countries can be kick-started by **virtual waste management platforms** that connect waste-producing households and businesses with individual waste collectors, transportation vehicle owners and even connected bins to visualize and organize collection and logistics more efficiently. Vehicles with mobile-based GPS tracking and IoT technology can enable local tracking of waste flows and provide transparency on volumes available for recycling.

Banyan Nation in India developed a mobile and cloud-based technology platform that integrates the informal sector's last mile collectors. It collects, aggregates, and analyses data and therewith helps cities make waste management more effective and economical. Banyan has recycled over 7 million pounds of plastics and integrated over 2,000 informal sector waste workers in their value chain in Hyderabad.

Software-as-a-Service company Plataforma Verde works with Sao Paolo's municipal government to connect private firms collecting and transporting municipal waste. All vehicles are equipped with GPS trackers; transport manifests and invoices are tracked and stored on a blockchain solution to trace material flows, ensure proper disposal and provide actionable intelligence for the municipality. In addition, permits of participating companies are automatically checked against the municipality's permit database and warnings are sent when they are about to expire.

In the future, collection systems can be upgraded with a tokenized blockchain application that automatically remunerates individual waste collectors based on volumes collected. Blockchain can help to efficiently valorize waste by providing rewards in the form of digital tokens or coins, thus encouraging the correct disposal and timely collection of waste. Current schemes like WASTED dispense tokenized rewards to consumers upon disposal of waste in dedicated smart bins, while Troventum aims to become a global system, connecting and rewarding stakeholders throughout the value chain.

By enabling the valorisation of waste, **blockchain-enabled remuneration schemes** will play a big role in preventing plastics leaking into natural ecosystems. They can also improve local socioeconomic conditions. Plastic Bank has developed networks of collection points in Haiti, the Philippines, Indonesia and Brazil, where collectors can exchange plastic waste for services, items and money, either in cash or via a blockchain-enabled token system in a mobile app.

Blockchain-enabled tokens address the risk of theft and crime associated with cash rewards by providing digital rewards that people can safely receive and spend in local stores. They also generate immutable data on collected materials and help plastic recycled through its schemes to be sold at a premium, because it comes with proof of its socioeconomic impact and transparency on material flows.

How can we optimize sorting and pre-processing?
Machine vision and robotics can enable **hyper-intelligent sorting** of plastic waste. Machine vision solutions combine a camera, an AI algorithm and a robotic arm to pick waste off a conveyor belt, sorting it by material, polymer type and even brand. Such solutions are highly scalable as the data it collects as it identifies materials can be stored in a neural network in the cloud to further improve the learning algorithm across all installations. The solution can also detect contamination levels in plastic streams, providing valuable information on their purity and quality.

AMP Robotics uses machine vision and robotics to sort different plastics from mixed waste with 99% accuracy. Subsequent sorting by brand – for which accuracy rates are similar[58] – could even enable closed-loop recycling, where brand owners can organize and finance the specific recycling of their own waste streams.

Existing optical sorting systems (e.g. NIR) can be enhanced by **visual signatures** such as UV-responsive fluorescent markers. The technology is in the piloting stage, with commercial trials conducted in Germany as part of the PRISM project. The project consortium developed a UV marker usable by many modern NIR sorting units demonstrating yields in the range of 88% to 96% with purity levels up to 100% in a single pass.[59]

Impact at Scale: What is Needed?

The emerging tech-based solutions outlined here will only deliver a circular economy at scale and speed under the right enabling conditions. As a first step to creating those conditions, the following five system-level areas have been identified that require collaboration between industry and government leaders:

1. **Standards and regulation**

For a circular economy to work at scale, data will need to flow quickly and reliably up and down complex global value chains, passing through efficient and streamlined processes.

Standardize materials and design: Standards for design and materials (e.g. types, composition, additives) reduce technical challenges, enable economies of scale and make solutions like a global circularity index feasible. The British Standard for the Circular Economy (BS8001) and the European Ecodesign Directive are already setting design and communication standards for energy-related products. To standardize without stifling innovation, the standardization process should be an open, transparent and consensus-based process. Their specification should, if possible, be technology neutral and performance-based.[60]

Align processes: Standards for repair, maintenance and remanufacturing – and common methods for collection, sorting, treatment and quality assurance – increase efficiency and enable economies of scale. Emerging examples like the American National Standard for remanufacturing[61] can be bolstered by legal frameworks that support remanufacturing and repair, but indemnify the service provider against issues such as IP infringement.

Facilitate data interchange: This means agreeing on the data that is needed, and how it is defined and exchanged. A product passport with a standardized hierarchical dataset is required, as well as communications protocols that enable exchange between stakeholders, and standards for product anchoring (set voluntarily, with government-backed regulation to ensure widespread application).

Ensure data security: Improved transparency and traceability will increase data generation and use. Sensitive data means standards must be complemented with policies regulating data use and ownership. The EU's General Data Protection Regulation is a useful starting point and the Charter of Trust, signed by several global companies,[62] is an example of good practice.

2. **Change drivers**

For optimal outcomes on a product's journey down the value chain, actors must become stakeholders who are invested in passing it forward by carefully tailored incentives.

Push through policy and taxation: The best legislation is harmonized across jurisdictions, with all actors – producers and recyclers alike – fairly incentivized and equally accountable. Policy-makers can push change by designing policy and incentive frameworks ranging from fines for non-compliant waste handling to raising societal awareness by banning single-use items. Today, regulation on single-use plastics bags has been implemented in over 60 countries.[63]

Design targeted rewards: Businesses and governments should collaborate to establish effective cross-border EPR systems that distribute incentives equitably between actors. Data interchange and efficient transaction systems, such as tokenized reward schemes, can make benefits or incentives more transparent, differentiated and targeted. In the Netherlands, manufacturers of more circular plastic packaging now pay lower EPR fees.

Leverage social movement: Grassroots citizen action is an increasingly powerful driver of change. The issue of plastics pollution in particular has instigated a broad social movement driving action from both governments and businesses alike.

3. **Data-enabled infrastructure**

Many of the underlying technologies for circular solutions (e.g. blockchain and IoT) have not yet been combined effectively or implemented at scale. A data-enabled infrastructure to support the solutions should borrow two features of the "regular" internet that enhance its ubiquity and availability.

Ensure open-source interoperability: Individual innovations should be tailored to local market needs at the same time that a jigsaw of interoperable solutions is built up and down the value chain. Solution designers should consider how standards and solutions can be shared to speed progress.

Establish a globally distributed architecture: Data on transactions, rewards and usage needs to be quickly available along the entire length of global supply chains. A distributed architecture in which commercial, government and academic organizations share responsibility can create a system that is resilient, reliable and extensible at scale.

4. **Investment**

Scaling technology applications requires investment, especially in lower-income countries, where underlying infrastructure may be absent. Complementary to traditional funding sources, technologies like blockchain now enable anyone to invest in projects.

Drive for-profit investment: Manufacturers and retailers can reduce product externalities by investing in circular business models and product designs, and contribute to shared circular data infrastructure. As the circular economy opportunity materializes, banks such as ING, Rabobank, ABN Amro and Banca Intesa San Paolo, and funds such as Circulate Capital and Capricorn Investment Group, are investing in businesses that are poised to seize the competitive advantage of the circular economy.

To identify circular projects with robust business cases, for-profit investors need to:

– Co-develop business cases with small- and medium-sized enterprises that require investment, and develop new investment criteria and risk models appropriate for a circular economy

– Work with government agencies to provide blended finance models that can de-risk circular economy investments

– Work with non-governmental institutions to connect investors to circular projects

Provide public investment: The EU has led the way here, making $364 billion[64] available through the Circular Economy Finance Support Platform. When financing the implementation of 4IR technologies, it is important to ensure they are developed inclusively and their benefits distributed fairly. This means supporting lower income economies via intergovernmental investment programmes.

Harness stakeholder investment: Digital technologies like mobile payments, blockchain and cryptocurrencies can help make investments more transparent and smaller investments more cost-efficient. Until recently, waste management almost exclusively involved large-scale public and private infrastructure investments. Today, individuals can co-invest in projects. Netherlands-based WASTED, for example, allows a local hairdresser to invest in waste collection by offering discounts in exchange for tokens that customers earn by disposing plastic in dedicated containers. Similar schemes might soon let consumers donate earned tokens to, say, overseas waste collection or ocean clean-up projects.

5. **Innovation and entrepreneurship**

Entrepreneurism is a key driver of the circular economy. In 2019, entries to the Tech Disruptor category of the Circular Economy Awards[65] rose substantially to 136. There are three crucial features for any public or private organization that wants to create the best conditions for circular innovation.

Nurture collaboration: New collaborations – with governments, non-government and multinational organizations, start-ups, or academic institutions – can deliver new technologies, approaches and market access. LWARB's Circular London[66] and The Ellen MacArthur Foundation's CE100[67] programme are leading examples of this.

Embrace disruption: Moving from incremental improvements of existing products and processes to completely rethinking the way that value is created and delivered also creates access to new markets.[68] Philips Healthcare and HP are doing this as they move from selling products to circular services.

Build skills and capabilities: Envisioning the future, and creatively using technology to build it, requires competencies that sit at the intersections of sustainable innovation, technology, data science and supply chain management. Michelin, for example, is transforming from a product-focused company towards a solution provider. By establishing a circular incubator programme, it is identifying client needs and providing guidance on agility and engagement methods.

Conclusions

To make the consumer electronics and plastics packaging value chains more circular, there are five major challenges that must be overcome. The analysis has also shown that innovators are already building solutions around the new and emerging technologies of the Fourth Industrial Revolution. Even in demanding settings these technologies – applied in an interoperable way – can help to develop more sustainable waste management systems. To unleash the full potential of 4IR technologies, however, and make the next steps towards completely circular economies in both industries, three things need to happen:

1. **Digitize the material flows**

Connecting the material world to a virtual world of data will make the circular design, use and recovery of materials and products more efficient and effective by providing visibility, transparency and actionable intelligence. The quality and scope of existing data needs to be improved and made available for private, public and civic actors to design targeted interventions and system-level optimization.

2. **Join up solutions**

Most challenges can be addressed using technologies that already exist and are ready to scale. However, in complex and interconnected global value chains, no single solution can make the big leap to a circular economy. Connecting multiple solutions and applying technologies in an interoperable, distributed architecture is key to scaling impact. Large-scale collaboration, coordination and interlinkage between business value chain and public sector actors will be required to make this possible and to share the steps along the path to a circular economy.

3. **Drive systems leadership**

Governments and business need to create a shared vison for change that mobilizes global action to enable a cicular economy. As circular solutions emerge, international multistakeholder coordination will be required to agree upon the coordinating principles, develop the policies and incentives, and align the technical standards that will balance the economics and allow circular solutions to scale.

While elected leaders will naturally have a key role in advocating change and developing policy frameworks, the breakneck speed of the Fourth Industrial Revolution and the urgency of the challenges will require agile governance, where circular policies can be coordinated across geographic boundaries and rapidly reviewed and updated as a circular infrastructure develops. Business must also be willing to think beyond their own organizational structures and develop new norms for their customers and their own operations that seize the opportunity of the circular economy and ensure equitable distribution of benefits across borders. This will require new business models, deep collaboration up and down the value chain, and, often, change at the core of the business.

With this in mind, the public and private sectors are encouraged to set the right context, explore the technologies and deliver the solutions that will overcome the shared challenges of the two presented industries. Collaboration platforms such as PACE can bring these actors together and give them the best possible chance of harnessing the Fourth Industrial Revolution to build the circular economies that society urgently needs.

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Appendix

Appendix 1: Fourth Industrial Revolution technology descriptions (Accenture research, 2018)

Type	Technology	Description
Digital	Artificial Intelligence	Applies a set of technologies like machine learning and vision that enable machines to simulate human intelligence and act without explicit instructions Example: Artificial intelligence can be used, to enhance sorting of waste streams through AI-based robots
Digital	Big data analytics	Computationally analyses extremely large data sets to reveal patterns, trends, and dependencies Example: Big data analytics can be applied to improve forecast of waste streams or provide suitable material recommendations for certain markets
Digital	Blockchain	Draws on distributed ledgers storing an immutable record of transactions shared with multiple participants in a business network Example: Blockchain can be applied to trace the origin of components back through every step in the supply chain
Digital	Cloud computing	Retrieves information through web-based tools and application instead of a direct connection to a server Example: Cloud computing enables establishing a platform to connect customers and drivers for e.g. a waste transportation platform
Digital, physical, biological	Cryptographic anchor	Is attached to or embedded in a physical product as means of authentication to link a physical product to the related data stream e.g. in a blockchain. Anchors can have different security levels and be physical (e.g. Fluorescence markers), digital (e.g. RFID tags) or biological (e.g. DNA marker) Example: Cryptographic anchors can be chemical marker applied to consumer electronics with a unique composition ensuring authentication and preventing counterfeits
Digital	Digital Twin	A virtual model of a process, product or service, pairing virtual and physical worlds. This allows the analysis of data and monitoring of systems to develop new solutions or conduct predictive maintenance Example: Digital twins can be used to simulate the performance of electronic devices in different usage scenarios under varying conditions to develop maintenance solutions
Digital	Internet of things	Deploys wireless devices with embedded sensors that interact and trigger actions Example: Internet of things can connect smart bins with a platform to communicate information on their fill level
Digital	Machine vision	Provides a computing device with the ability to acquire, process, analyse and understand digital images, and extract data from the real world Example: Machine vision can be used in waste sorting enabling waste sorting robots to identify certain waste types for separation
Digital	Machine learning	Enables machines to perform new tasks after being trained using historic data sets Example: Machine learning can be used to improve algorisms optimizing routing in reversed logistics e.g. based on historic patterns
Digital	Mobile device	Accesses a cellular radio system to exchange voice and data without a physical connection to a network Example: Mobile devices can be used to participate in a reward scheme
Physical	Robotics	Applies machines that are programmed to automatically carry out a complex series of actions. Especially suitable for repetitive and rule based processes using structured data Example: Robots can be used to sort and pick objects with various weight and shape
Physical	UV/ IR/ NIR/ NMR Spectroscopy	Uses different spectrums of electromagnetic radiation to analyse material based on the molecular composition of the matter Example: Near infrared sensors can be used in waste sorting machines

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